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Chapter 1

FACTORS AFFECTING DIGITAL IMPLANT IMPRESSIONS: SCANNING TECHNOLOGIES, OPERATOR VARIABLES, AND CLINICAL APPLICATION DYNAMICS

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Digital impression systems are modern technologies that provide high accuracy, speed, and patient comfort in the production of implant-supported restorations. The success of these systems depends on the interaction of many factors, such as the scanning technology used, software algorithms, scanning protocol, implant positioning, and operator experience. This chapter discusses the main factors affecting digital implant impressions, including the characteristics of scan bodies, sensor technologies of intraoral scanners, scanning direction and arch length, optical noise, artifact formation, and operator experience in detail.

The development of digital dentistry marks a revolutionary transformation in the prosthetic manufacturing process compared to traditional methods in terms of speed, accuracy, and patient comfort. Today, digital impression systems (Digital Impression Systems) can record the surfaces of teeth, implants, and soft tissues in three dimensions through intraoral scanners (Intraoral Scanner, IOS), replacing classical elastomeric impression materials. These systems process the obtained optical data with CAD/CAM software, enabling the rapid creation of virtual models and speeding up the prosthetic production process (Ruhi & Akaltan, 2024).

The emergence of digital impression technologies began with the first CEREC (Chairside Economical Restoration of Esthetic Ceramics) system developed in the 1980s. This technology digitally recorded the morphology of the tooth and moved to the computer-aided manufacturing stage (Moreira et al, 2015; Mangano et al, 2017). Today, these systems play a critical role in achieving passive fit in implant-supported prostheses. Passive fit in implant-supported restorations forms the basis of treatment success, and achieving this fit is directly related to the accuracy of the impression stage (Marques et al, 2021; Lee et al, 2021).

In traditional impression methods, issues such as polymerization shrinkage of elastomeric materials, deformation of impression trays, gypsum expansion, or operator-induced errors are common (Ruhi & Akaltan, 2024). In contrast, many of these errors have been eliminated in digital methods. However, it cannot be said that digital impression systems are completely error-free, as impression accuracy and repeatability (trueness, precision) depend on a combination of both device and clinical factors (Revilla-León, 2023, Mangano et al, 2017).

The main factors affecting impression quality in digital systems are as follows:

Scan body design and material,

Intraoral scanner (IOS) technology and software algorithm,

Scanning protocol and arch length,

Image resolution, optical noise, and artifacts,

Operator experience,

Implant position, angulation, and gingival height,

Patient-specific clinical factors (saliva, reflexes, moisture, etc.).

The interaction between these variables explains why impression accuracy may vary in different clinical scenarios. For example, in single implant cases, the impression accuracy is high, whereas, in multiple implant or full arch impressions, errors appear as "cumulative deviation" (Abou-Ayash et al, 2022). Additionally, the angle at which the implant is placed (e.g., 0°, 15°, 30°) has a significant effect on accuracy; in vitro studies have shown linear deviations of up to 100-150 μm at 30° angulations (Marques et al, 2021).

Implant Placement Depth Also Affects Accuracy

It has been stated that when the implant platform is located below the gingiva, the visibility of the scan body decreases, causing axial shifts during the software's "best-fit alignment" process. In contrast, the accuracy significantly improves in implants that are closer to the surface (supragingival) (Kim et al, 2015).

Intraoral scanners rely on different technological principles: triangulation, parallel confocal laser scanning, active stereophotogrammetry, or near-infrared (NIR) systems. Each system has its own advantages and limitations. Triangulation systems are fast but are sensitive to optical noise on shiny surfaces, while confocal systems provide more detailed data but have longer scanning times (Revilla-León, 2023). Therefore, the type of device should be evaluated in conjunction with the size of the area being scanned (Abou-Ayash et al, 2022; Lee et al, 2021).

The accuracy of digital impressions depends not only on the device's performance but also on the software algorithms. The "mesh generation" algorithms of the software combine the scanned point clouds using triangulation methods. During this process, a "stitching error" can occur, which, particularly in full arch scans, can accumulate and lead to measurement deviation. In edentulous maxilla, these errors are often more pronounced at the ends of the arch (posterior regions) (Revilla-León, 2023).

However, the operator factor cannot be overlooked. Inexperienced users may struggle to maintain consistent scanning speeds and angles, leading to 40-70 μm differences between measurements taken with the same device (Moreira et al., 2015; Abou-Ayash et al., 2022). Particularly in full arch scans, the inconsistent movements and guidance errors of inexperienced operators can cause data loss, whereas experienced users minimize such systematic errors. These findings further emphasize the importance of operator training and standardized protocols in clinical applications.

In conclusion, digital implant impression systems are a technology that enhances clinical effectiveness, provides patient comfort, and saves time in modern dentistry. However, due to the numerous factors affecting impression accuracy, each system needs to be optimized for the clinical scenario. The structure of the scan body, the version of the software, scanning protocol, operator experience, and patient-specific biological variables are all dynamic factors that determine the final quality of the impression.

Fundamentals of Digital Impression Systems

Digital impression systems are technologies that completely replace traditional analog methods and make the impression process entirely optical-based. In these systems, the intraoral scanner digitally detects the three-dimensional topography of the oral tissues and converts the data into a processable model in the computer environment. The impression-taking process is carried out without any physical contact, which both enhances patient comfort and eliminates impression distortions (Kim et al, 2015). Scanners detect reflected or refracted light to record the surface geometry of teeth, implants, and surrounding tissues with high resolution. The obtained data is transferred to CAD (Computer-Aided Design) software in formats such as STL, PLY, or OBJ, and then taken to the production stage through CAM (Computer-Aided Manufacturing) systems (Button et al, 2024; Mangano et al, 2017).

The basic principles used in these systems include triangulation, confocal microscopy, active stereophotogrammetry, and near-infrared (NIR) scanning methods. In triangulation, light emitted from a light source strikes the surface at a certain angle and is reflected. The sensor calculates the angular difference of this reflection to determine the distance. This method is fast and economical, but the error rate can increase on shiny surfaces or in areas where light does not reflect uniformly (Revilla-León, 2023). Confocal microscopy-based systems, on the other hand, use light waves reflected from different focal depths to create a detailed surface

map; this method allows for high-resolution, colored models. However, the complexity of the system and the longer processing time can be limiting in clinical applications (Marques et al., 2021; Button et al., 2024).

Active stereophotogrammetry is based on the principle of mathematically combining multiple images taken from different angles to determine the surface topography. This technique provides high levels of detail and precision, especially in deep and difficult-to-reach areas like around implants (Mangano et al., 2017). Obtaining realistic surface features is critical for implant placement and prosthetic fit (Moreira et al., 2015; Kim et al., 2015).

Near-infrared (NIR) light-based systems use infrared spectrum instead of visible light, which is particularly effective in reducing the effect of optical blockers such as saliva, moisture, and soft tissue reflections. This allows for clearer definition of soft tissue boundaries, thus improving scanning accuracy, especially in fully edentulous cases (Wang et al., 2024; Gehrke et al., 2024). The advantage provided by NIR systems supports their preference in clinical situations where soft tissue definition is crucial in intraoral scanning (Revilla-León et al., 2023).

Digital scanning accuracy is not only dependent on the optical sensor capacity of the scanner but also on the software algorithms used in the data processing, which are essential components that directly affect measurement accuracy. The millions of point clouds collected by the scanner are converted into a triangular mesh structure through software. The "meshing" algorithms used in this phase, including interpolation and smoothing parameters, are critical factors that determine the scanning precision (Marques et al., 2021; Mangano et al., 2017). Excessive smoothing can cause a loss of surface details, while insufficient smoothing can introduce optical noise into the scan data (Kim et al., 2015). Particularly in full-arch scans, micro-level errors accumulated during the "stitching" process—where different scanning segments are combined by software— can lead to cumulative deviations in the measurements (Oh et al., 2020; Mai et al., 2022; Revilla-León et al., 2023). This situation can pose a significant clinical risk, especially in implant-supported prosthesis planning.

Moreover, the accuracy of digital systems is also influenced by environmental factors and optical conditions. During scanning, ambient light, surface reflectivity, gingival color optical properties, and moisture levels affect the scanner's light reflection performance (Moreira et al., 2015). Shiny metal surfaces (such as titanium abutments) create high reflections, causing the software to misinterpret the reflection as the actual surface. In such cases, the use of an "opaque agent" or a mattifying spray

is recommended; however, this application can lead to measurement deviation due to the film layer it adds, which is 20-50 μm thick (Kim et al., 2015; Gómez-Polo et al., 2022).

The foundation of digital impression systems is not only based on the hardware of the scanning devices but also on the entire set of optical physics, software algorithms, and environmental conditions. The most critical parameters affecting system accuracy include sensor quality, the software's data integration strategy, scanning protocol, surface optical characteristics, and the operator's application discipline. When the correct device is selected, appropriate scanning protocols are followed, and controlled environmental conditions are maintained, digital impression systems provide more reliable results in terms of both speed and dimensional stability when compared to traditional methods (Marques et al., 2021).

Scan Body

Scan bodies play a critical role in accurately transferring the three-dimensional positions of dental implants into the digital domain. The materials from which these components are made, such as titanium, PEEK, or resin, as well as their surface properties, directly affect the accuracy of the data obtained by optical scanners (Revilla-León et al., 2023). Metal surfaces with high reflectivity can cause light to bounce back, creating optical noise; on the other hand, PEEK bodies with matte surfaces provide more stable and repeatable results (Kim et al., 2015).

The micromechanical stability of the connection between the scan body and the implant is also crucial for scanning accuracy. Microscopic gaps or misfit in the connection area can cause the software to incorrectly interpret the implant's axis and center. Additionally, the geometric design of the scan body (especially the positioning of flat surfaces on its upper part) directly affects the accuracy of the indexing process (Moreira et al., 2015; Marques et al., 2021).

In multiple implant cases, splinting (fixing together) scan bodies can increase the overall stability of the system, but this practice can cause access difficulties and angular deviations, especially in mesial-distal tilted implants. Therefore, the literature suggests that un-splinted bodies be preferred for single implants, while splinting methods that are partially fixed but do not obstruct access should be designed for multiple implant cases (Revilla-León et al., 2023).

Intraoral Scanners and Software

The performance of intraoral scanners depends not only on hardware features but also on manufacturer-specific software algorithms. For example, scanners like Trios 5 (3Shape), CEREC Primescan (Dentsply Sirona), and Medit i700 have different optical principles, sensor structures, and data processing strategies (Pereira et al., 2021; Gómez-Polo et al., 2022). The scanning accuracy of these devices varies according to technical parameters such as resolution level, sensor type, the software version used, and calibration frequency (Pereira et al., 2021). Software algorithms play a decisive role, especially in the process of converting the point cloud data obtained by the scanner into a triangular mesh structure. The interpolation, smoothing, and filtering algorithms used in this process directly affect the accuracy of the measurement data (Kim et al., 2015; Marques et al., 2021). Especially in full-arch scans, error accumulation during data merging (stitching) can lead to cumulative loss of accuracy (Pereira et al., 2021; Oh et al., 2020).

Some scanner software includes digital filters that automatically correct missing or faulty scan data. However, these automatic corrections can sometimes lead to a loss of surface details and deformities in the measurement data (Kim et al., 2015; Oh et al., 2020). Therefore, to ensure the reliability of digital measurements, it is crucial to regularly apply the calibration procedures recommended by the manufacturer and keep the software versions up to date.

Scanning Protocol

The scanning protocol applied during the digital impression process is a decisive factor in the accuracy and repeatability of the obtained data. The scanning protocol includes parameters such as the starting point of the scan, the scanning direction, scanning speed, the distance between the scanner and the surface, and the density of data collection. These elements should be carefully controlled to minimize both individual and systematic error risks (Revilla-León et al., 2023). Each intraoral scanner manufacturer recommends a specific scanning route and technique tailored to the device's optical system and algorithmic structure. Therefore, it is critical for the operator to adhere to the standard protocol defined by the manufacturer to prevent data loss, alignment errors, and geometric distortions during scanning (Lin et al., 2025). Especially in full-arch scans or clinical cases involving multiple implants, deviations from the recommended protocol can lead to errors during the

data merging process, known as "stitching errors." This situation can result in cumulative deviations in measurement outcomes and clinical discrepancies (Revilla-León et al.,2023; Lin et al.,2025).

The direction and sequence followed during the digital intraoral scanning process are crucial for the quality of the obtained data and the software's ability to match surfaces accurately. In clinical practice, scanning typically starts from the occlusal surfaces, followed by the buccal and lingual/palatal surfaces. This approach allows the software to more easily identify natural anatomical reference points. However, when scanning starts from the vestibular areas, the lack of anatomical landmarks can make the model matching process more challenging, increasing the risk of cumulative errors, especially in the distal regions of the arch (Kim et al., 2015). In addition to the scanning direction, the position of the scanner inside the mouth, including the scanning distance and angle, are important parameters that affect the accuracy of the digital measurement. Holding the scanner tip too close to the surface can lead to optical errors such as reflections and shadows, while holding it too far can reduce the data density, resulting in missing or distorted surface details. The literature suggests that the optimum scanning distance is generally between 10-20 mm (Marques et al., 2021).

Furthermore, the angle of the scanner relative to the surface is particularly critical for accurately scanning the marginal areas around implants. An angle of approximately 45° ensures better recording of morphological details in these regions, while scanning at a perpendicular angle may reduce the clarity of marginal lines and transition areas (Kim et al., 2015).

Scanning Speed

Scanning speed is an important factor that directly affects the accuracy and integrity of digital measurements. In very fast scans, the system may not achieve adequate overlap between successive images, leading to the formation of "data gap" errors in the digital model (Pereira et al., 2021; Oh et al., 2020). On the other hand, extremely slow scans can result in system issues such as overheating of the device, processor load, and delays in the software's response time (Lin et al., 2025; Revilla-León et al., 2023). To avoid such technical limitations, intraoral scanner manufacturers typically recommend performing scans within a fixed speed range that ensures optimum performance. For example, capturing 15-20 frames per second helps maintain data density and reduces alignment errors (Mangano et al., 2017; Marques et al., 2021). The anatomical and environmental challenges that the operator encoun-

ters during the scanning process can also impact the quality of the measurements. Especially in the mandibular posterior regions, factors such as limited access, patient movement, inadequate lighting, and saliva accumulation can make it difficult to position the scanning tip properly and may lead to data loss in these areas (Ruhi & Akaltan, 2024; Gehrke et al., 2024). In such clinical situations, regional (segmental) scanning strategies provide an effective alternative. In the segmental scanning approach, intraoral structures are scanned in different sections, and then these data are merged using software. This method has been shown to reduce "stitching" errors in full-arch scans (Mai et al., 2022; Revilla-León et al., 2023).

Moreover, the operator's ability to maintain a constant scanning speed and consistent orientation during the scan enhances repeatability, and working within the device's hardware and software limits contributes to maintaining data accuracy (Lin et al., 2025; Marques et al., 2021).

Therefore, for clinical validity of digital measurements, strict adherence to the manufacturer-recommended scanning speeds and protocols is crucial.

The digital scanning protocol involves not only the operator's scanning sequence and direction but also the optical characteristics of the device, the patient's anatomy, and the overall clinical environment. When a standardized protocol is not followed, the high accuracy potential of digital measurements is lost. Thus, the scanning sequence, fixed speed, and optimum scanning angle should be maintained according to the manufacturer's guidelines, and device calibration should be performed before each session (Revilla-León, 2023; Oh et al., 2020).

Scanned Area and Arch Length

One of the fundamental parameters affecting accuracy in digital implant measurements is the size of the scanned area and the arch length. As the scanning area increases, errors during the software's process of merging 3D surfaces gradually increase. This is referred to as "cumulative error" or "stitching error," and it becomes more pronounced, especially in full-arch scans (Kim et al., 2015). In long-segment scans, the system's ability to capture reference points and align them decreases, leading to progressively lower measurement accuracy along the segment. The digital scanning process involves collecting millions of point data from different regions of the surface. The software overlaps these point clouds to create a 3D "mesh" model. With each new image frame added, small alignment discrepancies occur. While these discrepancies are typ-

ically insignificant in short segments, they accumulate over long arches and can lead to substantial deviations. In full-arch scans, as the length of the scan segments increases, accuracy significantly decreases, and systematic errors increase in scans longer than 60 mm (Kim et al., 2015; Pereira et al., 2021).

Cumulative Errors in Edentulous Jaw Models

Such cumulative errors are more pronounced in edentulous jaw models because anatomical reference points (e.g., cusps, fissures, and tooth contours) are absent in these cases. This absence makes it difficult for the software to accurately determine the positions of implants, leading to the accumulation of measurement errors, especially at the distal areas of the arch. In edentulous arch scans, the software generally uses implants in the middle region as a reference, while positioning the end implants based on estimation, which increases deviations. The literature mentions that in long arch scans, deviations between 80-120 µm are observed in 3D coordinates, and these deviations can negatively impact the passive fit of restorations (Kim et al., 2015; Pereira et al., 2021; Revilla-León et al., 2023).

In long arch scans, such as those of the edentulous maxilla and mandible, the limited anatomical reference points negatively affect the spatial perception of digital systems, leading to accuracy loss. This issue has paved the way for the development of segmental scanning strategies. The segmental scanning method involves dividing the arch into three or four separate sections, scanning each segment independently, and then merging them digitally. This approach not only reduces the scanning time but also minimizes the cumulative error rate. The literature states that segmental scanning techniques, especially in full-arch implant measurements, effectively minimize cumulative errors and increase measurement stability (Mai et al., 2022; Marques et al., 2021; Wang et al., 2024).

Furthermore, the scanning sequence also has a significant effect on measurement accuracy. In clinical applications, scanning from the posterior region to the anterior region is usually preferred; however, some studies have suggested that starting from the middle of the arch can reduce the cumulative errors in the distal regions (Gehrke et al., 2024; Pereira et al., 2021). Nevertheless, the posterior-anterior direction is commonly used due to operator control and ease of access. Taking short breaks during scanning, particularly in full-arch cases, can enhance the device's data processing stability and reduce error rates (Button et al., 2024; Lin et al., 2025). As the size of the scanned area increases in digital measurement systems, accuracy decreases. Therefore, for long arch measurements, segmental

scanning should be preferred, the software's reference matching algorithms should be up to date, and the scanning path should be planned from the middle outwards. Clinically, high accuracy is maintained in short segments of up to three units; however, for full-arch implant-supported restorations, it is recommended to carefully assess digital measurements and, if necessary, support them with photogrammetric systems (Revilla-León, 2023).

Image Resolution

In digital measurement systems, image resolution is one of the key parameters that directly affects measurement accuracy. Resolution refers to the number of points (pixels or data points) that the scanner can detect per unit surface area, and this value varies depending on the sensor technology, the quality of the optical system, and the type of light source used (Marques et al., 2021; Pereira et al., 2021). High-resolution scanners can successfully capture micron-level details on the surface, but this leads to a significant increase in data volume. Therefore, processing the obtained high-density data may result in extended processing times, depending on the computer hardware capacity and optimization of the software algorithms (Lee et al., 2021; Kim et al., 2015). In this context, achieving a balanced optimization between resolution and processing efficiency is crucial for successful outcomes in clinical applications (Gómez-Polo et al., 2022).

Image resolution is not only related to the number of sensors but also to the wavelength of the laser used and the detection algorithm. Short-wavelength lasers (e.g., blue or green lasers) detect surface details more sharply, while long-wavelength infrared light sources provide deeper tissue penetration but may reduce edge sharpness (Kim et al., 2015). Additionally, the arrangement of the sensor array also affects resolution: in square-arranged sensors, horizontal and vertical axes are measured with equal precision, whereas in circular-arranged sensors, data density may decrease, particularly at the edge regions. For this reason, manufacturers are developing hybrid systems by combining different sensor geometries and light sources (Revilla-León, 2023).

High-resolution scanning provides significant advantages, especially in critical areas such as the implant neck, marginal edges, and occlusal morphology, by reflecting the surface topography more precisely and accurately (Kim et al., 2015). However, as resolution increases, sensitivity to optical noise also rises, as the scanner can detect even the smallest surface reflection or particles as data. This phenomenon

often results in the formation of parasitic data on metallic abutment surfaces and causes fluctuations on the model surface. Therefore, selecting the resolution based on clinical needs is important. For single tooth or localized implant applications, high resolution is preferred, while for full-arch scans, moderate-resolution modes provide more consistent and stable results (Marques et al., 2021; Lin et al., 2025). The software's data optimization process, i.e., point cloud filtering and mesh optimization, directly determines the impact of scanning resolution. Raw data obtained from the scanner is processed by the software, removing unnecessary points and converting surfaces into a triangular mesh structure. The excessive use of "smoothing" and "decimation" parameters at this stage can lead to the loss of surface details (Revilla-León, 2023). On the other hand, insufficient filtering may increase the file size, adversely affecting the software's processing and rendering performance. Therefore, carefully optimizing data processing parameters is crucial for both preserving details and keeping processing times at reasonable levels (Marques et al., 2021; Pereira et al., 2021).

There is a notable relationship between image resolution and accuracy in digital measurements; however, this relationship is not linear. Very high resolution does not always guarantee better results, as increased data density can overwhelm the software's processing capacity and cause measurement deviations. Therefore, resolution selection should be optimized considering clinical needs, the optical properties of the device, and software performance. In this context, various studies support that digital measurements obtained at appropriate resolutions provide similar or higher dimensional accuracy compared to traditional silicone-based measurement techniques (Marques et al., 2021; Pereira et al., 2021; Mai et al., 2022).

Optical Noise

Optical noise is one of the primary sources of error that negatively affects measurement accuracy in digital measurement systems. This phenomenon occurs when light beams emitted by the scanner are distorted due to reflection or refraction during their interaction with the surface. Sensors may interpret these distorted light signals as actual surface data, leading to errors at the micron level (Kim et al., 2015). Highly reflective surfaces, such as metallic restorations, ceramic crowns, and wet gingival tissues, change the direction of reflected light, reducing the measurement precision of the sensor. As the scattering angle of light on the surface increases, the signal-to-noise ratio (SNR) decreases, which creates a favorable environment for

noise artifacts in the digital model (Marques et al., 2021; Gehrke et al., 2024). In full ceramic crowns with high reflectivity, the increased amount of reflection often leads to the misinterpretation of surface details by the software, and irregularities are commonly observed in the marginal areas of digital models. Metallic or shiny surfaces reflect part of the light back to the scanner while scattering the rest, which disrupts data homogeneity. This results in decreased scanning accuracy, especially on surfaces such as titanium abutments or polished metal frameworks (Revilla-León et al., 2023).

To mitigate the reflectivity issues that negatively affect scanning accuracy, scanner manufacturers often recommend using opaque agents (matting sprays). The opaque agent reduces the surface reflectivity, allowing light to scatter more uniformly and improving the quality of the signal detected by the sensor. This way, the surface topography is recorded more consistently and accurately. However, the thickness of the matting layer is a critical factor; excessive application may negatively affect measurement accuracy, as the added material increases the surface's thickness. Literature suggests that the optimal thickness for the matting layer is between 20-30 µm, and measurement errors increase significantly when the thickness exceeds 50 µm (Marques et al., 2021; Lin et al., 2025). Therefore, it is recommended that the matting agent be applied as thin and uniform as possible and that the surface's uniformity is carefully checked before scanning.

One of the major sources of optical noise is intraoral environmental conditions. Factors such as saliva, blood, and condensate moisture create a thin microfilm on the surface during scanning, causing changes in the refractive index of light. This can prevent sensors from measuring distances correctly and lead to measurement errors (Moreira et al., 2015; Marques et al., 2021). Additionally, in subgingival implant areas, moist soft tissue structures may absorb light, causing deviations along the implant axis (Gehrke et al., 2024). In such cases, it is recommended to dry the area using air spray or to retract soft tissues using retraction cords before scanning to improve measurement accuracy (Kim et al., 2015; Pereira et al., 2021).

In clinical applications, optical noise is most often observed on shiny metallic surfaces, ceramic restorations, and gingival-implant junctions. In these areas, digital scanning software may misinterpret surface contours as missing or excessive data, leading to faulty representation and marginal fit problems on the model (Kim et al., 2015; Marques et al., 2021). Especially in multiple implant applications, these data losses may impair passive fit and negatively affect the clinical success of the restoration (Re-

villa-León et al., 2023; Pereira et al., 2021). Therefore, it is essential to ensure that surfaces are clean, dry, and homogeneous before scanning in a clinical environment. Reducing light reflections by applying a minimal amount of opaque agent to shiny surfaces enhances scanning accuracy (Gehrke et al., 2024; Marques et al., 2021).

Optical noise is an inevitable physical side effect of the digital scanning process, but it can be significantly reduced with effective control strategies. Ensuring proper lighting conditions, keeping the surface dry, using matting agents in a controlled manner, and optimizing software filtering parameters minimize the impact of such parasitic data on measurement accuracy. Additionally, advanced AI-supported software, which can recognize light reflection patterns and filter out parasitic data, has the potential to reduce the clinical effects of optical noise (Revilla-León, 2023).

Artifacts

Artifacts are types of digital distortions that occur during the digital measurement process and reduce measurement accuracy. They typically arise when inconsistencies occur in the surface data recorded by the scanner or when the system misinterprets optical signals (Kim et al., 2015). Artifacts often occur when the scanner's speed, angle, or focus distance changes and are observed as clusters of erroneous points in the "point cloud" data. These faulty clusters can be interpreted as actual surfaces by the software and cause surface undulations or geometric deformations in the three-dimensional model. The frequency of artifacts increases, particularly around implants, soft tissue boundaries, and regions with high reflectivity (Marques et al., 2021; Revilla-León et al., 2023).

One of the main causes of artifacts is instability in scanner movement and lack of operator control. When the device is moved for scanning without a fixed speed and angle, it results in "frame mismatch" errors. This causes the system to misalign images taken from different angles when overlaying them (Revilla-León, 2023). Clinically, especially in the posterior regions of the mandible, access difficulties create the potential for the scanner to change direction, leading to noise in the image. Sudden directional changes can compromise data integrity, especially in delicate areas such as the high-reflectivity regions around implants, leading to deviations in the model (Revilla-León et al., 2023).

Another significant source of artifacts is soft tissue movements. When the patient's tongue, cheeks, or lips move during scanning, the sensor may interpret this movement as "additional surface" (Kim et al., 2015). This

results in clusters of "redundant data" in the obtained model. Additionally, during scanning, the accumulation of saliva, air bubbles, or gingival vibrations can alter the optical reflection pattern of the surface, leading to "shadowing artifacts." Shadowing is often seen around the implant neck or in deep grooves. These shadowed areas are generally interpreted by the software as missing data, and some software attempts to automatically fill these gaps using "auto-completion" algorithms. However, since these corrections are often based on estimation, they do not accurately reflect the true surface geometry, thus reducing measurement accuracy (Marques et al., 2021; Mai et al., 2022).

Software-related artifacts are a significant issue in digital measurement systems. Raw data from the scanner is processed by the software using "filtering" and "smoothing" algorithms; these processes remove anomalies or outliers and provide a smoother appearance for the model (Revilla-León, 2023). However, when these filters are applied excessively, there is a risk of erasing the actual morphological details of the surface. For example, very high "noise thresholds" or excessive "smoothing" values can distort critical details, especially at the implant-gingiva junction, leading to measurement deviations in the model. On the other hand, keeping the filtering values too low may increase data noise, causing the software's "meshing" process to produce irregular triangular mesh structures (mesh deformations), and data integrity is compromised. This imbalance may manifest in the model as cracks, holes, or surface inconsistencies. In this context, adjusting the software parameters to appropriate levels is critical for preserving surface details and ensuring the structural integrity of the model (Marques et al., 2021; Pereira et al., 2021).

Additionally, the performance of mesh optimization techniques used during scanning (e.g., decimation, hole filling) also depends on the software's architecture and algorithmic precision. The software versions and updates applied during this process can directly influence the tendency for artifact formation (Oh et al., 2020; Button et al., 2024).

Various strategies can be applied at both the clinical and technical levels to reduce artifacts. Clinically, basic precautions include ensuring that the patient remains still during scanning, retracting the tongue and cheeks, and keeping the oral environment dry. It is recommended that the operator maintain a fixed hand position, moving the scanner at a distance of approximately 15-20 mm from the surface and at a 45° angle with a steady speed (Lin et al., 2025). Additionally, the surrounding lighting must be balanced, as external light sources can interfere with the sensor signal and create parasitic data. On the software side, it is optimal to keep filtering parameters at a "medium level"; for example, keeping the

"smoothing" rate in the range of 0.3% to 0.5% minimizes both optical noise and surface deformation (Marques et al., 2021; Gehrke et al., 2024).

Artifacts are multi-factorial errors that negatively impact digital measurement accuracy, originating from optical, software, and operator-related factors. Instability in scanner movement, inadequate environmental conditions, reflection, and light refraction, along with the unstable use of filtering algorithms in the software, all contribute to artifact formation. This situation especially compromises data integrity around implant necks, marginal edges, and reflective surfaces.

However, these negative effects can be significantly reduced with proper clinical and digital protocols. Stable hand movement, correct scanning angle and speed, keeping the surface dry, carefully matting shiny areas, and optimizing software filter settings are effective in limiting artifact formation (Kim et al., 2015; Marques et al., 2021).

Moreover, next-generation scanning software, with advanced algorithms, has the potential to better recognize artifact sources and filter them out from the data set, enhancing the accuracy of digital measurements. Specifically, AI-supported systems' ability to analyze optical noise and alignment errors in real-time will advance the reliability of digital measurement technology (Revilla-León et al., 2023; Oh et al., 2020).

Operator Experience

Among the factors affecting digital measurement accuracy, operator experience stands out as one of the most variable and user-dependent parameters. Regardless of the technological level of the scanner hardware or the processing capacity of the software, the accurate and efficient use of the system largely depends on the operator's clinical skills, knowledge level, and ability to understand the optical features of the device (Kim et al., 2015).

The operator's hand stability during scanning, ability to maintain a fixed scanning angle, sustain the proper scanning speed, and adapt the device according to surface conditions directly affect the quality of the obtained data. Specifically, in full arch and multiple implant scans, it has been reported that experienced operators generate more consistent and accurate digital models, whereas inexperienced users encounter more alignment errors and data loss (Marques et al., 2021; Revilla-León et al., 2023).

Therefore, for the successful application of digital scanning protocols,

it is crucial for operators to reach an adequate level of both theoretical knowledge and practical experience, as well as to be well-versed in the manufacturer's guidelines for the system used.

Operator experience is one of the key factors that determines the accuracy of digital measurements, especially in ensuring the stability of the scanning path and speed control during the scanning process. Moving the scanner at an inconsistent speed or frequently changing the scanning angle makes it difficult for the software to correctly align sequential images, leading to data merging errors, known as "stitching errors." These types of errors can significantly affect the overall geometric accuracy of the model, particularly in full arch and multiple implant cases (Revilla-León, 2023).

Experienced operators are able to control the scanner's focal length and movement speed more consistently, allowing the software to collect more homogeneous data without losing surface tracking (Oh et al., 2020). Additionally, these users can quickly detect system alerts, such as "tracking loss," and rapidly correct the scanning position, minimizing data loss. This reflexive control is related not only to the operator's device handling experience but also to their conceptual understanding of digital scanning algorithms.

Edentulous cases and multiple implant measurements are clinical situations where the effect of operator experience on digital scanning processes becomes more evident. In these cases, the limited anatomical reference points make it difficult for the software to match the three-dimensional model. Especially in regions with insufficient morphological data or areas that are not properly aligned, strategically planning the scanning path plays a critical role in measurement accuracy (Revilla-León, 2023; Oh et al., 2020).

Experienced operators can reduce alignment errors in such cases by segmenting the scan, selecting appropriate starting points, and keeping the scanner movement stable. Furthermore, since proper calibration of the device directly impacts the performance of optical sensors, it is essential for the operator to be familiar with system calibration and daily check protocols. Incorrect calibration negatively affects the software's data interpretation ability, causing small user errors to be magnified in the model.

Therefore, in edentulous models with limited reference points or in extensive implant-supported rehabilitations, involving an experienced operator is considered crucial for the reliability of digital measurements.

Conclusion and Recommendations

When applied correctly, digital implant measurement systems provide accuracy equivalent to or superior to traditional methods. However, high precision depends not only on the device's performance but also on the holistic control of human factors, environmental conditions, and protocol standardization. In this context, the widespread adoption of AI-supported scanning software, automatic optical correction systems, and photogrammetric hybrid technologies is expected to further enhance the accuracy and repeatability of digital measurements in the future.

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Chapter 2

FACIAL SCANNING IN PROSTHODONTICS: FROM CLINICAL APPLICATIONS TO THE VIRTUAL PATIENT CONCEPT

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1. Introduction

Advancements in digital technologies have led to profound transformations in dental practices. Today, intraoral scanners and computer-aided design and computer-aided manufacturing (CAD/CAM) systems have become standard procedures in dental restorations. As an extension of this digital revolution, facial scanners have started to be integrated into clinical workflows and have risen to prominence in the field of dentistry. Facial scanners are optical systems that capture the face and head region of an individual in high precision, transferring them into a three-dimensional digital format. The data obtained through this process can be used in various areas such as diagnosis, treatment planning, and patient-doctor communication. In fact, the use of facial scanning technologies in dentistry is not a new concept. In the early 1990s, Moss and colleagues (1991) were the first researchers to routinely use 3D laser scanning systems in clinical settings to monitor the growth and development of children with facial deformities. Later, in 2009, Lee and colleagues used this technology by analyzing craniofacial surface structures obtained from digital photographs to predict obstructive sleep apnea. With the acceleration of technological advancements, facial scanning systems have shown significant progress both in terms of accessibility and economic feasibility. Three-dimensional visualization forms the foundation for accurate diagnosis and effective treatment planning in prosthetic rehabilitation. Through facial scanners, it has become possible to digitally analyze the data obtained before and during treatment.

Facial scanning technologies offer a new paradigm in prosthetic dental treatment, particularly in aesthetic planning, functional evaluation, and patient communication (Donato et al., 2022). The face is at the center of both the aesthetic and phonetic integrity of an individual. Therefore, dental restorations need to be in harmony not only within the intra-oral anatomical boundaries but also with the general morphology and dynamic movements of the face. However, traditional two-dimensional photographs and manual measurements are insufficient in reflecting this multidimensional relationship (Coachman & Calamita, 2018). In this context, three-dimensional (3D) facial scanning technologies enable dentists to digitally record both static and dynamic facial data, contributing to the creation of virtual patient models. The concept of the virtual patient model is created by combining facial scanner, intraoral scanner (STL), and cone-beam computed tomography (CBCT) data. This digital model simplifies diagnostic processes, enhances the accuracy of patient analysis, and strengthens communication with the laboratory. Additionally, it allows the simulation of treatment outcomes in a digital environment. Shuto et al. (2025), in a comprehensive review examining the use of these

technologies in the dental literature, reported that facial scanning has rapidly spread, particularly in prosthetic dental treatments, orthodontics, and maxillofacial rehabilitation. Today, facial scanning systems are effectively used in aesthetic analysis, implant planning, occlusal evaluation, prosthetic design, and pre-treatment simulation processes.

2. Fundamentals of Facial Scanning Technologies

2.1. Definition and Conceptual Framework

Facial scanning technology refers to systems that recreate the individual's facial morphology in a three-dimensional digital format. These systems are based on structured light scanning, laser scanning, computed tomography (CBCT), and stereophotogrammetry principles (Shuto et al., 2025). The resulting 3D facial data can be used as an aesthetic reference in prosthetic planning or combined with intraoral scan data to create a virtual patient model.

2.2. Technologies Used

While digital technologies and facial scanners offer significant advancements in dentistry, the biggest barriers to the widespread adoption of these systems are high costs and the challenges of adapting to new technology. Understanding how facial scanning systems can be integrated into digital workflows will help clinicians better grasp the use of these technologies.

Currently, the facial scanners in use are generally based on four fundamental principles: photogrammetry, stereophotogrammetry, structured light, and laser scanning (Donato et al., 2022; Srinivasan et al., 2025). These technologies are classified into two primary operational approaches: passive and active systems.

Passive systems: The individual's face is modeled in three dimensions using two or more photographs taken from different angles (photogrammetry, stereophotogrammetry).

Active systems: The surface geometry of an object is detected in three dimensions by using light patterns or laser beams (structured light and laser scanning).

The common advantage of all these systems is that they are non-invasive, repeatable, and provide high-accuracy data. Photogrammetry is

a technique originally developed in mapping and topographic measurement fields. In this technique, photographs taken from different angles are combined through specialized software to create a three-dimensional facial model. Stereophotogrammetry, on the other hand, enables the creation of a 3D structure by photographing the object from two different planes and allows for distance, surface area, and volume calculations. However, this method may suffer from accuracy loss on bright or reflective surfaces (such as skin or hair). Structured light systems project a specific light pattern onto the surface, and cameras analyze the distortion of this pattern to compute the three-dimensional shape. Systems using blue light cause less reflection due to the shorter wavelength, resulting in higher accuracy than white light systems. Laser scanning systems measure the reflection of laser beams from the object's surface to calculate the three-dimensional shape. However, to achieve a complete facial scan, multiple scans from different angles are required. Laser systems offer extremely high accuracy, but the processing times are longer compared to structured light systems (Srinivasan et al., 2025). (Table 1).

The data obtained from these systems are typically exported in STL, OBJ, or PLY formats and can be processed using computer-aided design (CAD) software. Facial scan data are utilized in the early stages of the digital workflow to guide aesthetic planning. For instance, a facial scan aligned with intraoral scan data allows visualization of the relationship between the restoration and elements such as lip support and the smile line within the CAD environment.

Table 1: General Working Principles of Facial Scanning Technologies

Technology	Principle	Advantages	Limitations
Structured Light	Based on the distortion and reflection of projected light patterns on a surface	Fast, high-resolution, suitable for clinical use	Sensitive to lighting conditions
Laser Scanning	Based on distance measurement using laser beams	High accuracy and stability	Slow processing time, high cost
Photogrammetry / Stereophotogrammetry	3D modeling from 2D photographs taken from different angles	Low cost, compatible with mobile systems	Prone to lighting and exposure errors

Technology	Principle	Advantages	Limitations
Infrared Depth Sensing	Calculates depth maps (e.g., TrueDepth, Artec Eva)	Fast and portable	Limited accuracy, higher error rate in dynamic facial expressions

2.3. Accuracy of Facial Scanners

The clinical validity of facial scanning systems depends on the accuracy and precision of the data they produce. A key indicator of a system's effectiveness is the degree to which the digitally generated three-dimensional (3D) facial model corresponds to the individual's actual anatomical structure.

Accuracy is assessed based on two fundamental parameters:

Trueness: The degree to which the measured values correspond to the actual dimensions.

Precision: The consistency of repeated measurements yielding similar results.

These parameters directly affect the clinical reliability of facial scanning systems. Studies have shown that structured light scanners offer higher resolution and accuracy compared to other optical systems. Stereophotogrammetry is particularly effective for evaluating volumetric changes in facial morphology, such as soft tissue volume, swelling, or muscle activity. Laser scanning systems, while capable of sub-millimeter precision, may pose certain limitations in clinical settings due to longer scanning durations and sensitivity to patient micromovements.

Differences in accuracy can be influenced by a variety of factors, including sensor type, camera resolution, lighting conditions, surface reflectivity, and patient motion. Accuracy tends to decrease in dynamic regions such as the lips, eyelids, and cheeks, compared to more stable areas like the forehead or nasal bridge. Therefore, during facial scans, patients are typically advised to maintain a neutral expression without facial movement.

In clinical accuracy assessments, data obtained from various facial scanners are often compared with cone-beam computed tomography

(CBCT) or validated photogrammetric reference datasets. Most studies report that modern structured light systems achieve a mean deviation below 0.3 mm, which falls within the clinically acceptable threshold for prosthetic planning and aesthetic analysis (Ayoub et al., 2019). However, due to technological variations between different scanners, comparative evaluations should be conducted carefully. In clinical practice, the required level of accuracy should always match the intended application—acknowledging, for instance, that orthognathic surgery planning and smile design may have differing precision demands.

3. Clinical Applications of Facial Scanners in Dentistry

Facial scanning technology has a wide range of applications across various disciplines of dentistry, including diagnosis, treatment planning, simulation, and patient communication. When integrated into a digital workflow, it significantly enhances both the accuracy and predictability of clinical procedures.

3.1. Digital Smile Design and Aesthetic Planning

In aesthetic dentistry, facial scanning systems have become an integral part of Digital Smile Design (DSD). Capturing the face in natural rest, maximum smile, and various smile lines in a digital format enables clinicians to evaluate tooth shape, color, and position directly on the virtual model. This technology plays a crucial role not only in fixed prosthetics but also in complete dentures and provisional restorations by improving both functional and aesthetic outcomes.

In aesthetic planning, it is essential to design teeth not only within intraoral anatomical limits but also in harmony with the overall facial appearance. Facial scanners allow digital assessment of the smile line, lip dynamics, and facial midline. As a result, tooth form, length, and position can be optimized to align with facial proportions during the digital design process.

Lee et al. (2022) reported that digital facial scanning offers a reliable reference for determining the tooth-lip relationship in smile design. Additionally, facial data enable better evaluation of how teeth relate to surrounding facial soft tissues, guiding clinicians toward restorations that appear more natural.

3.2. Complete Denture and Implant-Supported Prosthesis Planning

In cases of complete edentulism, facial scans provide a digital means of assessing the vertical dimension**,** midline**,** phonetics, and lip support. This approach offers an alternative to conventional techniques and allows for the customization of prosthetic aesthetics based on the individual's facial morphology.

Moreover, when combined with intraoral scan data (STL) and CBCT imaging, facial scans contribute to the construction of a virtual patient model, which enables implant positioning to be planned with both aesthetic and functional considerations in mind (Donato et al., 2022).

3.3. Orthognathic Surgery and Maxillofacial Rehabilitation

In orthognathic surgery planning, facial scanners are used alongside CBCT data to simulate the interaction between bone structures and soft tissues. This allows for a visual preview of the postoperative facial outcome, which enhances patient communication and understanding of the proposed treatment.

Similarly, in maxillofacial rehabilitation following trauma or tumor resection, facial scans contribute to the design of custom prostheses with high accuracy, ensuring optimal fit and natural appearance.

3.4. Dynamic Facial Analysis

Unlike static scans, dynamic facial scanning analyzes the behavior of facial muscles during functional movements such as speaking, smiling, or chewing. This approach is particularly valuable in evaluating phonetic harmony and facial muscle coordination (Du et al., 2019). Dynamic facial data support the functional aspects of digital smile design, ensuring restorations are not only aesthetically pleasing but also biomechanically compatible.

3.5. Education and Patient Communication

Facial scanning significantly enhances patient communication. Digital simulations provide a realistic visualization of the patient's appearance before and after treatment, making expectation management easier and more effective (Hassan et al., 2017). This technology also improves patient

satisfaction and encourages greater engagement in the treatment process.

3.6. Integration of Digital and Radiological Data

In modern digital workflows, facial scan data are combined with intraoral scans (STL) and cone-beam computed tomography (CBCT) to create a virtual patient model. This integrated model enables both functional and aesthetic analyses to be performed within a single digital platform (Kim et al., 2019).

The alignment of datasets is typically achieved using fixed anatomical landmarks on the face-such as the tragus, nasion, and subnasale- as reference points.

4. The Role of Facial Scanning in Prosthetic Dentistry

The success of prosthetic restorations is evaluated not only by occlusal fit but also by their aesthetic integration with facial morphology. Facial scanning enables digital identification of key reference lines and landmarks such as the interpupillary line, facial midline, lip contour, smile line, and nasolabial angle (Coachman et al., 2012). These references allow for precise virtual measurements of central incisor positioning, incisal plane orientation, and their relationship to the lip line, thereby allowing restorations to be designed in harmony with the patient's facial anatomy.

Facial scanning technology, now increasingly adopted in prosthetic dentistry, offers numerous clinical advantages.

4.1. Fixed Prosthodontic Planning

In fixed restorations, particularly within the aesthetic zone, harmony between the teeth and facial soft tissues is critical. Facial scanning allows for the alignment of tooth form and position with the smile line (Lee et al., 2022). Within the CAD environment, elements such as central incisor length, incisal edge position, and lip support can be evaluated simultaneously. In addition, virtual mock-up models can be used during the pre-approval process to facilitate communication between the clinician and patient.

4.2. Full-Arch Implant-Supported Prostheses

Facial scanning serves as a valuable planning tool in total or partial maxillary cases involving loss of lip support. Facial features such as lip volume and facial symmetry can be analyzed in relation to the vertical dimension of the prosthesis and pink aesthetic parameters (Zaninovich et al., 2023). In FP-3 type full-arch implant restorations, facial scan data are often used to optimize lip support and overall facial aesthetics.

4.3. Removable Prostheses

In the planning of complete dentures, facial scans offer a digital alternative to conventional methods for evaluating vertical dimension, midline, phonetics, and lip line (Srinivasan et al., 2025). Digital facial data can aid in jaw relation records and determination of vertical dimension, enabling alignment of the occlusal plane with the patient's natural facial parameters.

4.4. Maxillofacial Prostheses

In cases of trauma, tumor resection, or congenital defects, facial scanning technologies provide a highly accurate recording of the size and depth of the defect, forming the basis for prosthesis design. The digital facial data can be superimposed with the healthy contralateral side to enable a symmetrical reconstruction (Beumer et al., 2019). This approach enhances both the anatomical precision and aesthetic integration of the final prosthesis.

4.5. Digital Smile Design

Digital Smile Design (DSD) is a multidisciplinary approach in aesthetic dentistry that incorporates digital photographs, videos, facial scans, and intraoral scans to evaluate and plan restorations. Within this process, facial scanning plays a pivotal role by allowing the 3D capture of the patient's facial morphology, which in turn enables alignment of tooth positioning and prosthetic design with facial proportions.

Shuto et al. (2025) highlighted that facial scanning data serve as a fundamental reference, particularly in analyzing the lip line, interpupillary line, facial midline, and smile curve. This makes it possible to evaluate the relationship between planned restorations and the face not only statical-

ly but also in motion, incorporating dynamic facial expressions into the design process.

Modern software platforms such as 3Shape Smile Design, Exocad Smile Creator, and DSDApp integrate these facial scan datasets directly into the digital prosthetic design workflow. By superimposing the facial scan with the intraoral scan, a comprehensive virtual patient model can be created. This allows for thorough aesthetic and functional analysis, and a virtual mock-up can be produced and presented to the patient for review and approval.

One of the most significant advantages of this integration is improved patient communication and increased treatment engagement. Patients can digitally preview how their prosthetic restorations will appear on their own face, while clinicians can make necessary aesthetic revisions before initiating treatment. As a result, facial scanning technologies have become an indispensable element of modern digital smile design workflows. These systems not only enhance aesthetic planning but also optimize functional compatibility, contributing to the overall success of contemporary prosthodontic treatments.

In the past, smile design was traditionally carried out using two-dimensional (2D) techniques to simulate the final esthetic outcome. This analog process involved manually cutting and drawing over printed facial photographs to plan the desired result, which was then translated into a three-dimensional (3D) wax-up model. That physical model would be used to create a mock-up for presentation to the patient (Antolin et al., 2018).

However, this multi-step analog process introduced a significant risk of error and distortion at each stage of conversion, often limiting the accuracy and predictability of the outcome. With technological advancements and the evolution of digital imaging, digital smile design protocols have emerged. The use of platforms such as Keynote, PowerPoint, or dedicated software has transitioned smile design into a fully digital environment, enabling faster planning and more predictable results.

The 3D virtual patient model generated through facial scanning facilitates more effective communication between the clinical team, multidisciplinary collaborators, and the patient. Communication is particularly critical in esthetic planning, as esthetic perception is inherently subjective and variable among individuals. The virtual model enables collaborative decision-making, allowing both clinician and patient to co-create a personalized treatment plan.

Moreover, 3D digital smile design is a non-invasive, efficient, and cost-effective method that can enhance patient motivation. The ability to visualize the expected treatment result in a digital environment helps patients assess whether the planned esthetic changes align with their personal expectations and provides a clear preview of how the prosthesis will affect overall facial aesthetics.

4.6. Obstructive Sleep Apnea (OSA)

According to a scientific statement by the American Heart Association, Obstructive Sleep Apnea (OSA) is a respiratory disorder characterized by partial or complete cessation of airflow in the upper airway during sleep. This condition can lead to a drop in oxygen saturation levels to as low as 80–89%, increased heart rate, and a heightened risk of stroke.

Obesity and craniofacial anomalies are among the primary predisposing factors that contribute to upper airway collapse, and the prevalence and anatomical variations of these factors may differ across ethnic groups. Currently, the polysomnography (PSG) test is considered the gold standard for diagnosing OSA. During PSG, the patient is monitored overnight with various sensors that record breathing patterns, heart rhythm, brain activity, eye movements, and body positioning. However, the high cost, long wait times, and limited access to PSG facilities prevent many patients from receiving timely diagnosis, making OSA an emerging public health concern.

Since the 1980s, researchers have explored the relationship between craniofacial morphology and upper airway collapse (Jamieson et al., 1986). Within this context, facial scanning systems have been proposed as an auxiliary diagnostic tool for identifying OSA.

Initially, 2D facial photographs were utilized in OSA classification due to their low cost and ease of acquisition (Espinoza et al., 2015). In one study, facial landmarks were placed on photographs of patients who had undergone PSG testing, and the data were processed using a computer algorithm to distinguish between individuals with and without OSA (Balaei et al., 2017). Among the recorded measurements were facial width, mandibular length, eye aperture, and the cervicomental angle. Both manual and automated landmark detection methods yielded classification accuracies of approximately 69–70%.

Building upon this, 3D facial scanning, which generates depth maps, offers a more comprehensive analysis of facial morphology. In a recent study, 3D facial scans acquired with the 3dMDface system (3dMD, Atlanta, GA, USA) were analyzed using a mathematical algorithm to predict both the presence and severity of OSA. This algorithm combined linear and geodesic distances between anatomical landmarks, achieving a diagnostic accuracy of up to 91% (Eastwood et al., 2020). These findings suggest that 3D facial scanners may serve as more efficient and accurate diagnostic tools compared to traditional 2D photographic analyses.

Facial scanning technologies have also been employed in the treatment of OSA. For instance, custom CPAP maskshave been designed using 3D facial scans from the 3dMDface system. These masks were fabricated with 3D printing technology and evaluated against commercial alternatives in terms of air leakage and comfort. In a small sample study involving six participants, the custom-designed masks demonstrated high patient satisfaction in terms of comfort, with comparable air leakage rates to standard commercial masks (Duong et al., 2020).

Although current research on the use of facial scanners in OSA patients remains limited, the potential of this technology to accelerate diagnostic processes and improve diagnostic accuracy is significant. Given the time-consuming and costly nature of PSG testing, algorithmic approaches based on facial scanning may pave the way for more accessible, rapid, and cost-effective diagnostic systems in the future.

5. Clinical Protocols and Data Management

5.1. Scanning Conditions

For accurate facial scanning, controlling environmental and subject-related variables is critical. Key factors include homogeneous lighting, proper head positioning, and neutral facial expression. Typically, scanning is performed with a neutral, relaxed facial pose, with the lips lightly closed.

For dynamic facial analysis, multiple scanning positions such as smiling, resting, or during phonation are preferred to capture soft tissue behavior in motion (Shuto et al., 2025).

5.2. Data Accuracy and Calibration

Facial scanners have an error margin of less than 1 mm (Papadopoulou et al., 2024). However, factors such as facial movements, presence of hair or beards can increase this error margin. Therefore, regular device calibration and software updates are essential before clinical use to ensure consistent accuracy.

5.3. Data Security and Ethical Considerations

Since facial data constitute biometric identifiers, special precautions must be taken to protect patient privacy and ensure ethical data management. Anonymization and secure storage of data are legal requirements that must be strictly observed.

6. Future Applications

In recent years, artificial intelligence (AI)-powered systems have been developed for the automatic analysis of facial scanning data. These systems can automatically measure facial proportions, simulate smiles, and predict optimal tooth positioning. Research is ongoing on integrating facial scanning systems with AI and machine learning (ML) technologies. Although the use of AI in orthognathic surgery is not new, existing systems have yet to reach their full potential due to limitations such as small sample sizes, insufficient mathematical models, and complex data processing workflows (Knoops et al., 2019). Nevertheless, combining the strengths of AI and facial scanning technology is expected to enhance clinical workflows significantly in the future.

For example, Jiang and colleagues (2013) developed an innovative method to digitally create dental arches. This approach aims to support or replace analog procedures commonly used in full denture tooth arrangement or orthodontic wire bending. The system, referred to as a "dental arch robot," generates coordinates that can be positioned according to the patient's unique arch characteristics. Besides the dental arch, which is just one component of the occlusal plane, esthetic, functional, and facial reference planes (e.g., horizontal plane, Camper's plane, interpupillary line) must also be considered for ideal prosthetic design. When combined with virtual articulators and facial scanning data, Jiang's machine learning–based robotic system has the potential to automate bilateral balanced denture tooth arrangement digitally.

In prosthetic-driven implant planning, particularly in full-mouth rehabilitation cases where occlusal plane references may be insufficient, facial scanning serves as a valuable complementary tool. The resulting virtual patient model facilitates the identification of necessary facial reference points for prosthetic design and improves treatment planning accuracy.

In the field of maxillofacial surgery, six-axis AI-driven robotic systems have been reported to perform orthognathic surgery based on preoperative 3D CT data (Woo et al., 2017). Incorporating facial scanning in such applications could enable prediction of postoperative soft tissue changes, thereby making both surgical planning and patient communication more effective and predictable.

AR/VR-based facial scanning applications provide dentists with real-time visualization of the relationship between restorations and the face. These systems are increasingly used for both educational purposes and patient communication (Dzyuba et al., 2021). Unlike traditional static scans, dynamic facial scanning analyzes facial muscle behavior during speech, smiling, or chewing movements, allowing better evaluation of phonetic harmony (Kim & Kim, 2025).

7. Limitations and Challenges

The accuracy and reproducibility of facial scanning systems may be affected by lighting conditions, variability in facial expressions, hair, and skin color. Additionally, errors during data integration, such as mismatches between intraoral scans and CBCT data, can cause deviations in restoration positioning (Rekow & Thompson, 2020). To achieve high-precision results in clinical practice, implementing multi-step calibration protocols is recommended.

8. Conclusion

Today, facial scanning systems lie at the heart of digital transformation in dentistry. These technologies, integrated with intraoral scanning and imaging systems, actualize the concept of the "virtual patient." This integration enables functional, esthetic, and biomechanical analyses to be conducted on a single digital platform. However, along with rapid technological advancements, challenges related to data standardization, file format compatibility, and ethical data usage remain important issues to address in the future.

Facial scanning technologies provide significant clinical value across a wide range of prosthetic dentistry applications from esthetic analysis to functional planning. These systems allow objective assessment of critical parameters such as smile design, lip support, facial symmetry, and vertical dimension. Integrating facial scanning into prosthetic workflows can lead to more successful outcomes.

Looking ahead, the incorporation of AI and augmented reality supported dynamic analyses into prosthetic decision-making is expected to further expand patient-centered, personalized prosthetic approaches.

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Chapter 3

ALTERNATIVE TREATMENT APPROACHES FOR TEMPOROMANDIBULAR JOINT DISORDERS

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Temporomandibular joint (TMJ) disorders are multifaceted conditions marked by pain and dysfunction that impact the masticatory muscles, the temporomandibular joint, and the associated orofacial structures. This review seeks to explore the limitations inherent in conventional treatment approaches, including splints and medications, for TMJ disorders. Additionally, it will evaluate the efficacy of alternative treatment modalities such as acupuncture, low-level laser therapy, masseter botox, corticosteroid injections, manual therapy, cognitive behavioral therapy, and prolotherapy, based on the existing literature.

Introduction

Temporomandibular disorders (TMD) refer to a comprehensive category of conditions characterized by symptoms associated with the masticatory muscles, the temporomandibular joint, and surrounding orofacial structures. These disorders lead to dysfunction within the stomatognathic system and represent the primary source of non-odontogenic pain in the orofacial region. Additionally, TMD is classified as a subset of musculoskeletal disorders [1,2]. TMD is a complex condition characterized by multifactorial symptoms, which include muscle and joint pain, restricted mandibular movements, limited mouth opening, and audible joint sounds. While a considerable segment of the population experiences these symptoms, the percentage of individuals who necessitate treatment is comparatively lower [1,3]. A variety of risk factors may contribute to the development of TMD. These factors include trauma, dental malocclusion, joint hypermobility, as well as anatomical, psychological, and systemic diseases [4,5]. Conservative interventions, including physiotherapy, behavioral therapy, occlusal splints, and pharmacological treatments, are recognized as the primary therapeutic approaches for the management of TMD [5,6]. There exists a diversity of opinions within the literature concerning the effectiveness and limitations of traditional treatment methods for TMD. This discrepancy has fostered an increased interest in alternative therapeutic approaches, including acupuncture, low-level laser therapy, botulinum toxin injections, corticosteroid injections, manual therapy, cognitive behavioral therapy, and prolotherapy. This review aims to provide a comprehensive analysis of the effectiveness of these alternative strategies in the treatment of TMD, particularly in scenarios where traditional methods may prove insufficient.

Inadequacy of Splints and Medications and the Need for Alternative Treatment

Limitations of Splint Treatment

Occlusal splints are commonly utilized in the management of TMD and are regarded as a straightforward and minimally invasive intervention. However, clinical evidence regarding the efficacy of splint therapy remains inconsistent, with some studies suggesting that the observed benefits may be attributed to a placebo effect rather than a true therapeutic impact [7]. Meta-analyses encompassing both short- and long-term follow-up studies indicate that there is insufficient evidence to support the efficacy of oral splints in reducing pain intensity or enhancing functional capacity in individuals experiencing temporomandibular joint dysfunction [7]. It has been observed that the control group exhibited more substantial outcomes in pain reduction, particularly in long-term studies [7].

Recent meta-analyses have provided further insights into the effectiveness of occlusal splints. While some studies suggest that occlusal splints can reduce the incidence of clicking and improve pain and mouth opening, particularly when compared to counseling or placebo [8,9], others still highlight the lack of strong evidence. For instance, a meta-analysis by Zhang et al. (2016) concluded that splint therapy increased maximal mouth opening (MMO) for patients with MMO <45mm and reduced pain intensity, also noting its effectiveness in reducing the frequency of painful episodes for patients with TMJ clicking [8]. However, another systematic review and meta-analysis by El-Moraissi et al. (2020) indicated that there is moderate to very low quality evidence confirming the effectiveness of occlusal splint therapy in the treatment of TMDs [10] .

The variability observed among study outcomes may be attributed to several factors. These include the heterogeneity of TMD patients, who exhibit diverse responses, as well as limitations such as inadequate sample sizes, brief follow-up durations, suboptimal quality of control groups, and potential biases in data reporting [7]. These limitations suggest that splint treatment may not be suitable or adequate for every patient, highlighting the need for more personalized or alternative therapeutic approaches.

Limitations of Medications

Medications, particularly non-steroidal anti-inflammatory drugs (NSAIDs), are commonly utilized in the management of TMD. While NSAIDs are effective in mitigating inflammation, they may also produce adverse effects, including gastrointestinal discomfort and nephrotoxicity [1,8]. The side effects associated with long-term medication use can present significant challenges for patients, indicating that pharmacological in-

tervention alone may not constitute a comprehensive solution. Additionally, while alternative treatments, such as antidepressants, are available, they also carry potential side effects and may not exhibit uniform efficacy across all patients [8].

Pharmacological interventions for TMD are diverse, but their effectiveness varies. A systematic review and meta-analysis by Minervini et al. (2024) concluded that there is no single first-choice drug for temporomandibular pain, emphasizing the need for clinicians to distinguish the type and etiology of pain for effective pharmacological management [11]. While some studies show that certain NSAIDs like naproxen can effectively reduce orofacial pain [11], the overall evidence suggests that medication alone may not be a comprehensive solution due to potential side effects and varying efficacy across patients. For example, botulinum toxin, while showing some promise, has not consistently demonstrated superiority over placebo or other treatments in meta-analyses for pain reduction [12].

Need for Alternative Treatment

The limitations associated with traditional treatment methods, coupled with their inconsistent efficacy across patient populations, have heightened the demand for alternative approaches in the management of TMD. There is a particular interest in treatments that exhibit lower profiles of side effects and employ different mechanisms of action in the realm of chronic pain management and symptom relief. Notable complementary and alternative therapies, such as acupuncture, low-level laser therapy, botulinum toxin injections in the masseter muscle, corticosteroid injections, manual therapy, cognitive behavioral therapy, and prolotherapy, represent potential options to address the needs of patients who either do not respond to conventional treatments or are unable to utilize them due to adverse effects. These approaches demonstrate promise for enhancing patient care in this challenging area of treatment [5,13].

Acupuncture

Acupuncture is a practice defined as the insertion of needles into designated points on the human body for the purposes of health maintenance, treatment, or disease prevention [14]. Traditional Chinese medicine operates on the principle of regulating the flow of "qi" (energy) within the body and enhancing the natural healing mechanisms of the organism.

The stimulation of acupuncture points using needles triggers the release of endogenous opioids from the central nervous system, which in turn provides analgesic and anti-inflammatory effects [14,15].

The World Health Organization (WHO) has indicated that chronic myofascial pain demonstrates a favorable response to acupuncture treatment. While acupuncture does not address the underlying causes of TMJ disorders, it effectively alleviates the discomfort and pain associated with these conditions [14]. Research indicates that acupuncture demonstrates a short-term analgesic effect and is comparable to occlusal splints in the management of muscular TMJ disorders [14,15]. Acupuncture may be considered a viable alternative for patients who exhibit low tolerance to occlusal splints, or it can serve as a supplementary treatment approach in cases where the response to splint therapy is limited [14]. Research indicates that the treatment is effective in both acute and chronic cases, with a more rapid response observed in acute instances. Additionally, it has the potential to alleviate stress and anxiety [14].

Further meta-analyses support the efficacy of acupuncture for TMD. A systematic review and meta-analysis by Park et al. (2024) found that acupuncture is short-term helpful for reducing the severity of TMD pain with muscle origin [16]. Another review by Yoon et al. (2023) concluded that acupuncture significantly improved outcomes versus active controls and when add-on treatments were applied, though noting the need for higher quality studies [17]. These findings reinforce the role of acupuncture as a valuable treatment option for TMD, particularly for pain relief.

The treatment consists of six sessions, which may be conducted on a quarterly basis until the patient's symptoms show improvement. During each session, the needles are retained in position for a duration of 30 minutes [14].

Low-Level Laser Therapy (LLLT)

In recent years, low-level laser therapy has been incorporated into the array of non-surgical treatment options available for patients [18]. These lasers, exhibiting an output power of less than 250 mW, facilitate photochemical reactions in cellular structures while avoiding thermal effects in surrounding tissues [18]. This treatment is utilized for a variety of medical conditions, including soft tissue injuries, rheumatoid arthritis, musculoskeletal pain, and dental issues, owing to its biomodulatory and analgesic properties [18]. Research indicates that it may alleviate pain intensity and enhance maximum mouth opening in individuals experiencing TMD

[18].

Research into the efficacy of low-level laser therapy (LLLT) for TMD has yielded varied results. Some studies indicate that LLLT effectively alleviates pain and associated symptoms, while other investigations suggest that its efficacy is comparable to that of a placebo [18]. Currently, there is no established standard protocol for laser applications documented in the literature [19]. Infrared lasers are generally regarded as more advantageous and more effective than red lasers [18]. The affected muscle points, TMJ points, or a combination of both muscle and joint points can serve as designated application areas. Research findings indicate that utilizing irradiation points on both the joint and muscle is more advantageous for effectively addressing all affected regions [18].

Recent systematic reviews and meta-analyses offer mixed conclusions on LLLT. While some studies, like one by Díaz et al. (2025), suggest that LLLT effectively reduces pain in TMD patients, demonstrating significant decreases in pain scores [20], others, such as a meta-analysis by Chen et al. (2015), found that LLLT was not superior to placebo in reducing chronic TMD pain [21]. Ahmad et al. (2021) also noted that LLLT might substantially enhance functional outcomes with limited pain amelioration [22]. This highlights the ongoing debate and the need for more standardized protocols and high-quality research to definitively establish LLLT's role in TMD management.

In applications of LLLT, the wavelengths of lasers typically range from 632 to 910 nanometers. The energy density may vary between 1 J/cm² and 112.5 J/cm². Power density is observed to fluctuate between 30 milliwatts and 500 milliwatts. The number of laser treatment sessions can range from 1 to 20, with the frequency of applications varying from daily to weekly intervals [18].

Masseter Botox (Botulinum Toxin)

Botulinum toxin (BTX) is a potent neurotoxin that is produced by the bacterium Clostridium botulinum. Its primary function is to mitigate excessive muscle contraction by inhibiting the release of the neurotransmitter acetylcholine at the neuromuscular junction [23]. Inhibiting muscle activity can be instrumental in managing various conditions. Furthermore, botulinum toxin (BTX) has demonstrated efficacy in diminishing central pain sensitivity and chronic pain through its influence on pain-related neurotransmitters and inflammatory mediators, including glutamate, calcitonin gene-related peptide, and substance P [23,24].

Current research on the application of botulinum toxin for the treatment of TMD has yet to produce conclusive findings. Systematic reviews and meta-analyses suggest that there remains a lack of consensus regarding the clinical efficacy of Botox in managing TMD [23,24].

A meta-analysis indicated that treatment with botulinum toxin did not yield statistically significant reductions in pain scores at 1, 3, and 6 months in comparison to a placebo. Furthermore, the study demonstrated that Botox was not superior to placebo or alternative treatments with regard to other outcomes, including mouth opening, frequency of bruxism events, and maximum occlusal force [23].

A recent review has indicated the lack of reliable evidence supporting the efficacy of Botox for pain management. While certain primary studies have reported improvements in pain scores, these results are not consistently observed. The current body of evidence suggests that botulinum toxin does not demonstrate superiority over alternative treatments, such as occlusal splints, dry needling, or fascial manipulation [24]. The heterogeneity observed in the clinical presentations of TMD, along with the variation in Botox application techniques and comparator treatments across different studies, presents significant challenges in drawing conclusive assessments regarding the clinical efficacy of Botox for TMD. Therefore, there is a pressing need for more high-quality, randomized controlled trials to rigorously evaluate the treatment's efficacy, cost-effectiveness, and the establishment of standardized application protocols [23,24].

Despite the mixed findings, some recent studies continue to explore the potential of BTX. A meta-analysis by Saini et al. (2024) found that while BTX did not show statistically significant reductions in pain scores compared to placebo, it was not inferior to other treatments in terms of mouth opening or bruxism events [12]. Another study by Li et al. (2024) suggested that both low and high doses of BTX type A were effective in reducing pain in patients with muscular TMD [25]. These ongoing investigations underscore the complexity of evaluating BTX efficacy and the need for more robust research.

Corticosteroid Injections

Corticosteroids are steroid hormones that possess significant anti-inflammatory capabilities. When administered intra-articularly into the TMJ, these substances function by diminishing inflammation and alleviating pain within the joint. The management of inflammation is crucial for symptom relief, particularly in cases of internal TMD [26].

Systematic reviews and network meta-analyses have demonstrated that intra-articular corticosteroid injections are effective in alleviating pain associated with TMD [26,27]. Betamethasone has been identified as one of the most effective corticosteroids for the reduction of pain in both the short and medium term, particularly when compared to arthrocentesis. Additionally, the combination of arthrocentesis with dexamethasone has demonstrated efficacy in alleviating pain for up to six months [26]. There is currently insufficient evidence to support the effectiveness of any intervention in comparison to arthrocentesis with respect to improving range of motion (ROM) and quality of life (QoL). Furthermore, it has been observed that methylprednisolone may pose greater risks than those associated with arthrocentesis [26].

Recent meta-analyses further support the role of corticosteroid injections. A systematic review and network meta-analysis by Al-Moraissi et al. (2024) confirmed that betamethasone and arthrocentesis plus dexamethasone are highly effective in managing pain in the short and medium term [28]. Another review Machado et al. (2013) also highlighted the effectiveness of intra-articular injections with corticosteroids for treating TMD [29]. These findings suggest that corticosteroids remain a valuable option for pain management in TMD, though further research is needed to compare their efficacy with other interventions for ROM and QoL improvements.

Manual Therapy

Manual therapy is a method utilized within physiotherapy that encompasses a variety of hands-on techniques aimed at the treatment of musculoskeletal disorders. In the context of TMD, manual therapy may involve interventions such as joint mobilization, muscle relaxation techniques, stretching, and manipulation. The primary objectives of these techniques are to enhance joint mobility, alleviate muscle spasms, and relieve pain [30].

Systematic reviews and meta-analyses indicate that manual therapeutic interventions targeting musculoskeletal conditions are effective in the treatment of temporomandibular joint disorders [30,31]. Research indicates that this approach yields a considerable enhancement, particularly in terms of mouth opening and pain management. In the short term, the observed effects are notably more pronounced when compared to other conservative treatment options [30]. Manual therapy has been identified as an effective intervention for TMD in the medium term; however, it is important to note that its efficacy may diminish over time [31].

Recent meta-analyses continue to affirm the benefits of manual therapy. A systematic review and meta-analysis by Vieira et al. (2023) found that manual therapy may have positive effects on pain intensity and maximal mouth opening [32]. Another review by Martins et al. (2016) also concluded that musculoskeletal manual approaches are effective in treating TMD patients [33]. These studies reinforce the importance of manual therapy as a conservative treatment option for TMD, particularly for improving jaw function and reducing pain.

Cognitive Behavioral Therapy (CBT)

Cognitive behavioral therapy (CBT) is widely acknowledged as an effective psychological intervention for managing chronic pain conditions. The primary objective of CBT is to modify maladaptive thoughts, behaviors, and emotional responses associated with pain, thereby enhancing coping mechanisms and promoting overall well-being [2,34].

Systematic reviews underscore the potential advantages of CBT in the management of temporomandibular joint (TMJ) disorders. Research indicates that CBT can be effective in enhancing pain outcomes and promoting overall well-being [2]. Cognitive Behavioral Therapy may serve as a supplementary or alternative method to traditional treatment interventions for individuals experiencing temporomandibular joint TMD [34].

Recent research further supports the role of CBT in TMD management. A review by Liu et al. (2012) indicated that CBT can be beneficial in reducing pain and psychological impairment in TMD patients [35]. Another study by Litt et al. (2010) demonstrated the short- and long-term efficacy of brief cognitive-behavioral therapy for chronic TMD [36]. These findings suggest that CBT is a valuable tool for addressing the psychological aspects of TMD and improving patient outcomes.

Prolotherapy

Prolotherapy, specifically hypertonic dextrose prolotherapy (HDPT), represents an injectable intervention designed for the management of chronic musculoskeletal pain. This technique involves the administration of a hypertonic dextrose solution directly into the affected joint [37]. While the precise mechanism of action remains inadequately understood, it is conventionally believed that it facilitates tissue repair and regeneration by inducing a localized inflammatory response, which in turn promotes the proliferation of fibroblasts and the synthesis of collagen [37].

Research on the efficacy of prolotherapy for TMD is growing. A recent systematic review and meta-analysis by Assiri et al. (2025) found that prolotherapy was more effective in reducing pain, maximal incisal opening (MIO), and clicking when compared to an occlusal splint in a single study [38]. Another meta-analysis by Sit et al. (2021) concluded that dextrose prolotherapy was significantly superior to placebo injections in reducing TMJ pain at 12 weeks [39]. These studies suggest that prolotherapy holds promise as an effective treatment for TMD, particularly for pain reduction and functional improvement.

Conclusion

The management of temporomandibular joint disorders presents a complex challenge, with the limitations of conventional methods, such as splints and pharmacological interventions, underscoring the necessity for alternative therapeutic approaches. Techniques including acupuncture, low-level laser therapy, botulinum toxin injections in the masseter muscle, corticosteroid injections, manual therapy, cognitive behavioral therapy, and prolotherapy may provide significant benefits in alleviating pain and alleviating symptoms. Nevertheless, there exists a need for more standardized and rigorous research to evaluate the effectiveness of these alternative treatments and to establish standardized application protocols. It is imperative to select the most suitable treatment modality through a multidisciplinary approach, which considers the individual patient's condition, symptomatology, and their response to conventional treatment strategies.

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Chapter 4

THE TECHNOLOGIES EMPLOYED IN DIGITAL OCCLUSION WITHIN DENTISTRY

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The technologies employed in digital occlusion within dentistry

Dental occlusion refers to the static and dynamic relationship between the cutting or chewing surfaces of the maxillary and mandibular teeth or their analogues (Prosthodontics, 1999). It plays a crucial role in the diagnosis and planning of prosthetic treatment, whether performed through conventional or digital methods. Occlusal contact areas and the forces exerted at these points are fundamental for both diagnosis and prognosis. Chewing efficiency is related to the number and strength of these contact areas (R. B. Kerstein & Radke, 2014a; Kuzmanovic Pficer et al., 2017; Qadeer et al., 2012a; Wilding, 1993a). Consequently, accurate recording of dental contacts in clinical settings and their precise transfer to the dental laboratory are essential.

Occlusal analysis identifies normal and abnormal tooth contacts by evaluating both static morphological contacts and dynamic mandibular movements. These occlusal interactions need to be in harmony with the stomatognathic system in order to work at their best. The stomatognathic system, defined as the dynamic morpho-functional interaction of various components, comprises the teeth, periodontal tissues, neuromuscular system, temporomandibular joint, and craniofacial structures (Abarza et al., 2016; Afrashtehfar & Qadeer, 2016). Occlusal contact is defined as the interaction of opposing teeth when the interocclusal distance is less than 50 μm, whereas near contacts occur when the distance is between 50 and 350 μm (Owens et al., 2002). Proper synchronization of occlusal contacts with the stomatognathic system is therefore indispensable for maintaining functional balance.

Occlusal analysis

The determination of occlusal contact locations and the measurement of their forces have traditionally relied on non-digital occlusal indicators and patient feedback, which provide complex and largely non-quantitative data (Wilding, 1993b). Such methods inherently lack objectivity, particularly during occlusal adjustment procedures.

To address these shortcomings, digital occlusal analyzers have been introduced for both diagnostic and therapeutic purposes. These devices are employed in the detection and management of temporomandibular disorders (Ferrato et al., 2017; Li et al., 2016), the evaluation of prosthetic restorations (Liu et al., 2015; Shinogaya et al., 2002), orthodontic treatment outcomes (Shinogaya et al., 2002), severe tooth wear(Wieczorek & Loster, 2015a) and masticatory muscle-related pain (Wieczorek & Loster, 2015b) Importantly, they provide detailed information regarding the balance of occlusal contact forces (BOCFs) relative to the mid-sagittal

plane, thereby enabling the assessment of right-to-left force distribution.

Given these clinical challenges, accurate occlusal assessment is indispensable for the correction of occlusal discrepancies. While qualitative occlusal recording tools remain common in clinical practice, their inherent limitations underscore the need for quantitative alternatives. Computerized occlusal analysis systems, developed for this purpose, provide a digital approach to the objective evaluation and visualization of occlusal contact pressure and timing.

Furthermore, a potential method of digitizing and virtually assessing both static and dynamic occlusion has been made possible by the extensive use of intraoral scanners (IOSs) in dental practice (Figure 1) (Hennen et al., 2022). Nevertheless, the accuracy and reliability of IOS-based occlusal analysis remain subjects of ongoing investigation (Abdulateef et al., 2020; Edher et al., 2018; Wang et al., 2022).
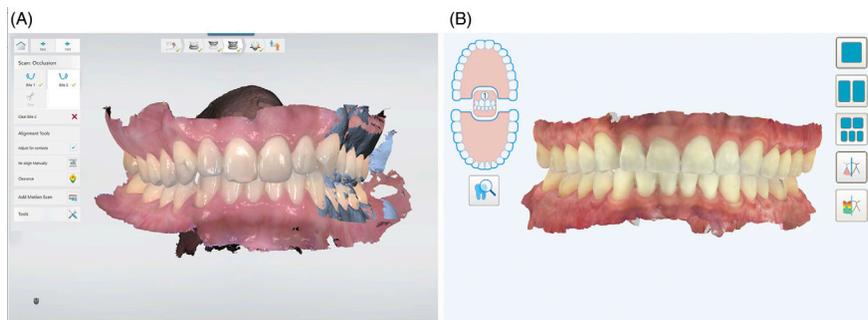
Figure 1: Intraoral scanner recording of the static maxillomandibular relationship. (A) 3Shape A/S Wireless Trios 4. (B) Align Technologies' Itero Element 5D Plus. (Revilla León et al., 2023)

Qualitative Occlusal Recording Instruments and Their Limitations

Traditional qualitative occlusal registration tools used in static positions include 40 μm articulation paper (Dr. Jean Bausch GmbH & Co. KG, Cologne, Germany)(Schelb et al., 1985), shim stock(Halperin et al., 1982a; Takai et al., 1993), waxes(Breeding et al., 1994; De Boever et al., 1978), and silicone impression(P. L. Millstein, 1985). These methods offer several advantages, such as simplicity of application, low cost, and the ability to visualize occlusal contact areas. However, they present significant limitations: they cannot provide information about occlusal force levels or the timing of contact events (R. B. Kerstein & Radke, 2014a).

Consequently, static recording devices are not considered ideal occlusal analyzers, as their results are inherently subjective and lack standardization. Moreover, the available literature provides insufficient evidence to confirm their reliability and repeatability (Halperin et al., 1982b; R. B. Kerstein & Radke, 2014b; P. Millstein & Maya, 2001).

Because there is no relationship between color depth, trace surface area, applied force, and the temporal sequence of contact generation, articulation paper, for instance, is unable to assess occlusal load (Carey et al., 2007a; P. L. Millstein, 1985). Additionally, articulation papers may tear, soften, or fail to leave accurate marks when exposed to saliva, resulting in incomplete or misleading records. Similarly, wax strips (12 μm thick), occlusal waxes, and silicone putties do not provide accurate reproductions of occlusal contacts (Gonzalez Sequeros et al., 1997a; Schelb et al., 1985; Takai et al., 1993). Most critically, interpretation of these methods depends heavily on clinician subjectivity, which can lead to significant inter-examiner variability (Schelb et al., 1985). These techniques are limited to identifying the location and width of contact areas and are incapable of quantifying occlusal load.

Another major concern is the inability of clinicians to reliably differentiate between strong and weak occlusal contacts based on articulation paper marks. Two studies demonstrated that only 12.8% to 13.3% of dentists correctly identified strong contacts, meaning that 87.7% to 88.2% misinterpreted the paper markings (R. B. Kerstein & Radke, 2014c; B. A. Sutter, 2018). Notably, no published data have contradicted these findings.

Some practitioners attempt to enhance diagnostic accuracy by combining articulation paper with shim stock foil. However, shim stock also relies heavily on subjective interpretation (Harper & Setchell, 2002). The procedure involves placing the foil between occluding teeth, asking the patient to "close and hold," and then attempting to remove the foil buccally while assessing the resistance to withdrawal. Despite this technique, shim stock remains a non-quantitative indicator that lacks force measurement, sensing, or reporting capabilities and does not record contact timing. Shim stock is therefore limited to a secondary rather than a primary diagnostic role because it does not leave visible imprints on teeth, necessitating the use of articulation paper to detect possible strong connections.

Quantitative Occlusal Recording Technologies

Technologies for quantitative occlusal analysis were created in order to overcome the drawbacks of qualitative recording techniques.

Among these, the T-Scan (Tekscan, USA) and OccluSense (Dr. Jean Bausch GmbH & Co. KG, Germany) systems are the most widely recognized for evaluating occlusal relationships (Table 1)(Figure 2). These computerized systems are capable of detecting occlusal contacts in a time-sequenced manner by analyzing pressure distribution across occlusal surfaces(Ayuso-Montero et al., 2020; Hsu et al., 1992; Lee et al., 2022; Maness et al., 1985; Türp et al., 2008). Furthermore, intraoral scanners (IOSs) have demonstrated potential for identifying occlusal contact areas, thereby expanding the scope of digital occlusal assessment (Figure 3) (Ayuso-Montero et al., 2020).
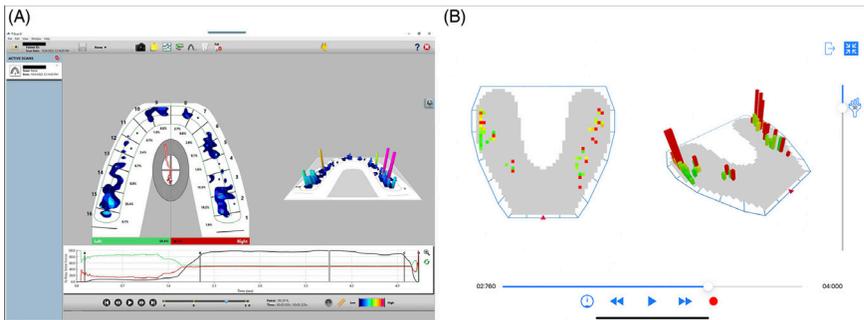

Figure 2. Systems for computerized occlusal analysis: (A) T-Scan (Tekscan, USA); (B) OccluSense (Bausch, Germany).(Revilla-León et al., 2023)
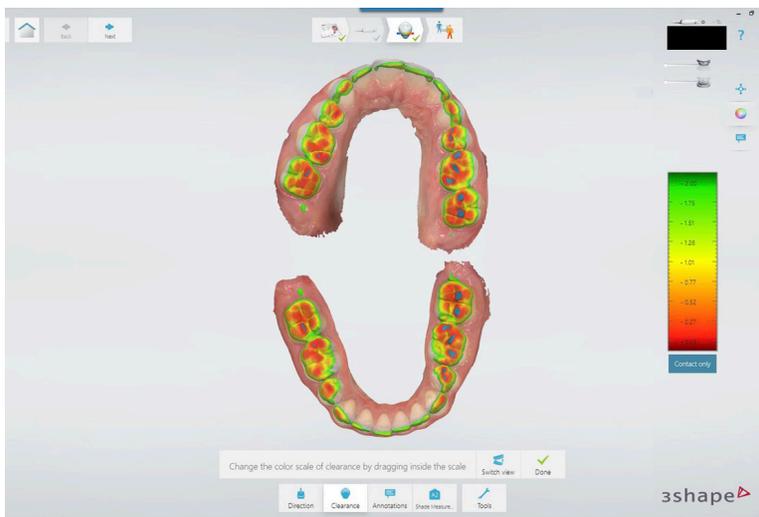

Figure 3. Determination of occlusal contact areas using an intraoral scanner (Trios 4, wireless; 3Shape A/S) (Revilla-León et al., 2023)

Manufacturer	Occlusal analysis system	Functionality	Occlusal sensor	Occlusal sensor thickness
Bausch	OccluSense	Static and dynamic occlusal contacts (pressure and timing)	OccluSense Electronic Pressure Sensor (Large and extra-large sizes)	60 µm
Dmtec	Accura	Static and dynamic occlusal contacts (pressure and timing)	Occlusal sensor (S and M sizes)	160 µm
Tekscan	T-scan Novus	Static occlusal contacts (pressure and timing) Total bite force (N)	T-scan sensor (S and L sizes)	100 µm

Table 1. An overview of the primary computerized occlusal analysis systems that are sold commercially (Revilla-León et al., 2023)

Advantages of computerized occlusal analysis technology

Traditional static occlusal measurement tools provide only the size and location of contact areas, whereas dynamic systems can additionally measure contact timing and force distribution (Maness, 1991). Notably, research has demonstrated that in more than 80% of cases, the size of articulation paper markings does not correlate with the magnitude of the applied occlusal load (Carey et al., 2007b). On the other hand, real-time variations in relative occlusal force from the first site of contact to maximum intercuspation (MIP) can be shown using computerized occlusal analysis systems (Qadeer et al., 2012b). For example, one study investigating the limitations of articulation paper revealed that the largest paper markings corresponded to only 38% of the highest recorded force load, indicating that clinicians would incorrectly identify and adjust the wrong tooth in approximately 62% of cases(Qadeer et al., 2012b).

Limitations of computerized occlusal analysis technology

T-Scan occlusal analysis technology provides measurable data on time and force variability from the first point of contact to maximum intercuspation (MIP). However, it lacks the ability to record absolute bite force. Complete intercuspation may be hampered by the sensor's 100 µm

thickness, which compresses up to 60 μm under occlusal pressure. According to the manufacturer, this high compressibility produces bilateral interference during mandibular movements, yielding more comprehensive occlusal force data compared to the unilateral interference generated by articulation paper strips, which are typically used to identify excessive contacts on one side of the arch.

A further limitation is the difference in sensor thickness between qualitative and quantitative occlusal analysis tools, which leads to a lack of standardization across recording methods and reduces their comparability (Manziuc et al., 2024).

Despite significant advances in digital dentistry, no single method provides an ideal solution for occlusal assessment. Both conventional and digital approaches have distinct strengths and weaknesses, and they should therefore be considered complementary rather than mutually exclusive. Importantly, patient proprioception remains a critical factor in achieving a comprehensive occlusal analysis.

One commonly reported drawback of computerized occlusal analysis systems is the increased clinical time required. High-quality digital recordings demand not only precise instrumentation but also active clinician involvement. Clinicians may find the process time-consuming as they monitor the screen and assist the patient in making the proper mandibular movements. Nonetheless, the additional chair time often results in greater accuracy and reduces the need for repeated adjustments, which are more frequently encountered in traditional methods.(Rues et al., 2008)

Another major limitation lies in the sensors themselves: they are both highly sensitive and costly. Repeated use may compromise their sensitivity and durability, which further increases clinical expenses (Kuzmanovic Pficer et al., 2017; Qadeer et al., 2012a).

T-Scan System

Maness was the one who initially created the T-Scan system and released the first studies on the technology in 1987 (William, 1987). Since the introduction of T-Scan I in 1984, the system has undergone continuous improvements over more than three decades, including the release of T-Scan II for Windows in 1995, T-Scan III with turbo recording in 2004, and the most recent T-Scan 10 in 2018)(D. M. D. Kerstein & Robert, 2014). The sensor film used in the T-Scan system has a thickness of 100 μm (Bozhkova, 2016; R. B. Kerstein et al., 2006) and consists of a grid of

transmission lines containing small, pressure-sensitive units known as "sensels." When occlusal force is applied, the voltage within these sensels decreases, and the resulting changes are digitized and displayed via the T-Scan software.

The poor resolution of T-Scan I and the variation in sensor sensitivity were the main reasons why early iterations of the T-Scan system were deemed unreliable and incorrect for capturing biting forces and occlusal contacts(Bozhkova, 2016; R. B. Kerstein et al., 2006; Patyk et al., 1989). Later, it was discovered that the T-Scan II was a trustworthy technique for examining the distribution of occlusal contact during maximal intercuspation (Gonzalez Sequeros et al., 1997b). T-Scan III further improved accuracy and speed, offering a rapid method for recording occlusal contacts (Koos et al., 2010; Stern & Kordaß, 2010) However, several reports indicated that the sensor film surface exhibited inconsistent sensitivity and required preparation before accurate use. Moreover, sensors occasionally altered occlusion during recordings, potentially affecting diagnostic outcomes (da Silva Martins et al., 2014a; Koos et al., 2010; Stern & Kordaß, 2010).

The T-Scan 10 system consists of several hardware components, including the Novus recorder, a two-dimensional plastic-molded sensor support, and a high-definition (HD) Novus-specific sensor. The Novus handpiece records incremental relative occlusal force and timing data in Turbo Mode with a resolution of 0.003 seconds. It requires no charging or daily function tests and is ready for use when connected to a computer via USB. This direct connection allows high-speed data transfer and enables clinicians to view recordings in real time during patient assessment (B. Sutter, 2019).

The system's sensor support arms stabilize the sensor during compression and mandibular movement, while a pre-positioning stabilizer ensures accurate and repeatable placement between the patient's upper central incisors. The HD Novus sensor is 100 μm thick and functions as a resistive, electronic tactile sensor with pressure-sensitive conductive ink arranged in a column-and-row matrix. Designed in the form of a dental arch and coated with Mylar(R. B. Kerstein et al., 2006), the sensor is saliva-resistant and can be disinfected with alcohol for reuse in the same patient across multiple visits (Figure 4). Studies have shown that this sensor maintains performance integrity for up to 24 uses. Furthermore, it is capable of recording 256 occlusal force levels simultaneously with 95% accuracy, capturing contact sequences in increments of 0.003 seconds(R. B. Kerstein et al., 2006; Koos et al., 2010) (Figure 5).

Numerous studies confirm the T-Scan's ability to reliably measu-

re occlusal contact sequences over time and to consistently report relative force levels (Cerna et al., 2015; da Silva Martins et al., 2014b; Koos et al., 2012; Mitchem et al., 2017) Additionally, T-Scan data can be superimposed on digital dental arch scans, facilitating the precise localization of excessive force areas relative to clinical occlusal contacts.

Figure 4. A tiny T-Scan HD Novus recording sensor with rows and columns of pressure-sensitive conductive ink. Through conductive ink rows that cross the sensor tab and intersect at the end, the recording matrix sends occlusal contact force data to the recording shaft.(B. Sutter, 2019).
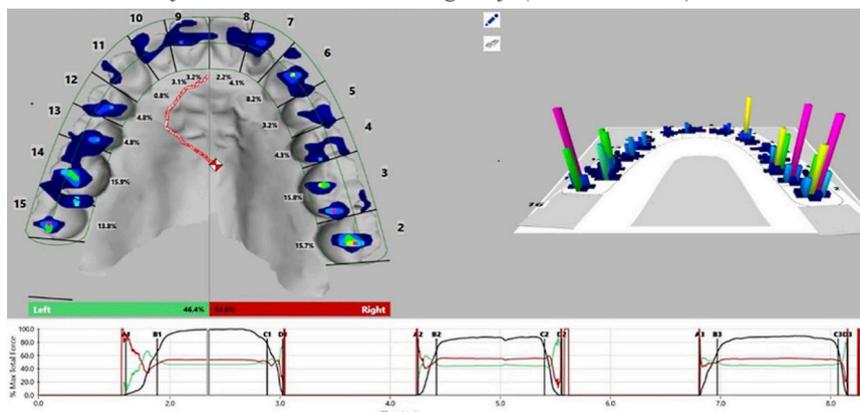

Figure 5. Color-coded force data superimposed over a digital image of the maxillary arch using T-image 10 desktop (B. Sutter, 2019)

The following are measured and reported by the T-Scan system:

• The distribution of occlusal forces on each tooth, on each half of the jaw arch, or on quadrants selected by the dentist

• The existence of closing forces and early and quick occlusal force contact at any particular time

• The locations of areas with excessive occlusal contact forces

• The proportion between the greatest force exerted to all occluding teeth and the occlusal force on each individual tooth

• Changes in force during movements around the jaw arch, showing changes as more teeth enter occlusion or separate through lateral movements.

T-scan has an advantage over traditional methods because it can show changes in occlusal force in real time using an intraoral sensor. T-Scan records in real time, and during this time, the dentist can monitor the entire recording as it happens and, if necessary, provide verbal coaching during the recording to help the patient improve their lower jaw movement(Anselmi & Kerstein, 2020). The dentist can see the development of the record, whether the patient's occlusion or escape is correct (or incorrect), and whether the record has been obtained properly from the patient.

Since the launch of T-Scan, additional digital occlusal analysis devices with similar functions have been developed and introduced to the market at lower costs. Some of these devices include Accura (Dmetec Co) and OccluSense (Dr Jean Bausch GmbH & Co KG).

Accura System

The Accura system (Dmetec Co., Bucheon, Korea) is a computerized occlusal analysis device introduced in 2017, designed to provide real-time visualization of occlusal force changes, similar to the T-Scan system. Marketed as a more cost-effective and user-friendly alternative, Accura shares many technical similarities with T-Scan. Depending on the film size, the T-Scan Novus sensor film has between 1122 and 1370 detection units overall (Lee et al., 2022) whereas the Accura film sensor has between 1172 and 1390 detection units. 256 occlusal force gradations can be recorded using both devices. (Lee et al., 2022).

According to manufacturer data, Accura is capable of measuring absolute occlusal force, a feature not offered by T-Scan (Jeong et al., 2020). Its film sensor is composed of polyimide and has a thickness of 160 μm(Jeong et al., 2020). While Accura demonstrates comparable accuracy to T-Scan in identifying occlusal contacts at maximum intercuspation, the two systems differ in terms of sensor thickness and spatial resolution(Jeong et al., 2020).

OccluSense System

Introduced in 2019 as an alternative to the T-Scan system, OccluSense (Dr. Jean Bausch GmbH & Co. KG, Cologne, Germany) is a digital occlusal analysis device designed to record and evaluate occlusal relationships. The system comprises a handheld device equipped with a sensor covered by articulating foil, which transmits data wirelessly via Wi-Fi to the OccluSense iPad application (Apple Inc., Cupertino, CA, USA). Similar to the T-Scan, the OccluSense sensor uses a matrix-style detecting surface. According to the manufacturer, the sensor is intended for single-session use because it cannot be sterilized or disinfected with antiseptics. Reuse leads to deterioration of the ink coating, thereby reducing its ability to consistently mark occlusal contact points (Figure 6).

Figure 6. (A) Daily function test performed to verify proper operation of the OccluSense system. (B) Recording arm and unused recording sensor (B. Sutter, 2019).

The OccluSense sensor is a 60-µm horseshoe-shaped foil that records occlusal contacts in protrusion, laterotrusion, and maximal intercuspation (MIP) in a sequential manner. Red ink is applied to both surfaces of the printed circuit with 1.018 pressure-sensitive pixels in the sensor to indicate tooth interactions. The data are processed by the iPad application, which provides both two-dimensional (2D) and three-dimensional (3D) visualizations. In 2D mode, contacts appear as colored squares, whereas the 3D view represents occlusal pressure intensity using bar charts with color gradients and varying heights. Sensors are supplied in a standard size, although a 6-mm wider version is available. OccluSense records 256 levels of occlusal force using a four-color coding scheme (green/yellow/orange/red). Each color encompasses 64 force levels, limiting the system's ability to detect subtle force differences between adjacent contacts (B. Sutter, 2019).

However, the main consideration when evaluating the accuracy of digital occlusal contact forces is related to the characteristics of the force jump gradient per color. OccluSense uses 4-color gradients and heights to represent 256 force levels. With the 4-color scheme, the force jumps from color to color are large, and there are 64 force levels per color. This poses a significant challenge in detecting subtle differences in occlusal contact forces between adjacent contacts (B. Sutter, 2019).

In contrast, the T-Scan system uses 18 gradients of color to represent the same 256 force levels, corresponding to 14 degrees of force for each color, thus offering greater sensitivity in detecting minor occlusal force variations (B. Sutter, 2019). In short, T-Scan provides finer gradation of force differences than OccluSense.

Despite its ability to capture occlusal force and contact duration, OccluSense presents several limitations. It cannot distinguish contact pressures at specific anatomical sites such as incisal edges, fossae, marginal ridges, or cusp tips. Furthermore, it uses a generalized arch form without anatomical customization. If a patient presents with missing teeth, these cannot be excluded from the digital arch model (Figure 7). Filters may be applied to the data to adjust the display of different force levels, but they do not alter the underlying recorded data.

The comparatively thin 60-µm sensor, which has 25% less material between opposing teeth than the T-Scan sensor and hence less resistance to recurrent occlusal stresses, is another drawback. Moreover, although live preview is available during data acquisition, these preview recordings cannot be stored, and clinicians cannot monitor in real time whether mandibular movements are performed correctly or whether data quality is adequate. Finally, OccluSense data are automatically resized to

fit a standardized arch outline without individual tooth demarcations, further limiting the system's diagnostic precision (B. Sutter, 2019).
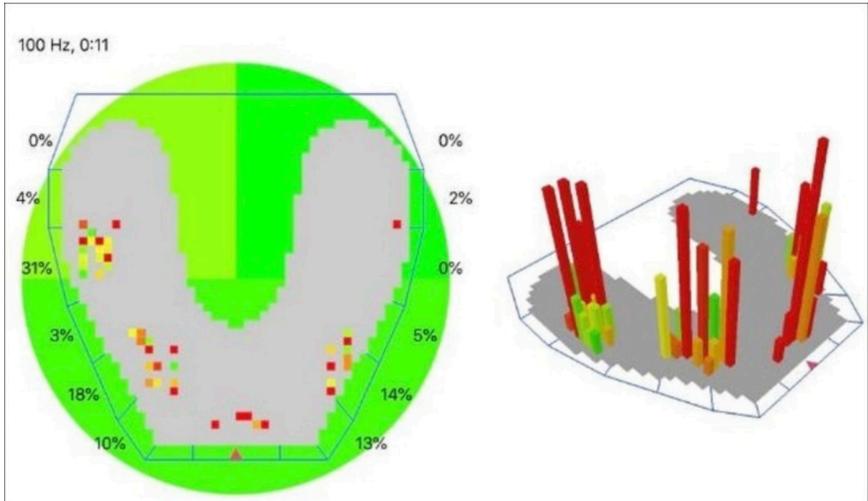
Figure 7. Standardized OccluSense arch form, which does not allow precise identification of individual teeth, complicating the localization of problematic occlusal contacts. (B. Sutter, 2019)

Conclusion

Occlusion should be regarded as a dynamic rather than a static phenomenon. Accordingly, static indicators used to analyze occlusal contacts must be complemented with dynamic approaches, particularly digital occlusal analysis systems. In clinical practice, both qualitative and quantitative methods should be evaluated in conjunction to ensure comprehensive assessment.

When performed correctly, computerized occlusal analysis combined with traditional qualitative methods can yield more accurate insights into occlusion and related discrepancies. This integrative approach enhances clinician–patient communication, reduces complications during restorative follow-up visits and management of occlusal imbalances, and contributes to more predictable treatment outcomes.

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