# DIGITAL AGE IN DENTISTRY

EDITOR **ASSOC. PROF. DR. DEĞER ÖNGÜL**

SERÜVEN
YAYINEVİ

**Genel Yayın Yönetmeni** • C. Cansın Selin Temana

**Kapak & İç Tasarım** • Serüven Yayınevi

**Editor** • Değer ÖNGÜL

**Birinci Basım** • © Ocak 2026

**ISBN** • 978-625-8559-51-4

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**Serüven Yayınevi / Serüven Publishing**
**Türkiye Adres / Turkey Address:** Kızılay Mah. Fevzi Çakmak 1. Sokak
Ümit Apt No: 22/A Çankaya/ANKARA
**Telefon / Phone:** 05437675765
**web:** www.seruvenyayinevi.com
**e-mail:** seruvenyayinevi@gmail.com

**Baskı & Cilt / Printing & Volume**
Sertifika / Certificate No: 47083

# Digital Age in Dentistry

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# CONTENTS

## CHAPTER 1
## DIGITAL SCANNING STRATEGIES FOR IMPLANT-SUPPORTED PROSTHESIS

## CHAPTER 2
## DIGITAL SCAN BODIES

## CHAPTER 3
## DIGITAL OCCLUSAL SPLINTS

## CHAPTER 4
## DIGITAL BITE REGISTRATION SYSTEMS IN OCCLUSAL ASSESSMENT

Chapter

1

# DIGITAL SCANNING STRATEGIES FOR IMPLANT-SUPPORTED PROSTHESIS

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## 1. Introduction

Intraoral scanners (IOSs) are increasingly being used in the planning and production of implant-supported prostheses, as they are in many areas of digital dentistry (Revilla-León et al., 2021; Vitai et al., 2023; Ren et al., 2022; Schmidt et al., 2022; Wulfman et al., 2020; Mangano et al., 2019). The successful application of digital impressions in implant-supported restorations requires not only a proper understanding of the technology used, but also consideration of operator and patient-related factors and the technical limitations of the system (Revilla-León et al., 2023a; Revilla-León et al., 2023b; Revilla-León et al., 2023c). In this context, selecting a scanning strategy appropriate to the purpose of the impression and clinical conditions is considered a critical step in terms of the predictability of digital workflows (Revilla-León et al., 2023a; Revilla-León et al., 2023b; Revilla-León et al., 2023c). This situation complicates the evaluation of digital impressions as a direct alternative to traditional approaches, particularly for implant-supported restorations (Revilla-León et al., 2023a; Revilla-León et al., 2023b). Although numerous studies in the literature have examined the trueness and precision of full-arch implant scans obtained using intraoral scanners, there are significant differences between the reported results (Schmidt et al., 2022; Wulfman et al., 2020; Ma et al., 2023; Zhang et al., 2021; Papaspyridakos et al., 2020; Flügge et al., 2018).This variability is reported to stem from heterogeneity in study design, clinical conditions, the IOS system and generation used, implant position and type, implant scan body design, scanning strategy, and impression methods (Schmidt et al., 2022; Wulfman et al., 2020; Ma et al., 2023; Zhang et al., 2021; Papaspyridakos et al., 2020; Flügge et al., 2018; Gómez-Polo et al., 2023; Yilmaz et al., 2022; Nedelcu et al., 2023). This situation makes it difficult to evaluate the clinical reliability of digital impressions on implants. In evaluating impression quality in digital scans of implant superstructures, the concepts of trueness, precision, and accuracy are accepted as fundamental criteria, with accuracy encompassing both trueness and precision. The literature emphasizes that these parameters are sensitive to clinical conditions, particularly in full-arch implant cases, and that no single digital approach provides ideal results for all cases (Revilla-León, Kois & Kois, 2023). Therefore, digital scans of implants must be systematically classified according to the scanning strategies employed and the associated digital workflows.

## 2. Essential Objectives of Digital Scanning in Implant Dentistry

The primary objective of digital implant scanning is to record the three-dimensional positions of implants within the jawbone with high trueness and precision within a digital workflow. In this context, the spatial positions of implants, their inter implant distances, and their angulations are considered critical parameters for achieving passive fit and ensuring long-term clinical success. However, the digital scanning process for implants is not limited to the recording of implant positions. To properly perform prosthetic planning, the morphology of the peri-implant soft tissues, the position of the existing dentition, information regarding the opposing arch, and the maxilla-mandibular relationship must also be digitally acquired (Schmidt et al., 2022; Wulfman et al., 2020; Ma et al., 2023; Zhang et al., 2021;

Papaspyridakos et al., 2020; Flügge et al., 2018; Gómez-Polo et al., 2023; Yilmaz et al., 2022; Nedelcu et al., 2023; Paratelli et al., 2023; Crockett et al., 2023; Roig et al., 2022; Klein et al., 2023; Llansana et al., 2022; Liaropoulou et al., 2023). These additional data enable the design of implant-supported prostheses in accordance with aesthetic, functional, and biological requirements (Revilla-León, Kois & Kois, 2023).

In this context, the ultimate goal of implant-based digital scanning workflows is to create a virtual implant model that contains all clinical and prosthetic information, defined in the literature as a 'definitive virtual implant cast' (Schmidt et al., 2022; Wulfman et al., 2020; Ma et al., 2023; Zhang et al., 2021; Papaspyridakos et al., 2020; Flügge et al., 2018; Gómez-Polo et al., 2023; Yilmaz et al., 2022; Nedelcu et al., 2023; Paratelli et al., 2023; Crockett et al., 2023; Roig et al., 2022; Klein et al., 2023; Llansana et al., 2022; Liaropoulou et al., 2023). This virtual model forms the basis for the computer-aided design and manufacturing (CAD/CAM) processes of implant-supported restorations and may involve different digital workflows depending on the selected scanning strategy. Studies in the literature emphasize that the accuracy of this virtual implant model is directly related to the scanning technique employed, additional scans, and the applied clinical protocols. (Revilla-León et al., 2023).

## 3. Digital Scanning Workflows for Implant-Supported Prostheses

Digital scanning workflows for implant-supported prostheses aim to capture the three-dimensional positions of implants and to acquire all clinical data required for prosthetic planning within a digital workflow. These data include peri-implant soft tissue morphology, implant positions, the position of the existing dentition, opposing arch information, and the maxillomandibular relationship. The literature reports that digital scanning processes for implants are not limited to a single protocol and that different digital workflows are applied depending on the selected scanning strategy Schmidt et al., 2022; Wulfman et al., 2020; Ma et al., 2023; Zhang et al., 2021; Papaspyridakos et al., 2020; Flügge et al., 2018; Gómez-Polo et al., 2023; Yilmaz et al., 2022; Nedelcu et al., 2023; Paratelli et al., 2023; Crockett et al., 2023; Roig et al., 2022; Klein et al., 2023; Llansana et al., 2022; Liaropoulou et al., 2023).

### 3.1. Single-Stage Digital Scanning Protocols

In single-stage digital scanning protocols, the information required for implant positioning and prosthetic design is obtained during a single intraoral scanning session. In this approach, following the placement of implant scan bodies, the implants, surrounding soft tissues, and existing anatomical structures are scanned sequentially, and the resulting digital data are merged using intraoral scanner software(Schmidt et al., 2022; Wulfman et al., 2020; Ma et al., 2023; Zhang et al., 2021; Papaspyridakos et al., 2020; Flügge et al., 2018; Gómez-Polo et al., 2023; Yilmaz et al., 2022; Nedelcu et al., 2023; Paratelli et al., 2023; Crockett et al., 2023; Roig et al., 2022; Klein et al., 2023; Llansana et al., 2022; Liaropoulou et al., 2023). Shortening the clinical time and increasing patient comfort are among the main advantages of single-stage protocols.

However, it has been reported that the impression accuracy of single-stage digital scanning protocols, particularly in full-arch implant cases, is highly dependent on the scanner technology employed, the scanning strategy, the operator's experience, and the clinical conditions (Crockett et al., 2023; Roig et al., 2022; Klein et al., 2023; Llansana et al., 2022; Liaropoulou et al., 2023) The literature emphasizes that as the scanning area expands, image registration errors and cumulative deviations may increase, which could negatively affect impression accuracy, particularly in full-arch implant rehabilitation (Revilla-León, Kois & Kois, 2023).

### 3.2. Multi-Stage Digital Scanning Protocols (Including Additional Scans)

Multi-stage digital scanning protocols rely on acquiring implant positions and additional information required for prosthetic planning through multiple scanning steps. Multi-stage digital scanning protocols rely on acquiring implant positions and additional information required for prosthetic planning through multiple scanning steps. In these protocols, implant scanning, acquisition of soft tissue contours, existing dentition, opposing arch information, and the occlusal relationship can be performed in separate stages (Schmidt et al., 2022; Wulfman et al., 2020; Ma et al., 2023; Zhang et al., 2021; Papaspyridakos et al., 2020; Flügge et al., 2018; Gómez-Polo et al., 2023; Yilmaz et al., 2022; Nedelcu et al., 2023; Paratelli et al., 2023; Crockett et al., 2023; Roig et al., 2022; Klein et al., 2023; Llansana et al., 2022; Liaropoulou et al., 2023). The literature reports that multi-stage approaches can enhance digital data integrity, particularly in full-arch implant cases involving large restorative areas (Crockett et al., 2023; Roig et al., 2022; Klein et al., 2023; Llansana et al., 2022; Liaropoulou et al., 2023).

Review and experimental studies in the literature indicate that error accumulation increases with the length of the scanning area and that selecting a scanning length appropriate to the restorative scope may improve clinical accuracy (Revilla-León et al., 2023). These findings suggest that multi-stage digital scanning protocols may provide more predictable outcomes in complex implant rehabilitation.

### 3.3. Clinical and Laboratory Integration

Digital scanning workflows for implants have a multi-stage structure that requires the integrated execution of clinical and laboratory processes. Digital data acquired in the clinical setting are processed using laboratory software to generate virtual implant models, on which prosthetic design is subsequently performed (Schmidt et al., 2022; Wulfman et al., 2020; Ma et al., 2023; Zhang et al., 2021; Papaspyridakos et al., 2020; Flügge et al., 2018; Gómez-Polo et al., 2023; Yilmaz et al., 2022; Nedelcu et al., 2023; Paratelli et al., 2023; Crockett et al., 2023; Roig et al., 2022; Klein et al., 2023; Llansana et al., 2022; Liaropoulou et al., 2023). The selected scanning strategy and digital workflow directly influence the design and production processes implemented during the laboratory phase.

Studies have emphasized that the accurate and complete transfer of clinical data into a digital workflow is critical for the success of digital processes and the long-term compatibility of implant-supported restorations (Revilla-León, Kois & Kois, 2023). Therefore, it is recommended that implant-supported digital scanning workflows be planned through the joint evaluation of clinical and laboratory requirements.

## 4. Classification of Digital Scanning Strategies for Implant-Supported Prostheses

Although various implant scanning techniques for obtaining full-arch implant impressions using intraoral scanners have been described in the literature, a comprehensive and systematic classification of these techniques remains limited. The increasing diversity of digital workflows and clinical application options demonstrates that implant scanning procedures are not limited to recording the three-dimensional positions of implants; they also require a comprehensive assessment of soft-tissue morphology, tooth positions, the opposing arch, and the maxillomandibular relationship, all of which are necessary for designing implant-supported prostheses. In this regard, a systematic classification of implant scanning techniques based on fundamental principles, workflow requirements, and clinical application characteristics reported in the literature is essential for accurate interpretation of digital implant impressions and for selecting a scanning strategy appropriate to the clinical indication. Accordingly, the classification presented in this section is based on the shared characteristics and clinical application principles of implant-related digital scanning approaches reported in the current literature. While not claiming to be a universally accepted or definitively established classification system, this approach aims to evaluate different scanning strategies within a more comprehensible framework and to facilitate their clinical interpretation. In this context, digital scanning strategies for implants are discussed below under specific subheadings (Revilla-León et al., 2025).

## 4.1. Non- Splinting Technique

### *4.1.1. Definition and Technical Principles*

Non-splinting digital scanning strategies rely on recording implant scan bodies (ISBs) splaced on implants using intraoral scanners, without the use of any connection or fixation elements. In this approach, the spatial positions of the implants are determined by combining the surface data captured by the IOS within the software environment. The technical principle is based on the alignment of sequentially acquired digital images using stable reference areas, and the absence of a direct reference structure between implants constitutes a fundamental characteristic of this method (Kim et al., 2019; Chochlidakis et al., 2020; Mizumoto et al., 2020; Bilmenoglu et al., 2020; Revilla-León et al., 2021; Revell et al., 2022; Knechtle et al., 2022).

### *4.1.2. Clinical Workflow Steps*

The first step in the non-splinting digital scanning protocol is to place ISBs on the implant platforms according to the manufacturer's instructions. Following this, the implants, surrounding soft tissues, and existing anatomical structures are digitally scanned using an intraoral scanner. The data acquired during scanning are progressively merged using IOS software to generate a virtual implant model. Because this approach does not require auxiliary devices or additional preparatory steps, it offers a relatively practical clinical workflow (Papaspyridakos et al., 2020; Knechtle et al., 2022; Rasaie et al., 2021; Al Hamad & Al-Kaff, 2023).

### *4.1.3. Advantages and Limitations*

The main advantage of non-splinting digital scanning strategies is that a definitive digital implant impression can be obtained in a single clinical session. The absence of additional splinting procedures or auxiliary structures reduces both treatment time and patient discomfort (Papaspyridakos et al., 2020; Knechtle et al., 2022; Rasaie et al., 2021; Al Hamad & Al-Kaff, 2023). However, the limitations of this approach become particularly evident in full-arch implant cases. The literature reports a wide variation in the accuracy of digital impressions obtained using non-splinting techniques. Reported mean trueness values ranging from 41 to 303 µm and precision values ranging from 25 to 181 µm indicate that the predictability of this approach is highly dependent on clinical conditions (Ren et al., 2022; Wulfman et al., 2020; Ma et al., 2023; Zhang et al., 2021; Papaspyridakos et al., 2020; Flügge et al., 2018; Gómez-Polo et al., 2023; Yilmaz et al., 2022; Nedelcu et al., 2023; Kim et al., 2019; Chochlidakis et al., 2020; Mizumoto et al., 2020; Bilmenoglu et al., 2020;

Revilla-León et al., 2021; Revell et al., 2022).Therefore, non-splinting digital scanning strategies are not considered an approach that can be systematically recommended for all clinical situations (Papaspyridakos et al., 2020; Nedelcu et al., 2023; Papaspyridakos et al., 2023a; Papaspyridakos et al., 2023b).

#### *4.1.4. Factors Affecting Accuracy*

*· Lack of Anatomical Reference Points*

In non-splinting digital scanning strategies, the lack of sufficient fixed anatomical reference points between adjacent implants in edentulous areas can complicate the alignment of digital data. Particularly in extensive edentulous regions, this limitation may lead to cumulative errors during scanning and increase the risk of digital distortion (Papaspyridakos et al., 2020; Knechtle et al., 2022; Rasaie et al., 2021; Al Hamad & Al-Kaff, 2023).

*· Mobile Soft Tissues*

Displacement of mobile peri-implant soft tissues during scanning can negatively affect the stability of surface data recorded by intraoral scanners. This tissue mobility is considered a significant factor that reduces the accuracy of full-arch implant scans by introducing errors during the image registration phase (Papaspyridakos et al., 2020; Knechtle et al., 2022; Rasaie et al., 2021; Al Hamad & Al-Kaff, 2023).

*· Scan body Design and Implant Position*

The geometry, height, and surface characteristics of implant scan bodies used in non-splinting digital scanning strategies directly influence the ability of intraoral scanners to capture reliable reference data. In addition, implant distribution within the arch, interimplant distances, and overall implant configuration play a decisive role in the accuracy of the digital data acquired during scanning. The influence of these factors is particularly pronounced in non-splinting protocols (Paratelli et al., 2023; Crockett et al., 2023; Roig et al., 2022; Klein et al., 2023; Llansana et al., 2022; Liaropoulou et al., 2023).

### 4.2. Non- Calibrated Splinting Technique

#### *4.2.1. The Concept and Purpose of Splinting*

Non-calibrated splinting scanning strategies are based on intraoral connection of implant scan bodies to enhance scanning accuracy and scannability during full-arch implant scans performed with intraoral scanners. In this approach, splinting elements are intended to increase the amount of reference surface captured by the IOS during scanning, thereby enabling more stable image alignment (Paratelli et al., 2023). However, because the splinting structures used in these techniques are not measured or calibrated after fabrication or assembly, it is not possible to mathematically compensate for distortions that may occur during the scanning process.

### *4.2.2. Splint Materials Used*

Numerous materials and auxiliary structures used for non-calibrated splinting have been described in the literature. The primary purpose of these materials is to provide additional reference areas for intraoral scanners by creating a physical connection between implants.

*·Resin-Based Materials*

Resin-based splinting materials include dental floss (Mizumoto et al., 2020), orthodontic wires (Cappare et al., 2019), thermoplastic resins, and light-cured composite resins (Imburgia et al., 2020). Although the clinical application of these materials is relatively straightforward, polymerization shrinkage and deformations that may occur during manipulation can negatively affect the accuracy of the acquired digital data (Rutkunas et al., 2022).

*·PMMA Bars*

Plates or arch-shaped bars fabricated from polymethyl methacrylate (PMMA) represent another group of materials described for non-calibrated splinting (Gómez-Polo et al., 2020; Mandelli et al., 2020). PMMA bars can enhance reference stability during scanning by providing a more rigid connection between implants. However, fabrication of these structures often requires additional clinical or laboratory procedures.

*·Auxiliary Structures Fabricated Using 3D Printing*

In recent years, splinting structures fabricated using three-dimensional (3D) printing technology have become increasingly prevalent. These structures include auxiliary elements incorporating tooth-shaped forms between implant scan bodies (Iturrate et al., 2019; Tallarico et al., 2020; Venezia et al., 2019), devices composed of geometric configurations (Crockett et al., 2023; Beretta et al., 2021; Anwar et al., 2024), and horizontal scan body designs featuring extensions that connect adjacent implant scan bodies (Ashry et al., 2024; Wu et al., 2024). However, only a limited number of these systems are currently commercially available (Crockett et al., 2023; Roig et al., 2022).

### *4.2.3. The Effect of Geometry and Color on Digital Scanning Accuracy*

The geometry and color of non-calibrated splinting structures can influence the quality of surface data captured by intraoral scanners. An in vitro study demonstrated that scanning accuracy varied when full-arch splint frames exhibited different geometric designs (circular, square, and irregular) and colors (beige, gray, and white). It was reported that structures with irregular surface textures and a beige color yielded higher accuracy values (Kernen et al., 2022). However, the generalizability of these findings across different intraoral scanner technologies and systems remains unclear.

### *4.2.4. Clinical and In Vitro Accuracy Data*

Studies evaluating the accuracy of non-calibrated splinting scanning strategies have reported wide variability. The literature indicates that reported mean trueness values range from 49 to 240 µm, while precision values range from 45 to 176 µm (Nedelcu et al., 2023; Mizumoto et al., 2020; Anwar et al., 2024; Ashry et al., 2024; Rutkunas et al., 2022; Kernen et al., 2022; Wu et al., 2023).

In a recent in vitro study, the distortion levels of eight different non-calibrated splinting techniques were evaluated, demonstrating that the splinting material used influenced the accuracy of the digitally recorded implant positions (Rutkunas et al., 2022). However, this study assessed only a single implant configuration and a limited number of implant scan bodies, thereby restricting the direct transferability of the findings to clinical conditions.

The apico-coronal position of the splint structure has also been identified as a factor influencing accuracy. Wu et al. reported higher accuracy values when splint elements were positioned closer to the mucosa; however, they emphasized that the observed differences may not be clinically significant (Wu et al., 2023).

In general, a substantial proportion of studies in the literature indicate that non-calibrated splint-based digital scanning strategies can provide higher trueness and precision compared with non-splinting methods (Ferreira de Almeida et al., 2021; Gómez-Polo et al., 2020; Mandelli et al., 2020; Iturrate et al., 2019; Tallarico et al., 2020; Venezia et al., 2019; Beretta et al., 2021; Anwar et al., 2024; Ashry et al., 2024; Wu et al., 2024; Wu et al., 2023). However, the marked methodological heterogeneity among the available studies makes it difficult to clearly identify the most appropriate non-calibrated splinting approach.

## 4.3 Calibrated Implant Scan Bodies

### *4.3.1. The Concept of Calibration and Measurement Principle*

Calibrated implant scan body systems are based on the prior high-precision definition of the scan body's actual geometric properties to enhance the accuracy of digital data acquired during intraoral scanning. In this approach, calibration extends beyond representing the scan body solely by its nominal CAD geometry; instead, it involves measuring its actual dimensions after fabrication and defining these measurements as reference data within the digital system. This enables the identification and mathematical correction of systematic distortions that may occur during intraoral scanning through software-based processes (Klein et al., 2023).

The concept of a calibrated scan body relates primarily to the interpretation of the digital data acquired during the scanning process rather than to the manufacturing quality of the scan body itself. In this context, the fundamental purpose of calibration is not to eliminate all errors that may occur during scanning, but to ensure that such errors are defined relative to pre-measured geometric references, thereby enabling control of measurement deviations. Accordingly, calibration refers not to a procedure applied directly to the scan body, but rather to the integration of the scan body's measured geometric data into the digital workflow as a reference.

This principle is particularly important in full-arch implant cases. As the distance between implants increases, even minor deviations in accuracy may accumulate, making measurement reliability critical. For this reason, calibration-based approaches are regarded as an effective strategy for improving trueness and precision in full-arch digital implant scans (Klein et al., 2023).

#### *4.3.2. CMM (Coordinate Measuring Machine)-Based Calibration*

In calibrated scan body systems, the geometric properties of scan bodies are measured in a contact-based manner using coordinate measuring machines (CMMs) after fabrication. CMM systems can determine the geometric parameters of the scan body, such as length, diameter, and angulation, with micron-level precision. The data obtained from these measurements are defined within the digital system specifically for each scan body set (Klein et al., 2023). Through this approach, the scanning data acquired by the intraoral scanner are evaluated not only based on visual surface matching but also with reference to the actual geometry measured by the CMM. Accordingly, this method aims to compensate for IOS-induced distortions on an implant-by-implant basis (Klein et al., 2023).

#### *4.3.3. Clinical Application Protocol*

The clinical application protocol for calibrated scan body systems differs from standard intraoral scanning approaches. The protocol recommended by the manufacturer requires two separate intraoral scans to be performed for the scanned arch. In this protocol, the same arch is scanned twice: the first scan begins at one side of the arch and progresses toward the opposite side, while the second scan starts at the opposite side and proceeds in the opposite direction. This approach aims to balance cumulative distortions that may occur depending on the scanning starting point and to calculate implant positions more accurately. The acquired digital data are processed using the manufacturer's software infrastructure, and the three-dimensional positions of the implants are calculated based on CMM reference data (Klein et al., 2023).

Although these systems allow the final implant scan to be obtained within a single clinical session, it is not possible to fabricate a conventional verification jig or a definitive implant plaster model. Consequently, the digital workflow must be conducted entirely within a virtual environment in clinical practice, and the verification process must be performed using digital data.

#### *4.3.4. Clinical Results Reported in the Literature*

The literature evaluating the clinical accuracy of calibrated implant scan body systems remains limited. To date, only a single clinical study has reported on the clinical performance of these systems. In that study, 37 completely edentulous arches were rehabilitated with full-arch implant-supported prostheses fabricated from intraoral scans acquired using a calibrated scan body system.

According to the reported outcomes, clinically acceptable implant–prosthetic fit was achieved in all cases, as assessed by the Sheffield test and radiographic evaluations. In addition, no mechanical or biological complications were observed during the one-year follow-up period (Klein et al., 2023). Nevertheless, the generalizability of these findings should be interpreted with caution due to the limited availability of clinical data.

#### *4.3.5. Advantages and Limitations*

The most important advantage of calibrated scan body systems is that systematic distortions that may occur during intraoral scanning can be identified on an implant-by-implant basis and mathematically compensated for. This capability can improve impression accuracy, particularly in full-arch implant cases (Klein et al., 2023). In addition, the ability to obtain the definitive implant scan in a single clinical session is another advantage that may accelerate clinical workflow.

However, these systems also present certain limitations. Dependence on manufacturer-specific software infrastructure in clinical practice, the inability to apply conventional verification methods, and the limited number of available clinical studies are among the factors restricting the widespread clinical adoption of this approach. Therefore, the accuracy and clinical effectiveness of calibrated scan body systems should be further supported by well-designed clinical and laboratory studies involving larger patient populations (Klein et al., 2023).

### 4.4. Calibrated Framework

#### *4.4.1. Technical Definition and Digital Pre-Preparation Requirements*

Calibrated framework systems are based on rigid reference structures that are custom-designed and fabricated for each patient, with the aim of obtaining the final virtual implant model using intraoral scanners in full-arch implant scans. In this approach, a metal framework is designed and manufactured using preliminary digital data acquired from the patient prior to implant scanning. Therefore, calibrated framework techniques require an additional digital pre-preparation step within the digital workflow, unlike non-splinting or non-calibrated splinting approaches (Llansana et al., 2022). This preparatory process allows the geometric properties and reference points of the framework to be defined prior to scanning and establishes a basis for enhancing the accuracy of the data acquired during scanning (Llansana et al., 2022).

### *4.4.2. Metal Framework and Reference Marker Structure*

The metal structure used in calibrated framework systems contains specialized reference markers positioned around the implants. These markers are typically designed in a truncated-cone shape, integrated into the framework body via milling, and secured with screws. The uniform distribution of markers along the framework enables the definition of interimplant relationships via a rigid, stable reference structure (Llansana et al., 2022). Following fabrication of the framework, the spatial position and orientation of the markers are measured with high precision using coordinate measuring machines (CMM), and these data are defined as reference data within the digital system (Llansana et al., 2022).

### *4.4.3. Literature Findings in Terms of Trueness and Precision*

Data reported in the literature indicate that calibrated framework systems yield improved trueness and precision**.** It has been shown that linear trueness and precision values obtained in full-arch implant scans using calibrated framework techniques fall within low deviation ranges, and that this approach yields higher trueness compared with non-calibrated splinting techniques (Revilla-León et al., 2024). However, because the currently available evidence is largely based on in vitro studies, further evaluation of the clinical performance of calibrated framework systems across different intraoral scanner systems and patient populations is required (Llansana et al., 2022; Revilla-León et al., 2024).

## 4.5. Reverse Impression Technique

### *4.5.1. Conceptual Definition*

The reverse impression technique is a digital impression approach based on recording implant positions by digitally capturing the implant-supported provisional restoration extraorally, rather than performing a direct intraoral implant scan. The aim of this technique is to reconstruct the spatial positions of implants within a virtual environment based on the existing fit and geometry of the implant-supported provisional restoration. Therefore, the reverse impression technique represents a conceptually different approach compared with scanning strategies that acquire data directly at the implant level (Liaropoulou et al., 2023).

In this method, scanning analogues or scan bodies incorporating implant analogue geometry are used as the primary components, and the acquired digital data can be integrated into existing CAD/CAM workflows through the corresponding system libraries (Liaropoulou et al., 2023).

### *4.5.2. Transfer of Implant and Prosthetic Information via Provisional Prosthesis*

In the reverse impression technique, implant positions are recorded using scanning analogs placed within the implant-supported provisional restoration. During the extraoral digitization of the provisional restoration, the volumetric dimensions of the restoration and tooth positions are simultaneously acquired, in addition to the implant positions. This characteristic allows the reverse impression technique to transfer both implant-related and prosthetic information concurrently (Liaropoulou et al., 2023).

However, the accuracy of the implant positions obtained using this approach depends on the fit accuracy of the directly scanned provisional restoration. In other words, the metrological reliability of the reverse impression technique is constrained by the passive fit of the implant-supported provisional restoration.

#### *4.5.3. Modified Reverse Impression Techniques*

· *Soft Tissue Adaptation*

The first modification proposed for the reverse impression technique is intended for clinical situations in which insufficient fit is present on the internal surface of the implant-supported prosthesis. In particular, changes in the volume and position of soft tissues during the healing period following implant surgery may negatively affect the current fit of the provisional prosthesis. In this modification, the internal surface of the implant-supported prosthesis is rebased with polyvinyl siloxane (PVS) prior to extraoral digitization, with the aim of ensuring adaptation of the prosthesis to the soft tissue conditions at the time the final impression is obtained (Rosmaninho et al., 2023).

· *Combination with Verification Jig*

The second modification is intended for clinical situations in which the passive fit of the implant-supported provisional prosthesis is inadequate. In such cases, a conventional verification jig can be used to record implant positions extraorally with greater accuracy. The implant positions obtained using the verification jig are subsequently transferred to the digital environment by integrating them with the reverse impression technique (Rosmaninho et al., 2024).

## 5. Factors Affecting Accuracy in Digital Scanning Strategies

Accuracy in digital implant impressions depend not only on the intraoral scanner used, but also directly on the selected scanning strategy and specific clinical application parameters. In particular, statistically and clinically significant differences in trueness and precision have been reported across scanning strategies for full-arch implant scans. Therefore, the selection of the scanning strategy should be planned in accordance with the implant configuration and prevailing clinical conditions. The scanning sequence, starting point, and data stitching approach may influence scanning time, the number of captured photograms, and cumulative error formation. In addition, the scanner technology employed, scan body design, and operator-related factors represent critical variables that determine the trueness and precision of digital implant measurements (Oh et al., 2020; Punj et al., 2017; Kernen et al., 2022; Kong, Li, & Liu, 2022; Dutton et al., 2020; Revilla-León et al., 2022; Imburgia et al., 2017; Chen et al., 2022; Park et al., 2018; Revell et al., 2022; Resende et al., 2021).

### *5.1. Critical Factors Affecting Accuracy in Implant-Based Measurements*

*Selection of scanning strategy:* Differences in trueness and precision have been reported among non-splinting, splinting, calibrated systems, and reverse techniques. Therefore, the selected scanning strategy is considered a decisive factor for measurement trueness and precision (Oh et al., 2020).

*Scanner technology and systems:* Confocal, triangulation and structured light have been shown to exhibit different trueness and precision performances. It has been reported that the data acquisition and processing principles of the system used directly influence measurement outcomes (Punj et al., 2017; Kernen et al., 2022; Kong, Li, & Liu, 2022).

Scan body design: The height, diameter, material, and geometric properties of the scan body have been reported to affect scannability and the accuracy of digital data matching. It is emphasized that scan body design parameters play a critical role in the precise transfer of implant position (Dutton et al., 2020; Revilla-León et al., 2022)(see Capter 2).

*Scan strategy and starting point***:** Error accumulation, particularly in full-arch implant scans, has been reported to vary depending on the scan pattern and starting point. Deviations occurring during the data stitching process are considered to influence trueness and precision (Imburgia et al., 2017)

*Operator experience:* It has been demonstrated that scan distance, scan angulation control, and rescan management can affect trueness and precision. Operator-related variables are therefore considered decisive for clinical measurement outcomes (Revell et al., 2022; Resende et al., 2021)

*Clinical conditions:* Clinical factors such as humidity, soft tissue movement, saliva presence, and a limited field of view may reduce data quality and negatively affect trueness and precision (Chen et al., 2022; Park et al., 2018)

## 6. Selection of a Scanning Strategy Based on Clinical Indications

A review of the current literature indicates that no single scanning strategy has been proven to be universally superior for all clinical situations in digital implant measurements. It is emphasized that the selection of a scanning strategy should be based on factors such as the number of implants, arch length, the presence of anatomical reference points, and the type of planned restoration. In particular, in full-arch cases, the potential for error accumulation during data merging increases; therefore, the scanning strategy should be selected in accordance with the specific clinical indications.

### *6.1. Case-Specific Selection Criteria*

#### *6.1.1. Partial Implant-Supported Prostheses*

It has been reported that non-splinting approaches can provide sufficient accuracy in most cases due to the short arch length and the presence of natural tooth reference points. It is stated that clinically acceptable results can be achieved using standard scanning patterns, as data matching errors are limited under these conditions.

#### *6.1.2. Full-Arch and Fully Edentulous Cases*

The current literature indicates that the risk of error accumulation during digital data fusion increases with greater arch length and limited anatomical reference points. It has been shown that digital data stability may decrease in cases of complete edentulism and multiple implants due to the presence of mobile mucosa and the lack of stable references. Under these clinical conditions, impression accuracy is reported to be influenced by factors such as implant distribution, interimplant distance, soft tissue volume, and the scan body design used.

Therefore, it has been reported that splinting techniques, calibrated framework systems, or optimized scanning patterns may improve accuracy in such cases. In addition, appropriate selection of the scanning starting point and the use of auxiliary devices that support data stability are emphasized as important factors for enhancing impression reliability.

## 7. Challenges in Implant-Supported Prosthetic Impression Procedures and the Development of Photogrammetry Systems

The main challenges encountered in full-arch implant impression procedures for implant-supported prostheses are associated with data fusion errors over long distances, insufficient reference structures, soft tissue movement, and scan body stability. In addition, scanning patterns, scanning starting points, and operator-related variables may influence accuracy. These limitations pose clinical risks, particularly in full-arch fixed implant-supported prosthetic rehabilitations, where passive fit requirements are critical.

Photogrammetry systems (PGS) have been developed to address these challenges. Photogrammetry aims to eliminate intraoral data registration errors during implant impression procedures by simultaneously recording implant positions using coded scan bodies. Consequently, this approach offers the potential for higher accuracy, especially in multiple implant and full-arch implant-supported prosthetic cases. However, system selection should take into account factors such as cost, the need for additional equipment, and the integrity of the overall digital workflow (Revilla-León et al., 2021; Negreiros et al., 2025).

## 8. Conclusion

Digital scanning strategies for implants play a decisive role in the success of fixed prosthetic rehabilitation. Particularly in full-arch and multiple implant cases, the selected scanning strategy can directly affect accuracy, passive fit, and the clinical success of the definitive prosthesis. Therefore, the selection of the scanning strategy should be based not only on the scanner system used but also on the clinical indication, implant distribution, and existing anatomical conditions.

The current literature demonstrates that there are significant differences in accuracy among different scanning approaches. This highlights the need for an evidence-based approach in clinical decision-making. Selecting the most appropriate scanning strategy based on case-specific characteristics and available scientific evidence may reduce the risk of mechanical complications and support long-term clinical success.

## References

Al Hamad, K. Q., & Al-Kaff, F. T. (2023). Trueness of intraoral scanning of edentulous arches: A comparative clinical study. *Journal of Prosthodontics, 32*(1), 26–31. https://doi.org/10.1111/jopr.13506

Anwar, H., Azer, A., & AboElHassan, R. G. (2024). Influence of a specially designed geometric device and modified scan bodies on the accuracy of a maxillary complete arch digital implant scan: An in vitro study. *Journal of Prosthetic Dentistry, 131*(4), 683.e1–683.e7.https://doi.org/10.1016/j.prosdent.2023.04.012

Ashry, A., Abdelhamid, A. M., Ezzelarab, S., & Khamis, M. M. (2024). Effect of using scan body accessories and inter-implant distances on the accuracy of complete arch implant digital impressions: An in vitro study. *Journal of Prosthodontics*. Advance online publication. https://doi.org/10.1111/jopr.13711

Beretta, M., Poli, P. P., Tansella, S., Aguzzi, M., Meoli, A., & Maiorana, C. (2021). Cast-free digital workflow for implant-supported rehabilitation in a completely edentulous patient: A clinical report. *Journal of Prosthetic Dentistry, 125*(2), 197–203. https://doi.org/10.1016/j.prosdent.2020.02.006

Bilmenoglu, C., Cilingir, A., Geckili, O., Bilhan, H., & Bilgin, T. (2020). In vitro comparison of trueness of 10 intraoral scanners for implant-supported complete-arch fixed dental prostheses. *Journal of Prosthetic Dentistry, 124*(6), 755–760. https://doi.org/10.1016/j.prosdent.2019.10.024

Cappare, P., Sannino, G., Minoli, M., Montemezzi, P., & Ferrini, F. (2019). Conventional versus digital impressions for full-arch screw-retained maxillary rehabilitations: A randomized clinical trial. *International Journal of Environmental Research and Public Health, 16*, 1–15.https://doi.org/10.3390/ijerph16122118

Chen, Y., Zhai, Z., Li, H., et al. (2022). Influence of liquid on the tooth surface on the accuracy of intraoral scanners: An in vitro study. *Journal of Prosthodontics, 31*(1), 59–64. https://doi.org/10.1111/jopr.13358

Chochlidakis, K., Papaspyridakos, P., Tsigarida, A., et al. (2020). Digital versus conventional full-arch implant impressions: A prospective study on 16 edentulous maxillae. *Journal of Prosthodontics, 29*(4), 281–286.https://doi.org/10.1111/jopr.13123

Crockett, R. J., Parikh, V., Ahn, B., & Yao, C. H. D. (2023). Use of a dual-purpose implant scan body to obtain both digital and analog records for complete arch fixed implant restorations. *Journal of Prosthetic Dentistry*. Advance online publication. https://doi.org/10.1016/j.prosdent.2023.02.017

Dutton, E., Ludlow, M., Mennito, A., et al. (2020). The effect that different substrates have on the trueness and precision of eight different intraoral scanners. *Journal of Esthetic and Restorative Dentistry, 32*(2), 204–218.https://doi.org/10.1111/jerd.12528

Flügge, T., van der Meer, W. J., Gonzalez, B. G., Vach, K., Wismeijer, D., & Wang,

P. (2018). The accuracy of different dental impression techniques for implant-supported dental prostheses: A systematic review and meta-analysis. *Clinical Oral Implants Research, 29*(Suppl. 16), 374–392.https://doi.org/10.1111/clr.13273

Gómez-Polo, M., Ballesteros, J., Perales-Padilla, P., Perales-Pulido, P., Gómez-Polo, C., & Ortega, R. (2020). Guided implant scanning: A procedure for improving the accuracy of implant-supported complete-arch fixed dental prostheses. *Journal of Prosthetic Dentistry, 124*, 135–139.https://doi.org/10.1016/j.prosdent.2019.05.003

Gómez-Polo, M., Cascos, R., Ortega, R., Barmak, A. B., Kois, J. C., & Revilla-León, M. (2023). Influence of arch location and scanning pattern on the scanning accuracy, scanning time, and number of photograms of complete-arch intraoral digital implant scans. *Clinical Oral Implants Research, 34*(6), 591–601.https://doi.org/10.1111/clr.14122

Gómez-Polo, M., Donmez, M. B., Çakmak, G., Yilmaz, B., & Revilla-León, M. (2023). Influence of implant scan body design on intraoral scanning accuracy: A systematic review. *Journal of Prosthodontics, 32*(Suppl. 2), 165–180.https://doi.org/10.1111/jopr.13588

Imburgia, M., Logozzo, S., Hauschild, U., Veronesi, G., Mangano, C., & Mangano, F. G. (2017). Accuracy of four intraoral scanners in oral implantology: A comparative in vitro study. *BMC Oral Health, 17*(1), 92. https://doi.org/10.1186/s12903-017-0383-4

Imburgia, M., Kois, J., Marino, E., Lerner, H., & Mangano, F. G. (2020). Continuous scan strategy (CSS): A novel technique to improve the accuracy of intraoral digital impressions. *European Journal of Prosthodontics and Restorative Dentistry, 28*, 128–141. https://doi.org/10.1922/EJPRD_01967Mangano14

Iturrate, M., Minguez, R., Pradies, G., & Solaberrieta, E. (2019). Obtaining reliable intraoral digital scans for an implant-supported complete-arch prosthesis: A dental technique. *Journal of Prosthetic Dentistry, 121*(2), 237–241.https://doi.org/10.1016/j.prosdent.2018.05.018

Kernen, F. R., Recca, M., Vach, K., Nahles, S., Nelson, K., & Flügge, T. V. (2022). In vitro scanning accuracy using different aids for multiple implants in the edentulous arch. *Clinical Oral Implants Research, 33*(10), 1010–1020.https://doi.org/10.1111/clr.13957

Kernen, F., Schlager, S., Seidel Alvarez, V., et al. (2022). Accuracy of intraoral scans: An in vivo study of different scanning devices. *Journal of Prosthetic Dentistry, 128*(6), 1303–1309. https://doi.org/10.1016/j.prosdent.2021.03.007

Kim, K. R., Seo, K. Y., & Kim, S. (2019). Conventional open-tray impression versus intraoral digital scan for implant-level complete-arch impression. *Journal of Prosthetic Dentistry, 122*(6), 543–549.https://doi.org/10.1016/j.prosdent.2019.03.021

Klein, M., Tuminelli, F. J., Sallustio, A., et al. (2023). Full-arch restoration with the NEXUS IOS® system: A retrospective clinical evaluation after one year. *Journal* *of Dentistry, 139*, 104741.https://doi.org/10.1016/j.jdent.2023.104741

Kong, L., Li, Y., & Liu, Z. (2022). Digital versus conventional full-arch impressions in linear and 3D accuracy: A systematic review and meta-analysis of in vivo studies. *Clinical Oral Investigations, 26*(9), 5625–5642.https://doi.org/10.1007/s00784-022-04607-6

Llansana, F., Guirao, S., Kois, J. C., & Revilla-León, M. (2022). Calibrated splinting framework for complete arch intraoral implant digital scans. *Journal of Prosthetic Dentistry*. Advance online publication.https://doi.org/10.1016/j.prosdent.2022.09.012

Liaropoulou, G. M., Kamposiora, P., Quílez, J. B., Cantó-Navés, O., & Foskolos, P. G. (2023). Reverse impression technique: A fully digital protocol. *Journal of Prosthetic Dentistry*. Advance online publication.https://doi.org/10.1016/j.prosdent.2023.03.004

Ma, J., Zhang, B., Song, H., Wu, D., & Song, T. (2023). Accuracy of digital implant impressions: A systematic review and meta-analysis. *International Journal of Implant Dentistry, 9*(1), 48.https://doi.org/10.1186/s40729-023-00457-9

Mangano, F. G., Hauschild, U., Veronesi, G., Imburgia, M., Mangano, C., & Admakin, O. (2019). Trueness and precision of five intraoral scanners. *BMC Oral Health, 19*, 101. https://doi.org/10.1186/s12903-019-0808-7

Mizumoto, R. M., Yilmaz, B., McGlumphy, E. A., Jr., et al. (2020). Accuracy of different digital scanning techniques. *Journal of Prosthetic Dentistry, 123*(1), 96–104. https://doi.org/10.1016/j.prosdent.2018.12.005

Nedelcu, R., Olsson, P., Thulin, M., Nyström, I., & Thor, A. (2023). In vivo trueness and precision of full-arch implant scans. *Journal of Dentistry, 128*, 104308. https://doi.org/10.1016/j.jdent.2022.104308

**Negreiros, W. M., et al.** (2025). Complete-arch implant scans: Photogrammetry versus intraoral scanning. *Journal of Dentistry, 150*, 105969. https://doi.org/10.1016/j.jdent.2025.105969

Papaspyridakos, P., Vazouras, K., Chen, Y. W., et al. (2020). Digital vs conventional implant impressions. *Journal of Prosthodontics, 29*(8), 660–678.https://doi.org/10.1111/jopr.13238

Paratelli, A., Vania, S., Gómez-Polo, C., Ortega, R., Revilla-León, M., & Gómez-Polo, M. (2023). Techniques to improve the accuracy of complete arch implant digital scans. *Journal of Prosthetic Dentistry, 129*(6), 844–854.https://doi.org/10.1016/j.prosdent.2022.08.016

Park, H. N., Lim, Y. J., Yi, W. J., Han, J. S., & Lee, S. P. (2018). A comparison of the accuracy of intraoral scanners using an intraoral environment simulator. *Journal of Advanced Prosthodontics, 10*(1), 58–64.https://doi.org/10.4047/jap.2018.10.1.58

Punj, A., Bompolaki, D., & Goodacre, C. J. (2017). Dental impression materials and techniques. *Dental Clinics of North America, 61*(4), 779–796. https://doi.org/10.1016/j.cden.2017.06.004

Ren, S., Jiang, X., Lin, Y., & Di, P. (2022). Crown accuracy and time efficiency of cement-retained implant-supported restorations. *Journal of Prosthodontics, 31*(5), 405–411. https://doi.org/10.1111/jopr.13423

Resende, C. C. D., Barbosa, T. A. Q., Moura, G. F., et al. (2021). Influence of operator experience, scanner type, and scan size on 3D scans. *Journal of Prosthetic Dentistry, 125*(2), 294–299.https://doi.org/10.1016/j.prosdent.2019.12.011

**Revilla-León, M., Att, W., Özcan, M., & Rubenstein, J.** (2021). Comparison of conventional, photogrammetry, and intraoral scanning accuracy of complete-arch implant impression procedures evaluated with a coordinate measuring machine. *The Journal of Prosthetic Dentistry, 125*(3), 1–8. https://doi.org/10.1016/j.prosdent.2020.02.009

Revell, G., Simon, B., Mennito, A., et al. (2022). Evaluation of complete-arch implant scanning with five different intraoral scanners. *Journal of Prosthetic Dentistry, 128*(4), 632–638.https://doi.org/10.1016/j.prosdent.2021.01.013

Revilla-León, M., Frazier, K., da Costa, J. B., Kumar, P., Duong, M. L., Khajotia, S., & Urquhart, O. (2021). Intraoral scanners: An ADA clinical evaluators panel survey. *Journal of the American Dental Association, 152*(8), 669–670.e2. https://doi.org/10.1016/j.adaj.2021.05.018

Revilla-León, M., Young, K., Sicilia, E., Cho, S. H., & Kois, J. C. (2022). Influence of definitive and interim restorative materials and surface finishing on the scanning accuracy of an intraoral scanner. *Journal of Dentistry, 120*, 104114. https://doi.org/10.1016/j.jdent.2022.104114

Rosmaninho, A., Vedovato, E., Kois, J. C., & Revilla-León, M. (2023). A modified reverse impression technique. *Journal of Prosthetic Dentistry*. Advance online publication. https://doi.org/10.1016/j.prosdent.2023.06.003

Rosmaninho, A., Vedovato, E., Kois, J. C., & Revilla-León, M. (2024). Altered reverse impression method. *Journal of Esthetic and Restorative Dentistry, 36*(4), 566–572. https://doi.org/10.1111/jerd.13084

Vitai, V., Németh, A., Sólyom, E., Czigola, A., Kivovics, M., & Varga, E. (2023). Evaluation of the accuracy of intraoral scanners for complete-arch scanning. *Journal of Dentistry, 137*, 104636. https://doi.org/10.1016/j.jdent.2023.104636

Wu, H. K., Wang, J., Chen, G., et al. (2024). Effect of prefabricated auxiliary devices and scanning patterns. *Journal of Dentistry, 140*, 104788. https://doi.org/10.1016/j.jdent.2023.104788

Wulfman, C., Naveau, A., & Rignon-Bret, C. (2020). Digital scanning for complete-arch implant-supported restorations. *Journal of Prosthetic Dentistry, 124*(2), 161–167. https://doi.org/10.1016/j.prosdent.2019.04.020

Zhang, Y. J., Shi, J. Y., Qian, S. J., et al. (2021). Accuracy of full-arch digital implant impressions. *International Journal of Oral Implantology, 14*(2), 157–179.

## Chapter 2

# DIGITAL SCAN BODIES

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## 1. INTRODUCTION

Digital workflows have become an indispensable component of modern implant prosthodontics, profoundly reshaping how implant positions are recorded and transferred into virtual planning environments. In this context, scan bodies (SBs) have gained a central role as critical intermediary components that enable the digital registration of implant position, angulation, and rotational orientation. Because endosseous dental implants are embedded within the alveolar bone and obscured by peri-implant soft tissues, their three-dimensional (3D) spatial location cannot be directly captured by digital scanners. To overcome this inherent limitation, a transmucosal component—referred to as the SB—is connected to the implant or implant analogue, serving as a geometric reference for 3D implant localization during digital scanning procedures (Çakmak, Yilmaz, Treviño, Kökat, & Yilmaz, 2020; Mohajerani, Djalalinia, & Alikhasi, 2025; Pan, Dai, Tsoi, Lam, & Pow, 2025; Park, Chang, Pyo, & Kim, 2024; Qasim, Akbar, Sadeqi, & Baig, 2024).

In clinical and laboratory workflows, SBs are connected either intraorally to implants or extraorally to implant analogues incorporated into working casts, after which they are digitized using intraoral scanners (IOSs) or laboratory scanners. The acquired scan data are transferred into computer-aided design (CAD) software, where the geometric features of the SB are matched to a corresponding digital library file. Through this surface-matching process, the virtual implant is positioned three-dimensionally within the digital dental arch, accurately reproducing the spatial position of the implant within the oral cavity and enabling the subsequent design and fabrication of implant-supported prosthetic restorations (Çakmak et al., 2020; Qasim et al., 2024; Uzel et al., 2023).

In comparison with conventional impression techniques—which are susceptible to material contraction, dimensional distortion, and technique sensitivity—digital impression workflows employing SBs permit high-resolution and reproducible data acquisition while enhancing patient comfort. These advantages have contributed substantially to the growing clinical adoption of IOS-based implant workflows (Gómez-Polo, Donmez, Çakmak, Yilmaz, & Revilla-León, 2023; Mohajerani et al., 2025). Nevertheless, the accuracy of digital implant impressions remains highly dependent on the precise 3D positioning of the SB, as even minor deviations in SB placement may be transferred to the virtual model and ultimately compromise the passive fit and accuracy of the definitive prosthetic restoration (Park et al., 2024).

Although SBs are designed to fulfil a common functional objective, they exhibit considerable variability in design, material composition, and geometric configuration. In general, SBs consist of three main regions: a base that connects to the implant platform, a body that provides structural rigidity, and a scan region responsible for registering spatial information during optical scanning (Figure 1). These components may be fabricated from metal alloys, polymer-based materials such as polyetheretherketone (PEEK), or hybrid combinations, and they differ in dimensions, surface characteristics, and connection mechanisms depending on the manufacturer and intended clinical application (Michelinakis, Apostolakis, Nikolidakis, & Lapsanis, 2024; Pachiou et al., 2023; Qasim et al., 2024).

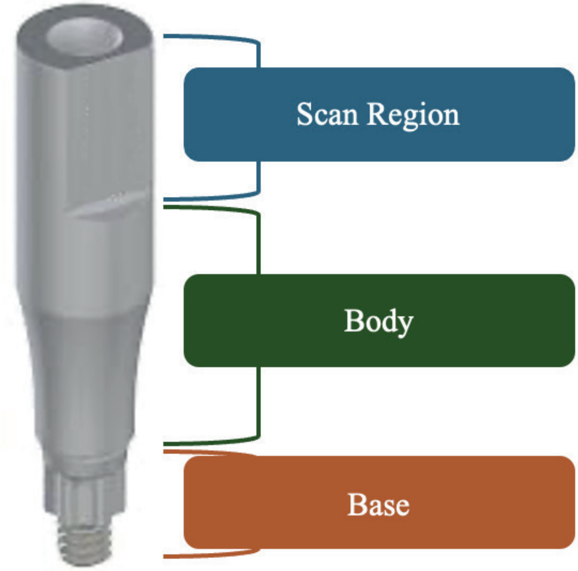

**Figure 1.** *Schematic illustration of a scan body, showing its three structural components: scan region, body, and base.*

SBs demonstrate significant variability in material composition, geometric design, and clinical handling characteristics in addition to their fundamental structural configuration. This heterogeneity has resulted in the development of several classification frameworks that are commonly employed in both research and clinical practice (Mohajerani et al., 2025; Revilla-León, Lanis, Yilmaz, Kois, & Gallucci, 2023; Wan et al., 2024). SBs can be systematically classified based on key parameters, such as material composition, retention system, geometric configuration, height, diameter, reusability, anti-rotational features, extensional features, and the type of geometric modification applied, from a clinical and technical perspective. Table 1 summarises the classification parameters and their respective categories.

**Table 1.** *General classification of scan bodies.*

| Classification category | Classification parameter | Categories |
|---|---|---|
| Design-related parameters | Geometry | Cylindrical<br>Cuboidal<br>Spherical<br>Dome-shaped |
| | Height | Short<br>Intermediate<br>Tall |
| | Diameter | Narrow<br>Standard<br>Wide |
| | Anti-rotational design features | Flat facets<br>Beveled surfaces |
| | Extensional design features | Bars<br>Wings |
| | Modification type | Subtractive modifications<br>Additive modifications |
| Material-related parameters | Single material | Polymers (PEEK)<br>Metals (titanium alloys, aluminum alloys) |
| | Hybrid material | Hybrid (Polymer-metal combinations) |
| Application-related parameters | Reusability | Single use<br>Reusable |
| | Retention system | Screw-retained<br>Snap-on or Friction fit<br>Magnet-retained |
| | Tightening torque | Manufacturer-dependent recommended value |

Design-related parameters—including SB shape, size, surface texture, and the incorporation of anti-rotational features—have been demonstrated to influence scanning accuracy. Many SBs incorporate flat surfaces or beveled geometries that simulate the implant's internal connection; even though the ideal arrangement of these characteristics is still uncertain. Furthermore, implant depth and SB visibility constitute critical variables, as deeper implant placement reduces SB exposure and increases the risk of scanning inaccuracies (Marques et al., 2021; Mohajerani et al., 2025).

Despite the extensive range of commercially available SBs (Figure 2), current clinical and experimental evidence remains insufficient to define standardized recommendations concerning optimal SB geometry, material selection, or compatibility across different IOS systems. In addition, factors such as manufacturing tolerances, positional distortion induced by tightening torque, material wear associated with repeated use, and the effects of sterilization cycles may further influence SB performance and scanning accuracy. Consequently, contemporary clinical practice continues to emphasize adherence to manufacturer-specific guidelines regarding tightening torque and reuse protocols until more robust scientific evidence becomes available to support standardized clinical recommendations (Revilla-León, Lanis, et al., 2023).

**Figure 2.** *Representative illustrations of commercially available scan bodies with different geometrical designs and materials.*

## 2. Design-related Parameters of Scan Bodies

Scan body geometry is a primary determinant of scanning trueness and precision within digital implant workflows, as geometric characteristics directly affect surface recognition, mesh acquisition, and virtual alignment during optical scanning procedures. Because SBs are digitized directly through intraoral or laboratory scanning systems, even minor variations in both macro- and micro-geometric features may significantly impact linear and angular accuracy when transferring implant position into the digital environment (Mohajerani et al., 2025; Wan et al., 2024).

At the macro-geometric level, SB shape, height, and diameter play a decisive role in determining scanning accuracy. Simplified cylindrical configurations generally exhibit superior trueness in comparison with more complicated cuboidal or spherical designs, which have been associated with increased surface deviations and angular inaccuracies. In addition, dome-shaped or smoothly contoured SBs further enhance accuracy by promoting consistent surface detection and minimizing optical artefacts during scanning (Michelinakis et al., 2024; Mohajerani et al., 2025; Pan et al., 2025).

Excessive geometric complexity—such as sharp edges, overlapping contours, or superfluous auxiliary elements—may adversely affect scanning accuracy by increasing light reflection, acute angular transitions, and data overlap (Pan et al., 2025). In response to these limitations, horizontally oriented implant scan bodies (Figure 3) have been developed to facilitate a more continuous, single-pass scanning trajectory along the dental arch, thereby reducing image overlap and stitching errors compared with conventionally vertically positioned scan bodies. This macro-design concept aligns with splinting strategies and the incorporation of auxiliary or extensional reference structures, which introduce additional horizontal landmarks that enhance scan alignment and positional stability during data acquisition (Azevedo et al., 2025; Etxaniz, Amezua, Jauregi, & Solaberrieta, 2025).

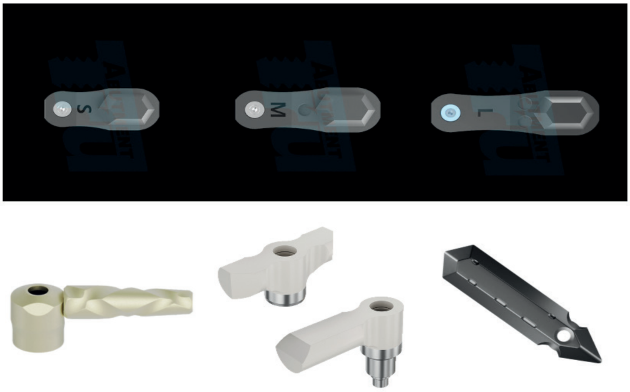

**Figure 3.** *Schematic illustrations of representative commercially available horizontal implant scan bodies.*

At the micro-geometric level, targeted design features—including limited extensional elements and well-defined surface facets—can refine scanning performance by improving mesh alignment and enhancing consistency between the scanned mesh file and the corresponding digital library file (Mohajerani et al., 2025). In this context, the incorporation of geometric references between adjacent scan bodies has demonstrated an improvement in the accuracy of complete-arch implant digital scans, with splinting (Figure 4) being among the most commonly used strategies. By minimizing relative movement between scan bodies, splinting improves overall trueness; however, excessive additive modifications or geometric complexity may impair both trueness and precision by introducing surface irregularities, optical artefacts, or angular inconsistencies, particularly in cases involving a limited scanner field of view or complex implant configurations (Wan et al., 2024). Additionally, most auxiliary splinting devices require customization, necessitating an initial intraoral scan and an extra patient appointment, thereby increasing clinical complexity and treatment time (Etxaniz et al., 2025). To mitigate these limitations, auxiliary geometric devices and horizontally extended or modified scan body designs—incorporating integrated extensional elements or attached auxiliary components—have been introduced. Although experimental and clinical evidence suggests their potential to improve scanning trueness, particularly in edentulous and full-arch rehabilitations, robust comparative data directly evaluating conventional scan bodies with and without such devices remain limited (Gianfreda et al., 2025; Mohajerani et al., 2025).

**Figure 4.** *Schematic illustration of the splinting approach for scan bodies using the Straumann EXACT™ system.*

Scan body height represents a critical geometric parameter influencing scanning outcomes. Commercially available scan bodies typically range from 3 to 17 mm in height, and evidence suggests that cylindrical SBs with intermediate heights tend to outperform both excessively short and overly tall designs. Optimal conditions are achieved when the implant is placed at tissue level, facilitating complete visibility of the scan body; in contrast, subgingival positioning reduces SB exposure and may compromise scanning accuracy. Although increased SB height may enhance visibility and facilitate angular referencing, excessive height can exceed the intraoral scanner's field of view, requiring additional scans and increasing the risk of stitching artifacts. Conversely, reduced SB height has been associated with improved trueness due to simplified data acquisition and reduced cumulative error; however, shorter designs may negatively affect accuracy in parallel or angulated implants and compromise seating verification, particularly in cases of deep implant placement or limited interarch space (Anitua, Lazcano, Anitua, Eguia, & Alkhraisat, 2025; Karthhik, Raj, & Karthikeyan, 2022; Marques et al., 2021; Pachiou et al., 2023).

Importantly, the optimal SB height appears to be context-dependent and influenced by surrounding anatomical conditions. Shorter SBs may be advantageous in the presence of adjacent teeth to facilitate scanner access, whereas taller designs may provide improved reference geometry in edentulous regions. Collectively, these findings indicate that SB height selection should be individualized according to implant depth, angulation, and peri-implant tissue conditions rather than determined by a single standardized value (Anitua et al., 2025; Karthhik et al., 2022; Marques et al., 2021; Pachiou et al., 2023).

## 3. Materials Used for Scan Bodies

Material selection, in conjunction with SB geometry, plays a decisive role in scanning accuracy, mechanical stability, and long-term clinical reliability. The majority of commercially available SBs are fabricated from synthetic polymers, metals, or hybrid polymer–metal combinations, with PEEK, titanium alloys, and aluminum alloys being the most frequently employed materials (Marques et al., 2021; Qasim et al., 2024). Table 2 summarizes the comparative features of various materials employed in the fabricating of scan bodies.

**Table 2.** *Comparative features of materials used in the fabrication of scan bodies.*

| Property | Polymers | Metals | Hybrid |
|---|---|---|---|
| **Surface reflectivity** | *Low* | *High* | *Low-Moderate (dependent on scan region material)* |
| **Repeated use resistance** | *Moderate* | *High* | *High* |
| **Mechanical stability** | *Moderate (tightening torque-sensitive)* | *High* | *High (metal base support)* |
| **Wear resistance** | *Low-Moderate* | *High* | *Moderate-High (interface-dependent)* |

Early SB designs were predominantly polymer-based due to their favorable optical properties, particularly low surface reflectivity, which facilitates intraoral data acquisition. However, frequent clinical use has sometimes resulted in deformation at the screw interface, thereby undermining mechanical integrity and scan accuracy. To overcome these limitations, hybrid SBs incorporating a polymer scan region and a titanium base have been proposed to enhance resistance to tightening forces and improve implant–SB stability. Although hybrid designs enhance mechanical robustness, the interface between dissimilar materials may introduce minor positional discrepancies. Consequently, monolithic SB designs have been developed to minimize interfacial variability and enhance dimensional stability (Anitua et al., 2025; Baranowski, Stenport, Braian, & Wennerberg, 2025).

PEEK remains the preferred material for scan regions because of its low reflectivity and favorable optical behavior during intraoral scanning, in addition to its chemical resistance and thermal stability, which allow repeated sterilization. Nevertheless, compared with titanium, PEEK demonstrates lower mechanical strength and wear resistance, rendering monolithic PEEK SBs more susceptible to deformation under tightening forces, particularly at the implant–SB interface (Baranowski et al., 2025; Qasim et al., 2024). In contrast, titanium and titanium alloy SBs provide superior mechanical stability and wear resistance but may present optical challenges due to higher surface reflectivity, potentially requiring surface treatment to optimize scanning performance (Baranowski et al., 2025).

Beyond PEEK and titanium, aluminium alloys and resin-based materials are primarily used within the body segment of SBs. Manufacturing precision and material machinability are critical, as even minimal geometric deviations can impair the alignment between the scanned mesh and the corresponding digital library file. Furthermore, cumulative wear from repeated tightening and sterilization cycles—particularly at the SB base—may induce positional displacement over time, ultimately reducing the precision of digital implant position transfer (Marques et al., 2021; Mizumoto & Yilmaz, 2018).

## 4. Clinical Applications of Scan Bodies

Scan body applications encompass a range of clinical handling approaches and workflow-related factors that directly affect the accuracy and reliability of digital implant impressions. Beyond to geometric and material characteristics, application-related factors—such as SB orientation, stabilization methods, and modifications to the scanning workflow—play a critical role in determining overall scan quality. One of the most influential application-related parameters is SB orientation, particularly the positioning of the bevel or indexed surface relative to the scanning path. Appropriate orientation enhances surface recognition and alignment during both data acquisition and subsequent software processing, whereas inconsistent or unfavorable positioning may result in deviations in the implant position within the digital model (Wan et al., 2024).

Scan body fixation and stabilization are critical determinants of scanning accuracy and the 3D transfer of implant position. Adequate tightening is necessary to ensure complete seating of the SB; however, excessive or inconsistent torque may induce positional displacement at the implant–SB interface. Evidence from single-tooth implant studies indicates that SB displacement generally increases with higher torque values. Tightening protocols reported in the literature vary widely (5–35 Ncm, including hand tightening), and material-dependent behavior has been observed. Under identical torque conditions, greater displacement has been reported for polyetheretherketone (PEEK) SBs compared with those incorporating titanium connections (Wan et al., 2024). Consequently, several authors recommend limiting tightening torque to ≤10 Ncm to ensure that the dislocation of one-piece PEEK SBs remains within clinically acceptable levels, whereas higher torque values (up to 30 Ncm) may be acceptable for metallic SBs (Pachiou et al., 2023). Overall, current evidence suggests that verification of complete seating and adaptation prior to scanning may be more influential than the mere application of higher tightening forces (Revilla-León, Lanis, et al., 2023; Wan et al., 2024).

Scan bodies may be categorized based on their retention system (Figure 5). In screw-retained systems, the SB is connected to the implant or implant abutment using a fixation screw, with the recommended tightening torque varying according to the manufacturer's specifications. In snap-on or friction-fit retention systems, the SB is seated onto the implant, implant abutment, or healing abutment without a screw, relying on mechanical engagement for retention. Magnet-retained systems are typically associated with two-piece PEEK SBs. In these designs, a metallic base component is first connected to the implant, and a separate PEEK scan component is subsequently located over the metallic base through magnetic retention (Revilla-León, Lanis, et al., 2023).

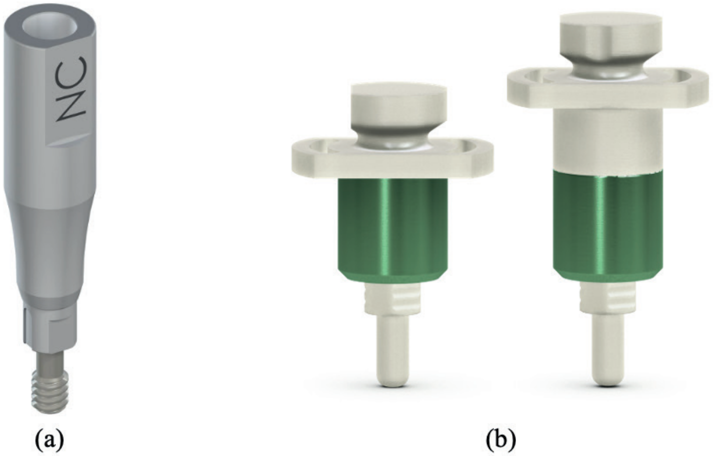

**Figure 5.** *Schematic illustrations of (a) a screw-retained (Straumann) and (b) a snap-on scan bodies (BioHorizons).*

Several implant scanning protocols have been proposed to capture the 3D implant position employing IOSs, including nonsplinted techniques, noncalibrated splinting approaches, calibrated implant SBs, calibrated frameworks, reverse SB methods and photogrammetry-based workflows (Revilla-León, Cascos, Barmak, Kois, & Gómez-Polo, 2026; Zhang et al., 2024).

In challenging clinical scenarios such as complete-arch and edentulous rehabilitations, splinting of SBs has been advocated to enhance scanning accuracy by minimizing relative movement between adjacent SBs during data acquisition. Various splinting materials and strategies—such as orthodontic wire, acrylic resin, bis-acryl composite resin, dental floss, implant-supported interim prostheses, and calibrated metal frameworks—have been described to improve IOS accuracy (Revilla-León, Barmak, Lanis, & Kois, 2025). Although splinting may slightly reduce 3D and linear deviations during digital scanning, these improvements do not consistently translate into clinically meaningful gains in overall scanning accuracy (Cheng et al., 2024).

To further improve full-arch implant scanning accuracy, calibrated intraoral scanning protocols have been introduced. In the calibrated intraoral scanning protocol (CISP), a prefabricated calibration jig is first digitized with a laboratory scanner to generate a distortion-free 3D reference model. During intraoral scanning, the jig is captured simultaneously with the implant SBs, and the acquired dataset is subsequently aligned and calibrated using the reference model to produce the final corrected digital cast (Li et al., 2024).

As an alternative workflow, the reverse SB technique has been proposed for full-arch implant rehabilitations. In this approach, SBs connected to interim implant-supported prostheses are digitized extraorally, thereby overcoming common intraoral challenges such as saliva contamination, scanner fogging, limited keratinized mucosa, and restricted access in severely resorbed arches. The resulting datasets are subsequently merged with intraoral scans of the opposing dentition and surrounding soft tissues, enabling reliable digital implant registration without fiducial markers (Papaspyridakos et al., 2023; Revilla-León, Lanis, et al., 2023). Beyond IOS-based modifications, alternative extraoral digital acquisition methods have also been introduced for full-arch implant rehabilitation. Photogrammetry (PG) technology represents a digital alternative for capturing the 3D implant position in full-arch cases (Revilla-León et al., 2025; Revilla-León, Kois, et al., 2023). By using coded scan bodies and calibrated imaging systems, PG determines implant positions through image triangulation based on stereophotogrammetric principles (Bi̇Lgi̇N Avşar & Ertan, 2025; Cheng et al., 2024). Compared with IOS workflows, PG has demonstrated high full-arch accuracy and reduced technique sensitivity (Papaspyridakos et al., 2023; Sicilia et al., 2024). However, its inability to capture soft tissue and dental structures necessitates an additional impression method, and factors such as higher cost and limited accessibility may restrict routine clinical use (Li et al., 2024; Revilla-León et al., 2025).

Overall, SB applications should be considered an integral component of digital implant workflows rather than isolated technical procedures. The interaction between SB geometry, material characteristics, fixation protocol, and selected scanning strategy ultimately determines scanning accuracy, underscoring the importance of case-specific adaptation to optimize digital implant outcomes (Cheng et al., 2024; Wan et al., 2024).

## 5. Clinical Considerations in Intraoral Scanning with Scan Bodies

The accuracy of 3D transfer of implant location is strongly influenced by SB-related parameters, including geometry, height, material composition, retention mechanism, and tightening torque. SB geometry plays a central role in digital impression accuracy, as well-defined facets, simplified macro-designs, and limited extensional features improve mesh alignment and congruence with the corresponding digital library file. Conversely, excessive geometric complexity and additive modifications may generate optical artefacts and angular inconsistencies, thereby compromising the accuracy of digital implant impressions (Mohajerani et al., 2025; Pan et al., 2025). Therefore, careful selection of SB design—favoring balanced, optically simple geometries with well-defined reference features—should be regarded as a fundamental clinical consideration to optimize the accuracy of digital implant impressions.

Scan body height and diameter further influence positional stability and visibility. Subgingival implant placement reduces the exposed SB height and may compromise digital impression accuracy, whereas excessively tall SB designs may increase leverage effects and cumulative deviation. Variations in SB diameter also affect scan congruence, with narrow PEEK SBs demonstrating favorable accuracy in selected configurations (Anitua et al., 2025; Karthhik et al., 2022; Marques et al., 2021; Pachiou et al., 2023). Accordingly, the selection of SB height and diameter should be carefully determined during the treatment planning phase, taking into account implant depth, angulation, and intraoral anatomical constraints to optimize digital implant impression accuracy.

Material choice impacts both optical behavior and mechanical stability. PEEK exhibits low reflectivity and favorable scanning characteristics but is more susceptible to deformation under tightening forces. Titanium alloys provide superior mechanical stability and wear resistance, although higher reflectivity may require surface modification. Hybrid designs aim to combine these advantages; however, interface discrepancies between polymer and metal components may influence positional consistency (Anitua et al., 2025; Baranowski et al., 2025; Qasim et al., 2024). Accordingly, material selection should be based on a careful evaluation of the respective advantages and limitations of each material type in relation to the specific clinical scenario.

Retention mechanism and fixation protocol are clinically decisive. Screw-retained SBs exhibit torque-dependent displacement, particularly in polymer-based designs (Pachiou et al., 2023; Wan et al., 2024). Lower torque values (≤10 Ncm) are recommended for one-piece PEEK SBs to minimize deformation, whereas metallic SBs may tolerate higher torque magnitudes without significant positional distortion (Pachiou et al., 2023). Clinically, complete seating must be verified—radiographically when necessary—and snap-on systems require tactile confirmation of proper engagement prior to scanning. Furthermore, adherence to manufacturer-recommended torque values is essential to ensure dimensional stability and consistent implant position transfer. Ultimately, accurate digital implant impression is not determined by a single SB parameter but by the integrated interaction between design, material properties, fixation protocol, and clinical handling.

## 6. Current Limitations and Potential Solutions

Despite advances in SB design and materials, several structural and workflow-related limitations continue to affect the accuracy of digital implant position transfer. Variability among commercially available SB geometries, manufacturing tolerances, and inconsistencies between scanned meshes and corresponding digital library files may compromise positional congruence (Mohajerani et al., 2025; Marques et al., 2021). Furthermore, repeated tightening and sterilization cycles may contribute to cumulative deviation over time, particularly at the implant–SB interface (Mizumoto & Yilmaz, 2018).

To address these limitations, standardization of SB–library congruence and stricter manufacturing tolerances are essential. High-precision milling or additive manufacturing protocols, routine verification of library accuracy, and controlled torque application using calibrated torque drivers may reduce interfacial discrepancies and material-related deformation. Additionally, limiting repeated reuse of polymer-based SBs and implementing material-specific torque protocols may help minimize cumulative positional deviation.

In full-arch implant rehabilitations, IOS workflows remain susceptible to cumulative alignment errors, especially in edentulous arches lacking sufficient geometric reference landmarks (Gimenez-Gonzalez et al., 2017; Thanasrisuebwong et al., 2021; Revilla-León et al., 2026). Although splinting and artificial landmark strategies may enhance the accuracy of digital impressions (Pozzi et al., 2022; Retana et al., 2023), their impact on overall accuracy appears inconsistent (Azevedo et al., 2023).

To overcome these limitations in full-arch implant rehabilitations, photogrammetry-based systems have emerged as a promising alternative. By capturing implant positions through coded markers, these systems significantly reduce cumulative alignment error and enhance full-arch accuracy (Papaspyridakos et al., 2022; Sicilia et al., 2024). However, their higher cost, limited accessibility, and technique sensitivity currently restrict widespread clinical implementation. Therefore, selective integration of photogrammetry in high-risk full-arch cases—especially in edentulous arches with multiple implants—may represent a rational and cost-effective clinical strategy.

Future optimization strategies should focus on improving SB–library standardization, enhancing manufacturing precision, refining material-specific torque protocols, and integrating photogrammetry selectively in complex clinical scenarios. Nevertheless, the predominance of in vitro evidence underscores the necessity for carefully planned clinical studies to validate these approaches under real intraoral conditions (Qasim et al., 2024).

## References

Anitua, E., Lazcano, A., Anitua, B., Eguia, A., & Alkhraisat, M. H. (2025). Influence of scan body geometry on the trueness of intraoral scanning. *BDJ Open*, *11*(1), 83. https://doi.org/10.1038/s41405-025-00374-0

Azevedo, L., Laureti, A., Marques, T., Pitta, J., Fehmer, V., Pozzi, A., & Sailer, I. (2025). Effect of Horizontal and Vertical Intraoral Scan Bodies on the Trueness of Complete-Arch Digital Implant Impressions: A Comparative In Vitro Study With Six Implants. *Clinical Oral Implants Research*, *36*(9), 1136–1145. https://doi.org/10.1111/clr.14463

Baranowski, J. H., Stenport, V. F., Braian, M., & Wennerberg, A. (2025). Effects of scan body material, length and top design on digital implant impression accuracy and usability: An *in vitro* study. *The Journal of Advanced Prosthodontics*, *17*(3), 125. https://doi.org/10.4047/jap.2025.17.3.125

Bilgin Avşar, D., & Ertan, A. A. (2025). Implant Scan Bodies in Digital Dentistry. *Necmettin Erbakan Universitesi Dis Hekimligi Dergisi (NEU Dent J), Necmettin Erbakan*, 2. https://doi.org/10.51122/neudentj.2025.160

Çakmak, G., Yilmaz, H., Treviño, A., Kökat, A. M., & Yilmaz, B. (2020). The effect of scanner type and scan body position on the accuracy of complete-arch digital implant scans. *Clinical Implant Dentistry and Related Research*, *22*(4), 533–541. https://doi.org/10.1111/cid.12919

Cheng, J., Zhang, H., Liu, H., Li, J., Wang, H., & Tao, X. (2024). Accuracy of edentulous full-arch implant impression: An in vitro comparison between conventional impression, intraoral scan with and without splinting, and photogrammetry. *Clinical Oral Implants Research*, *35*(5), 560–572. https://doi.org/10.1111/clr.14252

Etxaniz, O., Amezua, X., Jauregi, M., & Solaberrieta, E. (2025). Improving the accuracy of complete arch implant intraoral digital scans by using horizontal scan bodies with occlusal geometry: A dental technique. *The Journal of Prosthetic Dentistry*, *133*(1), 57–61. https://doi.org/10.1016/j.prosdent.2024.01.026

Gianfreda, F., Raffone, C., Martelli, M., Pitino, A., Caponio, V. C. A., & Bollero, P. (2025). Conventional scan body vs. scan bodies with auxiliary geometric devices: An in vitro study for edentulous full-arch implant impressions. *Frontiers in Oral Health*, *6*, 1574149. https://doi.org/10.3389/froh.2025.1574149

Gómez-Polo, M., Donmez, M. B., Çakmak, G., Yilmaz, B., & Revilla-León, M. (2023). Influence of implant scan body design (height, diameter, geometry, material, and retention system) on intraoral scanning accuracy: A systematic review. *Journal of Prosthodontics*, *32*(S2), 165–180. https://doi.org/10.1111/jopr.13774

Karthhik, R., Raj, B., & Karthikeyan, B. V. (2022). Role of scan body material and shape on the accuracy of complete arch implant digitalization. *Journal of Oral Research and Review*, *14*(2), 114–120. https://doi.org/10.4103/jorr.jorr_63_21

Li, J., Chen, Z., Nava, P., Yang, S., Calatrava, J., & Wang, H. (2024). Calibrated intraoral scan protocol ( CISP ) for full-arch implant impressions: An in vitro comparison to conventional impression, intraoral scan, and intraoral scan with scan-aid. *Clinical Implant Dentistry and Related Research*, *26*(5), 879–888. https://doi.org/10.1111/cid.13338

Marques, S., Ribeiro, P., Falcão, C., Lemos, B. F., Ríos-Carrasco, B., Ríos-Santos, J. V., & Herrero-Climent, M. (2021). Digital Impressions in Implant Dentistry: A Literature Review. *International Journal of Environmental Research and Public Health*, *18*(3), 1020. https://doi.org/10.3390/ijerph18031020

Michelinakis, G., Apostolakis, D., Nikolidakis, D., & Lapsanis, G. (2024). Influence of different scan body design features and intraoral scanners on the congruence between scan body meshes and library files: An in vitro study. *The Journal of Prosthetic Dentistry*, *132*(2), 454.e1-454.e11. https://doi.org/10.1016/j.prosdent.2024.05.016

Mizumoto, R. M., & Yilmaz, B. (2018). Intraoral scan bodies in implant dentistry: A systematic review. *The Journal of Prosthetic Dentistry*, *120*(3), 343–352. https://doi.org/10.1016/j.prosdent.2017.10.029

Mohajerani, R., Djalalinia, S., & Alikhasi, M. (2025). The Effects of Scan Body Geometry on the Precision and the Trueness of Implant Impressions Using Intraoral Scanners: A Systematic Review. *Dentistry Journal*, *13*(6), 252. https://doi.org/10.3390/dj13060252

Pachiou, A., Zervou, E., Tsirogiannis, P., Sykaras, N., Tortopidis, D., & Kourtis, S. (2023). Characteristics of intraoral scan bodies and their influence on impression accuracy: A systematic review. *Journal of Esthetic and Restorative Dentistry*, *35*(8), 1205–1217. https://doi.org/10.1111/jerd.13074

Pan, Y., Dai, X., Tsoi, J. K., Lam, W. Y., & Pow, E. H. (2025). Effect of shape and size of implant scan body on scanning accuracy: An in vitro study. *Journal of Dentistry*, *152*, 105498. https://doi.org/10.1016/j.jdent.2024.105498

Papaspyridakos, P., Bedrossian, A., Kudara, Y., Ntovas, P., Bokhary, A., & Chochlidakis, K. (2023). Reverse scan body: A complete digital workflow for prosthesis prototype fabrication. *Journal of Prosthodontics*, *32*(5), 452–457. https://doi.org/10.1111/jopr.13664

Park, G. S., Chang, J., Pyo, S.-W., & Kim, S. (2024). Effect of scan body designs and internal conical angles on the 3-dimensional accuracy of implant digital scans. *The Journal of Prosthetic Dentistry*, *132*(1), 190.e1-190.e7. https://doi.org/10.1016/j.prosdent.2024.04.008

Qasim, S. S. B., Akbar, A. A., Sadeqi, H. A., & Baig, M. R. (2024). Surface Characterization of Bone-Level and Tissue-Level PEEK and Titanium Dental Implant Scan Bodies After Repeated Autoclave Sterilization Cycles. *Dentistry Journal*, *12*(12), 392. https://doi.org/10.3390/dj12120392

Revilla-León, M., Barmak, A. B., Lanis, A., & Kois, J. C. (2025). Influence of connected and nonconnected calibrated frameworks on the accuracy of complete arch implant scans obtained by using four intraoral scanners, a desktop scanner, and a photogrammetry system. *The Journal of Prosthetic Dentistry*, *134*(3), 800–808. https://doi.org/10.1016/j.prosdent.2024.01.017

Revilla-León, M., Cascos, R., Barmak, A. B., Kois, J. C., & Gómez-Polo, M. (2026). Accuracy of a complete arch noncalibrated splinting implant scanning technique with a palatal orientation recorded by using different intraoral scanners. *The Journal of Prosthetic Dentistry*, *135*(1), 109–117. https://doi.org/10.1016/j.prosdent.2025.02.020

Revilla-León, M., Kois, D. E., & Kois, J. C. (2023). A guide for maximizing the accuracy of intraoral digital scans: Part 2—Patient factors. *Journal of Esthetic and Restorative Dentistry*, *35*(1), 241–249. https://doi.org/10.1111/jerd.12993

Revilla-León, M., Lanis, A., Yilmaz, B., Kois, J. C., & Gallucci, G. O. (2023). Intraoral digital implant scans: Parameters to improve accuracy. *Journal of Prosthodontics*, *32*(S2), 150–164. https://doi.org/10.1111/jopr.13749

Sicilia, E., Lagreca, G., Papaspyridakos, P., Finkelman, M., Cobo, J., Att, W., & Revilla-León, M. (2024). Effect of supramucosal height of a scan body and implant angulation on the accuracy of intraoral scanning: An in vitro study. *The Journal of Prosthetic Dentistry*, *131*(6), 1126–1134. https://doi.org/10.1016/j.prosdent.2023.01.018

Uzel, S. M., Guncu, M. B., Aktas, G., Arikan, H., Reiss, N., & Turkyilmaz, I. (2023). Influence of the implant scan body modifications on trueness of digital impressions. *Journal of Dental Sciences*, *18*(4), 1771–1777. https://doi.org/10.1016/j.jds.2023.04.004

Wan, Q., Limpuangthip, N., Hlaing, N. H. M. M., Hahn, S., Lee, J.-H., & Lee, S. J. (2024). Enhancing scanning accuracy of digital implant scans: A systematic review on application methods of scan bodies. *The Journal of Prosthetic Dentistry*, *132*(5), 898.e1-898.e9. https://doi.org/10.1016/j.prosdent.2024.06.010

Zhang, T., Yang, B., Ge, R., Zhang, C., Zhang, H., & Wang, Y. (2024). Effect of a Novel ‘Scan Body’ on the In Vitro Scanning Accuracy of Full-Arch Implant Impressions. *International Dental Journal*, *74*(4), 847–854. https://doi.org/10.1016/j.identj.2024.01.015

Chapter

3

# DIGITAL OCCLUSAL SPLINTS

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## Introduction

Temporomandibular disorders are clinical conditions affecting the temporomandibular joint, masticatory muscles, and associated structures, with a multifactorial etiology. The development of these disorders may involve a combination of occlusal factors, parafunctional habits, muscle hyperactivity, psychosocial stress, trauma, intra-articular structural alterations, and systemic conditions. Clinically, TMD may present with a wide spectrum of symptoms, including pain, joint sounds, limitation of mandibular movement, muscle tenderness, and functional discomfort. Due to this heterogeneous nature, the management of TMD requires a comprehensive evaluation and treatment planning approach based on the biopsychosocial model rather than reliance on a single therapeutic modality (Okeson, 2019).

According to current literature, the first-line management of temporomandibular disorders consists of reversible and conservative treatment approaches. Patient education and behavioral modification, reduction of parafunctional activities, physiotherapy interventions, exercise protocols, pharmacological management, stress control strategies, and, when indicated, minimally invasive procedures constitute the core components of this approach. Physical therapy modalities, manual therapy, and structured exercise programs are frequently preferred for the management of muscle-related pain, whereas pharmacological support or intra-articular interventions may be considered for inflammatory or intra-articular causes. The common objective of these treatment modalities is to reduce pain, restore function, and improve the patient's adaptive capacity (Mauro et al., 2024).

The effective management of temporomandibular disorders often relies on a combination of therapeutic approaches tailored to clinical findings, rather than a single treatment modality. In this context, occlusal splints should be viewed as just one aspect of TMD management and should be assessed alongside other conservative treatments. The impact of occlusal splints on the stomatognathic system, their biomechanical principles, and modern digital manufacturing techniques thus constitute a distinct area that deserves separate consideration within this wider clinical framework (Ferrillo, 2023).

## Occlusal Splints

Occlusal splints are non-invasive therapeutic appliances designed to temporarily regulate the relationship between the functional components of the stomatognathic system. Clinically, the effects of these appliances are evaluated based on how mandibular position is guided, how occlusal contacts are organized, and the biomechanical consequences of these arrangements on the masticatory muscles and the temporomandibular joint. In the literature, the fundamental mechanism of action of occlusal splints is described as guiding the mandible toward a more predictable and neuromuscularly balanced functional position and redistributing occlusal contacts in a controlled manner. Through these mechanisms, modulation of muscle activity, temporary elimination of occlusal interferences, and more balanced distribution of joint loading are achieved. In addition, occlusal splints function as mechanical barriers that protect dental hard tissues from parafunctional forces, thereby limiting wear and microtrauma, particularly in patients with bruxism. Taken together, these effects indicate that the clinical role of occlusal splints extends beyond mere symptom control and should be considered a comprehensive clinical tool that supports both the diagnostic process and the therapeutic management of temporomandibular disorders (Okeson, 2019) (Figure 1).

**Figure 1.** *Stabilization splint*

## Conventional Occlusal Splint Production Methods and Limitations

For many years, the basic approach in the clinical application of occlusal splints has been conventional methods involving taking impressions and manual production steps in the laboratory. In this method, splints are produced using acrylic-based materials on plaster models prepared from impressions obtained by conventional impression techniques. Due to its established presence in clinical practice and long history of use, conventional splint production is still widely used today. The conventional production process consists of multiple steps, including impression-taking, model casting, transfer to the articulator, and polymerization. This multi-step structure increases the interaction between clinical and laboratory processes and brings with it the potential for operator-related variability at each step. In particular, the manual shaping of occlusal contacts stands out as a critical step that directly affects the final occlusal accuracy of the splint (Okeson, 2019).

In conventional production using acrylic-based materials, the polymerisation process is a key factor affecting the splint's dimensional stability. Shrinkage during polymerisation can cause unwanted changes in the splint's tissue adaptation and occlusal contact distribution. This may necessitate additional occlusal adjustments in the clinic, extending the treatment duration and increasing operator dependence. Additionally, surface quality and material homogeneity can vary depending on the technique used and the laboratory's experience. Another significant limitation of conventional splint fabrication concerns standardization and reproducibility. If a splint for the same patient is lost or damaged, it is practically impossible to produce an identical copy of the existing appliance. Usually, new impressions are required, and the production process must be repeated from the start. This is disadvantageous for both patient comfort and clinical time management (Albagieh et al., 2025).

When evaluated in terms of occlusal accuracy and fit, splints obtained by conventional methods often provide clinically acceptable results; however, consistent standardization is difficult to achieve due to variables in the production process. The limitations of manual production steps become more apparent, especially when precise occlusal contact adjustments and mandibular guidance are required. This increases the time the clinician spends on occlusal adjustments and makes the treatment process more unpredictable. While all these limitations do not negate the clinical value of conventional splint production, they highlight the need for more controlled, predictable, and standardized production approaches. This need, coupled with technological advances in digital dentistry, has paved the way for the preparation of occlusal splints using computer-aided design and manufacturing methods (Kois et al., 2025).

## The Concept of Digital Occlusal Splints and the Digital Workflow

Technological advancements in digital dentistry have led to a significant shift in the design and manufacturing processes for occlusal splints. The traditional production chain, which relied on impression taking, model fabrication, and manual laboratory procedures, has progressively evolved into a data-driven workflow characterized by increased control and standardization within digital approaches. This transformation has not only improved production efficiency but also introduced new possibilities for occlusal accuracy, reproducibility, and clinical predictability (Mauro et al., 2024).

The concept of digital occlusal splints involves the acquisition of patient-specific three-dimensional anatomical and functional data, the analysis of this information within a software environment, and the subsequent conversion of the virtually designed splint into a physical appliance through computer-aided manufacturing technologies. Within this framework, the clinical success of digitally manufactured splints depends not solely on the final product itself, but on the accuracy of each stage of the digital workflow and the reliability of data transfer between these stages (Muresanu, Hedesiu, Dinu, Roman, & Almasan, 2022).

### Digital Programs Used in Occlusal Splint Design

Computer-aided design (CAD) software used in the design of digital occlusal splints enables the entire splint geometry to be created in a fully virtual environment, unlike conventional methods. These programs involve a multi-stage workflow that includes the processing of intraoral scan data, establishment of the maxillomandibular relationship, arrangement of occlusal contacts, and optimization of the design for manufacturing. The primary objective of digital design software is to facilitate the creation of splints that are clinically appropriate, reproducible, and characterized by a high level of fit accuracy.

With the integration of these software systems, splint design has evolved beyond a purely static modelling procedure into a dynamic planning process that incorporates functional occlusion and mandibular movement considerations. Designing within a digital environment allows the operator to evaluate occlusal relationships three-dimensionally and to perform necessary modifications prior to manufacturing, thereby improving the predictability of the final clinical outcome.

#### *3Shape Splint Studio*

3Shape Splint Studio is a module within the 3Shape Dental System software that focuses specifically on occlusal splint design. The program stands out for its guided design flow and high level of automation. The design process is structured to guide the user step by step, aiming to achieve standardized results. The design process in Splint Studio begins with selecting the splint type, determining the jaw where the splint will be placed, and automatically defining the splint boundaries. The program automatically generates the general form of the splint, accounting for anatomical reference points. This provides an advantage, especially for users new to digital splint design.

During occlusal contact adjustment, the program uses automated algorithms to achieve an even, balanced distribution of contacts. Thanks to the virtual articulator integration, mandibular movements can be simulated, and interferences that may occur in lateral and protrusive movements can be evaluated during the design phase. However, since the occlusal adjustments offered by the automatic system may not perfectly match every clinical scenario, manual control and correction by experienced users is important.

The most notable advantage of Splint Studio is its functional simulation capacity and guided workflow. On the other hand, the relatively limited scope for manual intervention can be considered a disadvantage in complex temporomandibular disorder cases requiring advanced occlusal customization (Shopova, Yordanova, & Yordanova, 2022). (Figure 2).

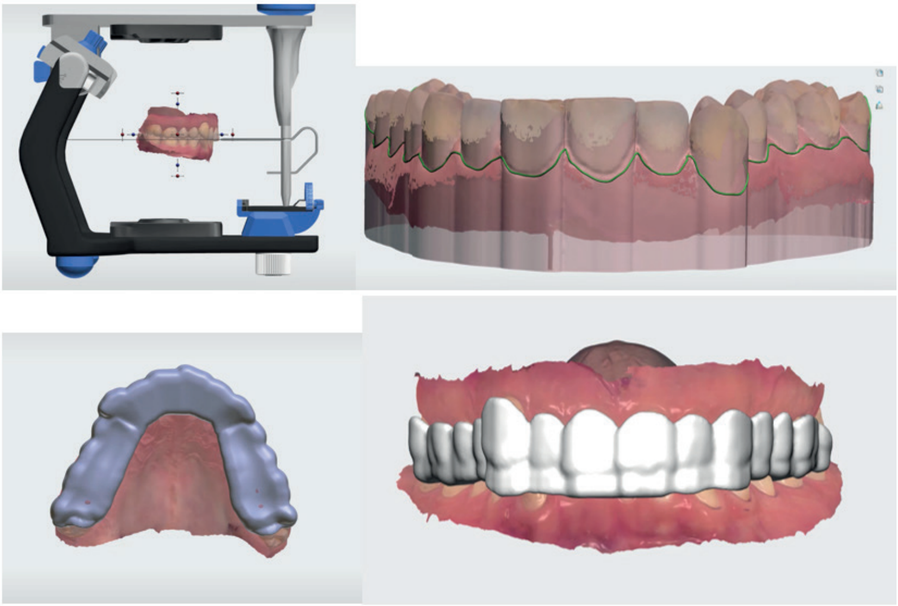

**Figure 2.** Digital occlusal splint design workflow in a CAD environment (3Shape Splint Studio)

## Exocad DentalCAD – Splint Module

The splint module in exocad DentalCAD software is distinguished by its open-system architecture and high design flexibility. The program allows the user to manually intervene at nearly every stage of the design workflow, enabling detailed modification of splint geometry to meet specific clinical requirements (Figure 3).

In the exocad environment, splint design begins with the selection of the splint type and the definition of splint margins. Splint margins may be generated automatically or refined manually by the operator. This capability provides a particular advantage in clinical situations where gingival sensitivity, soft-tissue considerations, or retention requirements necessitate individualised margin adjustments.

Design parameters such as splint thickness and internal surface adaptation can be adjusted in detail by the user. Occlusal contacts are visualized through color-coded mapping, allowing precise modification of contact points within the digital environment. Through integration with a virtual articulator, mandibular movements can be simulated, with the extent and accuracy of these simulations largely determined by operator input.

One of the primary advantages of exocad lies in its high level of customization, which allows greater clinical flexibility, particularly in cases involving complex occlusal relationships or temporomandibular disorders. However, the software's degree of freedom also increases reliance on operator experience, making design outcomes more dependent on the clinician's technical proficiency.

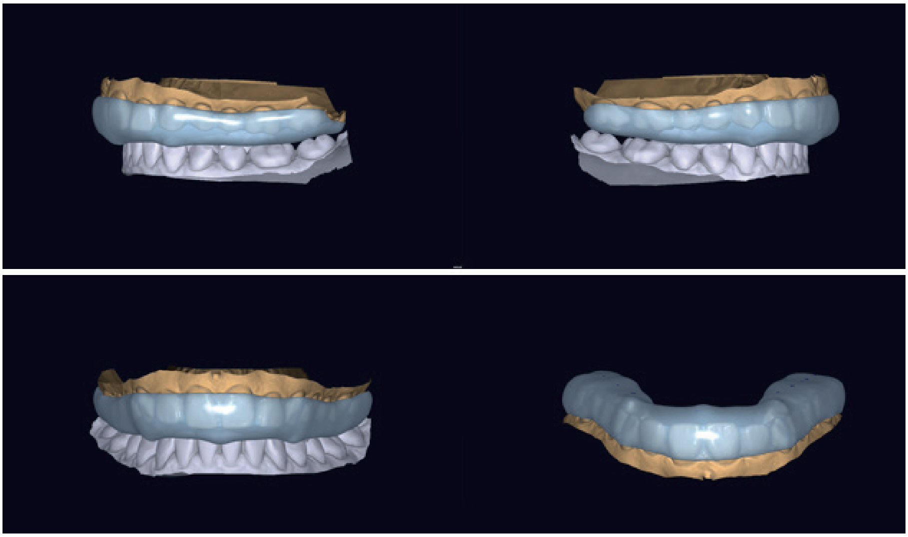

**Figure 3.** *Digital occlusal splint design workflow in a CAD environment (Exocad DentalCAD – Splint Module)*

## Dental Wings CAD Software

Dental Wings CAD software is a digital splint design platform characterized by its semi-automated workflow and user-friendly interface. The software facilitates the efficient and practical design of occlusal splints, particularly in cases requiring standard stabilization concepts. The design process is largely automated, allowing limited yet sufficient manual intervention by the user. Splint margins and overall geometry are generated automatically by the software, while occlusal contact adjustments are primarily performed within predefined design parameters. This structured workflow supports consistent design outcomes and reduces operator-dependent variability (Figure 4).

Dental Wings software confers benefits by reducing clinical and laboratory durations and delivering predictable outcomes in uncomplicated clinical situations. Nonetheless, its limited manual occlusal control and restricted capacity for advanced functional simulation may constrain its use in cases involving complex occlusal relationships or severe temporomandibular disorders.

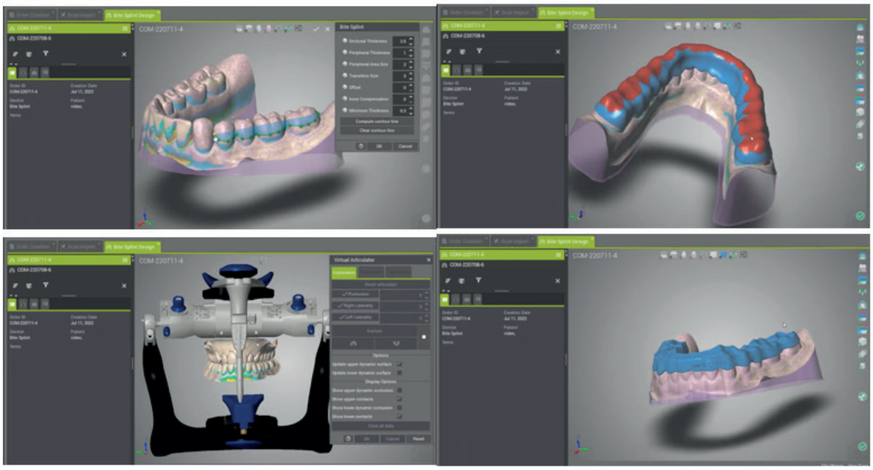
Bite Splint
Occlusal Thickness 1.5
Peripheral Thickness 1
Peripheral Area Size 2
Transition Size 3
Offset 0
Inner Compensation 0
Minimum Thickness 0.3

**Figure 4.** Digital occlusal splint design workflow in a CAD environment (Dental Wings DWOS)

## Digital Occlusal Splint Design Principles

The clinical success of digitally manufactured occlusal splints depends not only on the production technology itself but also directly on the accuracy of the biomechanical and occlusal parameters defined during the design phase. The digital design (CAD) process enables many decisions traditionally shaped by operator experience in conventional methods to be systematically and reproducibly controlled within a software environment. This highlights that digital splints represent a distinct approach not only in terms of fabrication, but also in treatment planning and clinical decision-making.

The primary objective of digital splint design is to produce an appliance that provides a balanced distribution of occlusal contacts while either maintaining or deliberately guiding mandibular position, thereby supporting functional harmony within the muscle–joint–tooth system. Achieving this objective requires that each design parameter be carefully adjusted in accordance with the intended clinical goals (Muresanu et al., 2022).

### *Splint Thickness and Vertical Dimension Control*

Splint thickness is one of the most critical parameters determined during the digital design process. Thickness determines not only the mechanical durability of the appliance but also the extent to which the vertical dimension will be altered. The ability to adjust splint thickness homogeneously or regionally in the digital environment allows the clinician to plan vertical dimension increase in a controlled manner.

Insufficient thickness increases the risk of splint fracture, while excessive thickness can lead to excessive vertical dimension increase and musculoskeletal adaptation problems. Therefore, in digital design, the thickness parameter should be determined based on both the material's mechanical properties and the patient's functional tolerance (Ferreira, Simamoto-Júnior, Soares, Ramos, & Fernandes-Neto, 2017; Sun et al., 2025).

### Distribution and Symmetry of Occlusal Contacts

The distribution of occlusal contacts in digitally designed splints intended for stabilization purposes represents one of the key factors influencing treatment effectiveness. CAD software enables the number, location, and symmetry of occlusal contacts to be evaluated and adjusted in a virtual environment, allowing bilateral, simultaneous planning of posterior contacts.

The digital adjustment of occlusal contacts aims to establish symmetrical load distribution, thereby regulating muscle activity. Whereas such adjustments in conventional workflows largely depend on chairside modifications, digital design allows the occlusal contact pattern to be defined and evaluated prior to manufacturing. This capability represents one of the principal factors enhancing the repeatability and standardization of digitally designed occlusal splints (Crout, 2016).

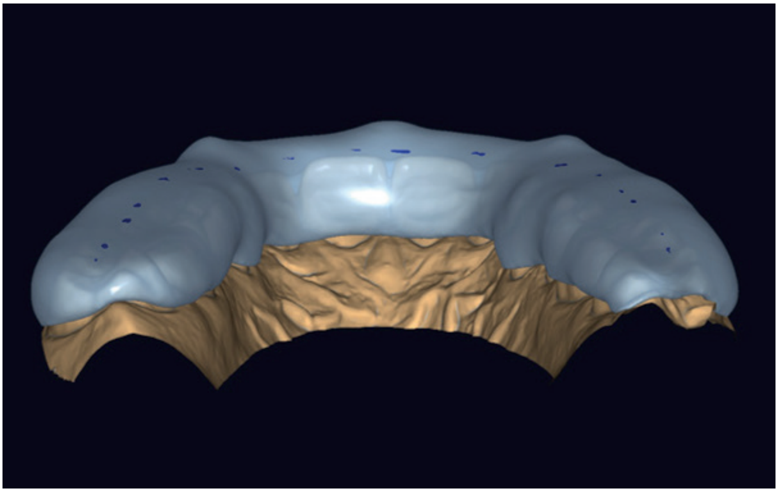

**Figure 5.** *Visualization of occlusal contacts during digital splint design performed in the Exocad DentalCAD environment.*

### Anterior Guidance and Disocclusion Patterns

In digital splint design, anterior guidance should be planned to allow for the disocclusion of posterior teeth during mandibular movements. The elimination of posterior contacts during protrusive and lateral movements is important for protecting dental tissues and limiting excessive loads on the muscle–joint system (Okeson, 2019).

Within the CAD environment, the anterior guidance angle and contact points can be controlled through virtual articulation tools. This enables the disocclusion pattern to be designed in accordance with clinical objectives. This aspect of digital design provides a distinct advantage over conventional methods, particularly in splints intended for stabilization purposes (Albagieh et al., 2025; Muresanu et al., 2022) (Figure 6).

**Figure 6.** *Clinical image demonstrating posterior disocclusion achieved through canine guidance in a stabilization splint.*

## Splint Margins Design

Splint margins and margin design are important design parameters for patient comfort and appliance stability. In the classical occlusal splint literature, it is emphasized that splint margins should be planned in a manner that avoids trauma to the gingival tissues, minimizes plaque retention, and preserves the passive fit of the appliance. In digital design workflows, splint margins can be defined with high precision in accordance with these biological and functional principles, ensuring harmony with tooth surfaces while avoiding excessive pressure on the gingival tissues (Sun et al., 2025).

Adapting splint margins to tooth surfaces is critical for long-term wear tolerance and overall patient comfort. The digital CAD environment enables margins to be evaluated individually for each tooth and optimized according to patient-specific morphology, thereby reducing fit discrepancies and soft-tissue irritation commonly encountered in conventional fabrication methods (Crout, 2016).

## Design Modifications Based on Clinical Scenarios

Digital splint design should be approached as a process that can be modified according to the clinical scenario, rather than based on a single template. While the design priority in muscle-related temporomandibular disorders is occlusal contact symmetry and stabilization, material thickness and wear resistance come to the fore in cases where parafunctional habits are predominant.

In this context, digital design offers a platform where clinical goals can be directly reflected in design parameters. This flexibility in the design process is considered one of the most important advantages of digital splints, enabling individualized treatment approaches (Blasi, Henarejos-Domingo, Palacios-Bañuelos, Aparicio, & Roig, 2023).

### Virtual Articulation and Occlusal Simulation

One of the most distinctive components of digital occlusal splint design is the concept of virtual articulation. Virtual articulation refers to the modeling of patient-specific static and dynamic occlusal data within a software environment and the simulation of mandibular movements in a virtual setting. This approach extends beyond evaluations performed within the mechanical limitations of conventional articulators, allowing for a more comprehensive and predictable analysis of occlusal relationships (Kordaß et al., 2022).

In digital systems, virtual articulation is primarily based on static records, with the maximum intercuspal position (MIP) or a recorded occlusal relationship serving as the principal reference. Within this context, virtual articulation should be regarded as a simulation tool that supports and guides the design process rather than an exact replication of the patient's actual mandibular movements. Recognizing this distinction is essential for a proper understanding of the clinical limitations associated with digital splint design.

The clinical value of virtual articulation becomes particularly evident in splints intended for stabilization purposes. As these appliances do not aim to forcibly reposition the mandible, the static occlusal relationships established within the virtual environment are generally consistent with treatment objectives. Digital articulation enables the symmetry, simultaneity, and distribution of occlusal contacts to be evaluated prior to manufacturing, thereby improving the clinical predictability of the design process (Alqutaibi, Algabri, Ibrahim, & Borzangy, 2021) (Figure 7).

In contrast, in splints where mandibular position is intentionally directed anteriorly, the role of virtual articulation becomes more limited. In such cases, the primary determinant is the accuracy of the mandibular record obtained clinically and the extent to which this record is transferred into the digital workflow without distortion or loss of positional accuracy. Accordingly, virtual articulation should be considered a supportive tool for maintaining the recorded position rather than a method capable of replacing clinical registration.

**Figure 7.** Use of a virtual articulator in CAD/CAM systems: occlusal splint design performed with dynamic simulation of mandibular movements between the maxillary and mandibular models.

## Digital Planning of Static and Dynamic Occlusal Contacts

In digital splint design, occlusal contacts should be evaluated within two fundamental contexts: static and dynamic. Static contacts refer to the contact relationships established at the splint's maximum closure position, whereas dynamic contacts encompass the contact patterns occurring during mandibular movements. Digital CAD software enables the independent evaluation and planning of contacts at these two levels, allowing a more structured and clinically guided design process.

Static contact planning plays a central role in the effectiveness of digitally designed stabilization splints. The primary objective is to achieve balanced load distribution within the musculoskeletal system by establishing bilateral and simultaneous posterior contacts. In the digital environment, the number, location, and intensity of contact points can be controlled through visual and numerical analysis tools, allowing adjustments traditionally performed during the clinical phase in conventional workflows to be incorporated into the design stage.

Dynamic contact planning involves assessing anterior guidance and disocclusion patterns. The elimination of posterior contacts during protrusive and lateral mandibular movements is considered a desirable design characteristic in stabilization splints. Within the digital workflow, these functional patterns can be simulated virtually, enabling potential posterior interferences to be identified and addressed prior to manufacturing (Nota, Ryakhovsky, Bosco, & Tecco, 2021).

The clinical role of static and dynamic contacts in anterior repositioning splints should be interpreted within a different framework. In these splints, the primary function of occlusal contacts is to maintain mandibular stability in the intended therapeutic position. Consequently, contact symmetry and contact area are not primary objectives to the same extent as in stabilization splints (Okeson, 2019). This difference explains the biomechanical basis for the presence of more limited or asymmetrical occlusal contacts in anterior repositioning splints. The ability to analyze static and dynamic contacts independently within a digital environment allows splint design to be directed consciously according to specific clinical objectives. This capability represents one of the fundamental elements that transform digital design from a purely manufacturing process into a clinical decision-support approach (Figure 8)

Tamamlanan tasarım belgeleri taşlama veya 3D baskı yöntemleriyle işlenebilir.

Tamamlanan tasarım belgeleri taşlama veya 3D baskı yöntemleriyle işlenebilir.

**Figure 8.** *Image showing the digital analysis of occlusal contacts during virtual articulation within the Exocad DentalCAD software. The location and intensity of occlusal contacts are evaluated prior to manufacturing to guide the splint design.*

## Mandibular Position Records and Their Relationship with Digital Design

In digital occlusal splint design, mandibular position records are a defining element of the process, especially in clinical scenarios where the goal is to preserve or consciously guide the mandible's current position. While the digital workflow enables the acquisition of highly accurate geometric data, the clinical reference used to define mandibular position and the degree to which it is accurately transferred to the digital environment directly affect the clinical effectiveness of the splint.

The primary purpose of mandibular position records is to define the functional or therapeutic target position of the mandible relative to the maxilla. These records are mostly evaluated by taking the existing occlusal relationship as a reference in splints for stabilization purposes, while in splints where the mandibular position is directed anteriorly, they serve to maintain the clinically achieved target position. Therefore, the clinical role of mandibular records takes on a different level of importance depending on the purpose of the splint.

In conventional approaches, mandibular position records are defined by physical records obtained in the clinical setting, whereas in the digital workflow, transferring these records to the virtual environment creates an additional requirement for accuracy. Digital systems should be considered as tools that represent a position defined in the clinic and integrate it into the design process, rather than directly “creating” the mandibular position. This distinction is critical for correctly understanding the limitations of digital design (Solaberrieta, Otegi, Goicoechea, Brizuela, & Pradies, 2015).

In splints where the mandibular position is directed anteriorly, the success of digital design largely depends on the accuracy of the mandibular record obtained in the clinic and the lossless transfer of this record to the digital environment. In such splints, virtual articulation and digital simulation tools can help maintain the targeted mandibular position and adjust occlusal contacts accordingly; however, they should not be considered an independent method that replaces the clinical record. Digital systems play a supportive and validating role here (Thu Tra, Viet Anh, & Minh Duc, 2026).

In stabilization splints, the influence of mandibular records on the design is more limited, and the digital workflow mostly focuses on symmetrically and evenly rearranging the existing occlusal relationship. In this context, while mandibular records are important as the initial reference for the design process, treatment effectiveness is primarily shaped by the distribution and stabilization of occlusal contacts (Araújo de Souza, da Veiga Kalil Associate, & Theresa Alves da Cunha Kalil, 2021).

This relationship between mandibular position records and digital design demonstrates that the clinical success of digital splints depends not only on software capabilities but also directly on the quality of clinical data. Digital design should not be considered a mechanism that replaces the clinical decision-making process; rather, it should be viewed as a tool that enables the more controlled and predictable implementation of goals determined in the clinic. This approach highlights that, particularly in anterior repositioning splints, the role of digital systems is limited to facilitating the controlled application of the clinically established mandibular position, without replacing the clinical decision-making process itself.

## Digital Occlusal Splint Production Technologies

Digital occlusal splint production technologies should be considered as a set of processes that convert design data defined in a digital environment into a physical appliance. These processes are not only technical approaches that increase production speed or standardization, but also fundamental factors that determine the mechanical behavior, surface properties, and performance of splints during clinical use. Digital production involves reinterpreting the geometry envisioned in the digital environment within the constraints of the material and production method, rather than simply copying the design.

The effects of digital manufacturing approaches on splints are shaped by the interaction between the manufacturing technique used, material properties, and post-production processes. The same digital geometry can exhibit different mechanical properties and clinical behaviors when produced using different manufacturing methods. This situation demonstrates that the clinical success of digital occlusal splints depends not only on design accuracy but also on a comprehensive evaluation of the manufacturing process (Nassif, Haddad, Lara, & Amine, 2023).

## Fundamental Principles of Digital Production Approaches

The approaches used in digital occlusal splint production are fundamentally based on two different principles, depending on how the geometry is transferred to the physical product. These principles determine not only the production technique but also the microstructure, surface character, and mechanical behavior of the resulting splint. In this respect, digital production processes should be considered a transformation process in which the designed form is reshaped within the framework of specific production constraints and material properties, rather than a passive copying of the form.

The choice of production principle determines the extent to which the geometry created in the digital environment can be preserved, where inevitable changes will occur, and how these changes should be interpreted clinically. Therefore, digital production approaches should be considered not only as technical alternatives but also as strategic choices that directly affect clinical outcomes.

## Subtractive Manufacturing Approach

Subtractive manufacturing is one of the most commonly used methods in digital occlusal splint production and is based on the principle of controlled material removal from prefabricated blocks. The geometry of the resulting splint is directly related to the physical properties of the milling tool and the machine's motion capabilities.

Production accuracy in milling systems is determined by a combination of factors such as the number of machine axes, milling cutter diameter and geometry, machining strategy, and access limitations. Particularly in areas with complex morphology, such as occlusal surfaces and anterior guidance areas, the use of milling cutters with specific diameters and forms can limit the direct transfer of the designed sharpness and surface details. This situation causes some geometric features predicted in the digital design to appear in a more rounded or simplified form during the production stage (Kaygusuz, Mazlouminia, & Dumanli Gök, 2025).

A significant advantage of subtractive manufacturing is that the block materials used are polymerized under industrial conditions and have a homogeneous, low-porosity microstructure. This feature provides clinically predictable results in terms of splint mechanical strength and long-term dimensional stability. However, high material loss, access limitations in complex geometries, and relatively long production times are among the inherent limitations of this approach (Araújo de Souza et al., 2021).

### Additive Manufacturing Approach

Additive manufacturing is increasingly preferred for the production of digital occlusal splints, owing to its layered construction from digitally defined geometry. In this method, production accuracy is determined by the printing technology, layer thickness, printing direction, and the quality of the post-processing stages.

Layered production offers significant flexibility compared to subtractive approaches, particularly in the production of complex internal geometries and fine details. The ability to largely preserve surfaces designed in a digital environment is considered one of the most prominent advantages of additive manufacturing. However, this advantage is directly related to the quality of interlayer bonding and the adequacy of post-production polymerization processes (Perea-Lowery, Gibreel, Garoushi, Vallittu, & Lassila, 2023).

In additive manufacturing, the mechanical behavior of the splint can exhibit anisotropic properties, depending on layer orientation and bonding integrity. This can lead to different strength and wear patterns in different areas of the splint. Furthermore, post-production surface roughness plays a decisive role in occlusal contact accuracy and clinical adaptation. Therefore, despite offering design freedom, additive manufacturing requires careful evaluation of clinical performance (Reich, Berndt, Kühne, & Herstell, 2022).

### Digital Splint Materials and Microstructural Properties

The clinical performance of digital occlusal splints depends not only on their design and production technology but also on the microstructural properties of the material used. Materials used in digital production exhibit an internal structure and surface character specific to the production method, unlike acrylics processed by conventional methods. These microstructural differences are among the key factors determining the splint's mechanical strength, wear behavior, and long-term dimensional stability.

Prefabricated blocks used in subtractive manufacturing are polymerized under industrial conditions and have a high-density, homogeneous microstructure. Porosity is minimal in such materials, and the bonding between polymer chains exhibits a more consistent structure. This contributes to the predictability of the mechanical strength and surface stability of milled splints. Furthermore, the complete polymerization of block materials during the production process is considered a factor that reduces the risk of dimensional change during clinical use (Blasi et al., 2023; Marcel, Reinhard, & Andreas, 2020).

In resins used in additive manufacturing, the microstructure varies due to the nature of the layered manufacturing process. The quality of interlayer bonding, the printing direction, and the adequacy of post-curing processes directly affect the mechanical integrity of the material. The presence of layer boundaries can lead to stress concentration and anisotropic mechanical behavior in some areas. These characteristics explain why additively manufactured splints exhibit different wear or deformation patterns under certain clinical conditions (Wada et al., 2023).

Surface character in digital splint materials also plays an important role in clinical performance. While surfaces obtained after subtractive milling exhibit a relatively smoother, more homogeneous structure, surface roughness in additive manufacturing varies with printing parameters and post-processing stages. Surface roughness is a factor that affects not only patient comfort but also occlusal contact accuracy and long-term wear behavior (Wada et al., 2023).

Considering these microstructural differences, digital splint materials should not be evaluated as a homogeneous group; they should be selected in line with clinical expectations, taking into account the production method.

## Effect of Production Parameters on Mechanical and Clinical Performance

The mechanical properties and clinical performance of digital occlusal splints depend not only on the material used but also on the technical parameters applied during production. In digital production technologies, the production parameters used during the conversion of the design into a physical product play a decisive role in the splint's durability, surface properties, occlusal fit, and long-term clinical stability. Therefore, the effects of production parameters must be evaluated from both mechanical and clinical perspectives.

### *Effect of Production Parameters on Mechanical Properties*

The mechanical performance of digital occlusal splints is evaluated using fundamental parameters, including elastic modulus, fracture resistance, wear resistance, and deformation behavior. Subtractive and additive manufacturing technologies have different effects on these mechanical properties. Pre-polymerized block materials used in subtractive manufacturing exhibit more predictable mechanical behavior due to their homogeneous structure. In contrast, the layered structure in additive manufacturing methods can cause direction-dependent variations in the mechanical properties of the splint. In particular, the printing direction and layer thickness significantly affect the elastic modulus and fracture resistance. Post-processing steps applied during production are a critical factor in determining the final mechanical properties. Inadequate or inappropriate post-curing applications can result in a low degree of polymerization in the splint material and consequently mechanical weaknesses. This increases the risk of cracking or breaking during clinical use (Grymak, Waddell, Aarts, Ma, & Choi, 2022).

### *Effect of Production Parameters on Surface Properties*

The surface properties of digital occlusal splints are considered an important parameter for both mechanical performance and clinical use. Surface roughness directly affects the plate retention, patient comfort, and soft-tissue compatibility of the splint.

In subtractive manufacturing technologies, the diameter and movement precision of the cutting tools used during milling determine surface quality. Splints produced by milling generally exhibit lower surface roughness values and require minimal clinical polishing. In additive manufacturing, layer thickness and print orientation are the primary factors determining surface roughness. Layer lines can cause micro-irregularities, particularly on occlusal surfaces, which may increase mechanical wear. Therefore, post-production surface finishing and polishing processes are critical to the clinical performance of splints produced by additive manufacturing (Orgev, Levon, Chu, Morton, & Lin, 2023).

### *Effect of Production Parameters on Occlusal Fit and Clinical Adjustment*

The ideal occlusal contact pattern obtained in the digital design process can be transferred to the clinical environment, depending on the accuracy of the production parameters. Minimal dimensional deviations occurring during the production process may require the occlusal contacts to be rearranged in the clinic.

In subtractive manufacturing, the difference between digital design and clinical fit is relatively minimal due to high dimensional accuracy. Conversely, in additive manufacturing, factors such as polymerization shrinkage and tolerances resulting from the layered structure can influence occlusal fit. Such discrepancies may necessitate extended clinical adjustments, particularly in stabilization splints that require precise occlusal contact. Poor occlusal fit adversely impacts splint stability, complicates patient adaptation, and diminishes overall treatment success. Consequently, the selection of appropriate production parameters is essential to minimize the need for clinical adjustments (Blasi et al., 2023).Metin girmek için buraya tıklayın veya dokunun.

### *The Importance of Production Parameters in Terms of Clinical Performance*

The effect of production parameters on clinical performance is evaluated in terms of splint usage time, patient comfort, and treatment effectiveness. Mechanically inadequate splints or those with unoptimized surface properties may cause early deformation, breakage, or patient discomfort during clinical use (Lawson, Brown, Hamdan, Alford, & Nejat, 2025).

Standardizing parameters in digital production technologies increases the predictability of splint clinical outcomes. When evaluated clinically, proper management of production parameters directly affects the long-term stability of the splint, occlusal control, and patient satisfaction. In this context, digital occlusal splint production should be considered not only as a technological process but also as a controlled treatment phase that supports clinical goals.

## Production Method Selection Criteria for Clinical Applications

In digital occlusal splint treatment, the production method should be selected based on clinical requirements. Subtractive production methods are preferred when high mechanical stability and long-term use are targeted, while additive methods may be preferred for rapid production and ease of adaptation during production. Conscious management of production parameters in clinical applications is critical for translating the advantages of digital design into clinical success.

## Materials Used in Digital Occlusal Splints

The clinical effectiveness and long-term success of digital occlusal splints depend not only on design and production technologies but also directly on the physical, mechanical, and surface properties of the material used. Materials used in digital production processes are standardized under industrial conditions, unlike acrylic materials prepared using conventional methods, and offer more predictable and reproducible properties.

Today, materials used in digital occlusal splint production are generally classified into two main groups based on production methods: block materials suitable for subtractive manufacturing and resin-based materials suitable for additive manufacturing.

### *Materials Used in Subtractive Manufacturing*

Materials used in subtractive manufacturing methods are supplied in the form of pre-polymerized blocks and are shaped into splints through computer-aided milling. This approach ensures that the material's internal structure is homogeneous and that its mechanical properties remain more stable regardless of the production method.

### *CAD/CAM Blocks Based on PMMA (Polymethyl Methacrylate)*

Polymethyl methacrylate (PMMA) is the most commonly used material in digital occlusal splint production. CAD/CAM PMMA blocks have high molecular weight and low residual monomer content thanks to industrial polymerization processes. These properties increase the material's mechanical strength and biocompatibility (Araújo de Souza et al., 2021).

The main advantages of PMMA-based CAD/CAM blocks in occlusal splint applications are high mechanical strength, dimensional stability, low water absorption, and good polishability. Thanks to these properties, PMMA splints resist deformation during long-term use and reduce the risk of occlusal contacts changing over time. Furthermore, the ease with which surface quality can be optimized is an important factor that enhances patient comfort. For these reasons, PMMA-based milled splints are considered the preferred base material, especially for stabilization splints, bruxism cases, and clinical scenarios where long-term use is planned (Nassif et al., 2023).

### *High-Performance Polymer Blocks*

In addition to PMMA-based CAD/CAM blocks, certain material groups are defined as high-performance polymer blocks for the production of digital occlusal splints. These materials have been developed to offer increased mechanical strength, wear resistance, or modified elastic properties compared to PMMA. However, the clinical applications and level of evidence for materials in this group are more limited compared to specific polymers such as PEEK.

High-performance polymer blocks include PEKK (polyetherketoneketone), fiber-reinforced polymer blocks, and mechanically modified PMMA derivatives. These materials can offer theoretical advantages, particularly in clinical scenarios where intense occlusal forces are expected or wear resistance is paramount (Wang et al., 2020).

Keton-based polymers such as PEKK have a chemical structure similar to PEEK but can exhibit variable mechanical behavior due to their different crystallization properties. Fibre-reinforced polymer blocks aim to provide increased rigidity and fracture resistance thanks to their structures containing glass or carbon fibres. Modified PMMA blocks are characterized by a higher degree of cross-linking and improved wear resistance compared to classic PMMA (Yalçın, Altıntaş, & Tekin, 2024). However, the use of these high-performance polymer blocks in digital occlusal splint applications is still limited, and long-term clinical data is insufficient. Therefore, these materials are evaluated in selected cases and situations with specific clinical requirements rather than being routinely preferred. In this context, high-performance polymer blocks are considered a material group positioned between PMMA and PEEK in digital occlusal splint treatment, requiring further research and clinical evidence.

### Materials Used in Additive Manufacturing

Additive manufacturing methods encompass production approaches that convert design data into a physical structure layer by layer for digital occlusal splint production. The materials used in these production methods are mostly photopolymer resin-based systems with formulations developed specifically for digital production processes. Additive manufacturing materials play an important role in digital splint applications due to the design freedom and production flexibility they provide.

The properties of splint materials used in additive manufacturing are shaped not only by their chemical composition but also by production parameters, layer structure, and post-production processes. Therefore, these materials should be evaluated in conjunction with the production process.

#### *Photopolymer Resin-Based Materials*

Occlusal splint materials used in additive manufacturing are based on light-curing photopolymer resin systems. These resins are formulated to be compatible with the wavelength and energy intensity of light sources used in digital manufacturing processes, aiming to provide a balanced performance between mechanical strength, wear resistance, and surface quality for occlusal splint production. Photopolymer materials produced by additive manufacturing can exhibit a microstructurally oriented structure due to the layered production principle; this can cause the material's mechanical behavior to vary with the direction of production. In other words, the bonding properties within and between layers may differ, which can affect the material's physical and mechanical properties and be influenced by production parameters (Venezia, Muzio, Furia, & Torsello, 2019).

In this context, the printing direction, layer thickness, and polymerization strategy play a decisive role in the mechanical behavior and surface properties of occlusal splints obtained through additive manufacturing. This relationship between production parameters and material properties necessitates that the production process be considered an integral part of the material when evaluating additive manufacturing materials (van Lingen & Tribst, 2025).

### Clinical Implications and Future Perspectives

Digital occlusal splints demonstrate that digitalization in dentistry is not merely a production convenience but also an approach that reshapes treatment planning. When current information on digital design, production technologies, material options, and surface optimization is evaluated together, it becomes clear that the success of digital splints in clinical practice depends not on a single factor but on the balanced management of numerous variables.

## The Role of Digital Splints in the Clinical Decision-Making Process

One of the most important contributions of digital occlusal splints in clinical practice is that they make the treatment process more predictable and repeatable. Thanks to the digital workflow, splint design, occlusal contact adjustment, and production stages can be planned more effectively. However, this does not mean that digital splints offer absolute superiority in every clinical scenario.

The decision to use digital splints in the clinical decision-making process should be evaluated based on the patient's profile, expected duration of use, presence of parafunctional habits, and treatment goals. While the digital approach offers advantages, particularly in cases involving stabilization splints and long-term use, conventional methods remain a clinically adequate and practical alternative in some situations. Therefore, digital splints should be considered not as the "one true solution" but as part of the clinical toolkit.

## Compatibility of Material and Production Method with the Clinical Scenario

The data discussed throughout this section demonstrate that the material and production method of digital occlusal splints play a decisive role in clinical outcomes. PMMA-based CAD/CAM blocks currently constitute the most reliable and widely used material group in the literature, while PEEK and other high-performance polymers are positioned as alternatives that offer potential advantages in specific clinical scenarios, albeit to a more limited extent (Yalçın et al., 2024).

Similarly, the choice between subtractive and additive manufacturing methods is directly related to clinical objectives. Splints obtained using the milling method generally offer higher dimensional stability and homogeneous surface properties, while additive manufacturing methods stand out for their design flexibility, offering, in addition to rapid production, the ability to apply complex geometries and regional design modifications without milling constraints. Clinical success depends not on the absolute superiority of one method over another, but on selecting the appropriate production approach for the correct clinical scenario (Benli, Al-Haj Husain, & Ozcan, 2023).

### *Limitations of the Digital Workflow and Clinical Responsibility*

Although the precision and automation offered by digital technologies support the clinical decision-making process, clinical responsibility cannot be delegated to software algorithms. Virtual articulation, occlusal simulation, and automatic contact adjustment tools should be viewed as auxiliary systems that guide clinical evaluation.

Especially in splint applications where the mandibular position is consciously altered, simulations provided by digital systems should not be interpreted as an exact representation of real biomechanics. The accuracy of clinical records, patient follow-up, and occlusal adjustments made when necessary remains an indispensable component of the digital workflow. In this context, digital splint applications should be positioned as an approach that supports clinical experience rather than replacing it.

## Future Perspectives

The future of digital occlusal splints is shaping up around goals of higher levels of personalization and biomechanical accuracy. Artificial intelligence-supported occlusal analysis systems, the integration of dynamic mandibular movement records into digital design, and new-generation polymer materials form the fundamental directions of development in this field.

In the coming period, digital splint design is expected to be built on patient-specific biomechanical models fed by more functional data rather than static records. However, the integration of new materials and production technologies into clinical practice must continue to be supported by long-term clinical data. In this process, the production of scientific evidence will enable the clinical limitations of digital splints to be more clearly defined.

## General Evaluation

In summary, digital occlusal splints constitute a significant and evolving domain within the field of contemporary dentistry. They hold substantial promise for enhancing the control and predictability of design, manufacturing, and clinical application processes. Nonetheless, the successful translation of digital technologies into clinical practice is contingent upon a careful and balanced assessment of their capabilities alongside the biological and functional realities inherent to each patient. When employed with appropriate indication, suitable materials, and a judicious clinical approach, digital splint applications can make meaningful and valuable contributions to the advancement of current treatment modalities.

## REFERENCES

Albagieh, H., AlWazzan, A. K., Alhelal, F. A., Alem, M. F., Albaiz, A. M., Aloraini, T. K., & Alselmi, M. K. (2025). Effectiveness of Occlusal Splints in the Management of Temporomandibular Disorders: Comparisons of Treatment Approaches and Digital Versus Conventional Fabrication Techniques. *Cureus*. doi:10.7759/cureus.77451

Alqutaibi, A. Y., Algabri, R., Ibrahim, W. I., & Borzangy, S. (2021). Does the facebow affect the outcome of CAD/CAM occlusal splint. Randomized clinical trial. *Saudi Dental Journal*, *33*(7), 628–634. doi:10.1016/j.sdentj.2020.07.002

Araújo de Souza, J., da Veiga Kalil Associate, M., & Theresa Alves da Cunha Kalil, M. (2021). *OCCLUSAL SPLINTS: TYPES, MATERIALS AND PROPERTIES-A LITERATURE REVIEW*. Retrieved from http://www.periodicos.uff.br/index

Benli, M., Al-Haj Husain, N., & Ozcan, M. (2023, December 1). Mechanical and chemical characterization of contemporary occlusal splint materials fabricated with different methods: a systematic review. *Clinical Oral Investigations*. Springer Science and Business Media Deutschland GmbH. doi:10.1007/s00784-023-05360-0

Blasi, Á., Henarejos-Domingo, V., Palacios-Bañuelos, R., Aparicio, C., & Roig, M. (2023). Comparison accuracy of digital and analog method using milled occlusal splints. *Journal of Esthetic and Restorative Dentistry*, *35*(7), 1103–1112. doi:10.1111/jerd.13039

Crout, D. K. (2016). *Anatomy of an occlusal splint*. *Exercise* (Vol. 401). Retrieved from www.agd.org/generaldentistry

Ferreira, F. M., Simamoto-Júnior, P. C., Soares, C. J., Ramos, A. M. de A. M., & Fernandes-Neto, A. J. (2017). Effect of occlusal splints on the stress distribution on the temporomandibular joint disc. *Brazilian Dental Journal*, *28*(3), 324–329. doi:10.1590/0103-6440201601459

Ferrillo, M. (2023, February 1). Temporomandibular Disorders: Current and Future Concepts in Diagnosis and Management. *Medicina (Lithuania)*. MDPI. doi:10.3390/medicina59020223

Grymak, A., Waddell, J. N., Aarts, J. M., Ma, S., & Choi, J. J. E. (2022). Evaluation of wear behaviour of various occlusal splint materials and manufacturing processes. *Journal of the Mechanical Behavior of Biomedical Materials*, *126*, 105053. doi:https://doi.org/10.1016/j.jmbbm.2021.105053

Kaygusuz, N. A., Mazlouminia, E., & Dumanli Gök, G. (2025). Okluzal Splintler ve Gelenekselden Dijitale Üretim Teknikleri. *Biruni Health and Education Sciences Journal (BHESJ)*, *8*(1), 13–33.

Kois, J. C., Zeitler, J. M., Barmak, A. B., Yilmaz, B., Gómez-Polo, M., & Revilla-León, M. (2025). *Discrepancies in the occlusal devices designed by an experienced dental laboratory technician and by 2 artificial intelligence-based automatic programs.*

Kordaß, B., Gärtner, C., Sö, A., Bisler, A., Voß, G., Bockholt, U., & Seipel, S. (2022). *The virtual articulator in dentistry: concept and development.*

Lawson, N. C., Brown, P., Hamdan, S., Alford, A., & Nejat, A. H. (2025). *Wear resistance of 3D printed occlusal device materials.*

Marcel, R., Reinhard, H., & Andreas, K. (2020). Accuracy of CAD/CAM-fabricated bite splints: milling vs 3D printing. doi:10.1007/s00784-020-03329-x/Published

Mauro, G., Verdecchia, A., Suárez-Fernández, C., Nocini, R., Mauro, E., & Zerman, N. (2024, June 1). Temporomandibular Disorders Management—What's New? A Scoping Review. *Dentistry Journal*. Multidisciplinary Digital Publishing Institute (MDPI). doi:10.3390/dj12060157

Muresanu, S. A., Hedesiu, M., Dinu, C., Roman, R., & Almasan, O. (2022). Digital occlusal splints for temporomandibular joint disorders: a systematic review. *Romanian Journal of Stomatology*, *68*(3), 97–105. doi:10.37897/RJS.2022.3.1

Nassif, M., Haddad, C., Lara, H., & Amine, Z. (2023). Materials and manufacturing techniques for occlusal splints: A literature review. *Journal of Oral Rehabilitation*, *50*. doi:10.1111/joor.13550

Nota, A., Ryakhovsky, A. N., Bosco, F., & Tecco, S. (2021). A full digitalworkflow to design and mill a splint for a patient with temporomandibular joint disorder. *Applied Sciences (Switzerland)*, *11*(1), 1–10. doi:10.3390/app11010372

Okeson, J. P. (2019). *Management of Temporomandibular Disorders and Occlusion - Jeffrey P. Okeson - 8th Edition (2019) 512 pp., ISBN: 9780323582100.*

Orgev, A., Levon, J. A., Chu, T. M. G., Morton, D., & Lin, W. S. (2023). The effects of manufacturing technologies on the surface accuracy of CAD-CAM occlusal splints. *Journal of Prosthodontics*, *32*(8), 697–705. doi:10.1111/jopr.13610

Perea-Lowery, L., Gibreel, M., Garoushi, S., Vallittu, P., & Lassila, L. (2023). Evaluation of flexible three-dimensionally printed occlusal splint materials: An in vitro study. *Dental Materials*, *39*(10), 957–963. doi:10.1016/j.dental.2023.08.178

Reich, S., Berndt, S., Kühne, C., & Herstell, H. (2022). Accuracy of 3D-Printed Occlusal Devices of Different Volumes Using a Digital Light Processing Printer. *Applied Sciences (Switzerland)*, *12*(3). doi:10.3390/app12031576

Shopova, D., Yordanova, M., & Yordanova, S. (2022). 3Shape Digital Design Software in Splints Creation-A Pilot Study. *European Journal of Dentistry*, *16*(4), 815–819. doi:10.1055/s-0041-1739546

Solaberrieta, E., Otegi, J. R., Goicoechea, N., Brizuela, A., & Pradies, G. (2015). *Comparison of a conventional and virtual occlusal record.*

Sun, Z., Sun, R., Zhang, M., Zhong, Q., Huang, M., Yan, X., … Li, J. (2025). How do palatal extensions and brands affect the retention of custom-made mouthguards? An in vitro study. *BMC Oral Health*, *25*(1). doi:10.1186/s12903-025-05786-w

Thu Tra, N., Viet Anh, N., & Minh Duc, N. (2026). *A completely digital workflow for an anterior repositioning device.*

van Lingen, C., & Tribst, J. P. M. (2025, May 1). 3D-Printed Occlusal Splints: A Narrative Literature Review. *Journal of Advanced Oral Research*. Sage Publications India Pvt. Ltd. doi:10.1177/23202068251317825

Venezia, P., Muzio, L. L. O., Furia, C. D. E., & Torsello, F. (2019). Digital manufacturing of occlusal splint: From intraoral scanning to 3D printing. *Journal of Osseointegration*, *11*(3). doi:10.23805/JO.2019.11.03.10

Wada, J., Wada, K., Garoushi, S., Shinya, A., Wakabayashi, N., Iwamoto, T., … Lassila, L. (2023). Effect of 3D printing system and post-curing atmosphere on micro- and nano-wear of additive-manufactured occlusal splint materials. *Journal of the Mechanical Behavior of Biomedical Materials*, *142*. doi:10.1016/j.jmbbm.2023.105799

Wang, S., Li, Z., Ye, H., Zhao, W., Liu, Y., & Zhou, Y. (2020). Preliminary clinical evaluation of traditional and a new digital PEEK occlusal splints for the management of sleep bruxism. *Journal of Oral Rehabilitation*, *47*(12), 1530–1537. doi:10.1111/joor.13083

Yalçın, E., Altıntaş, E., & Tekin, S. (2024). The use of polyetheretherketone material as an occlusal splint. *Journal of Dental Sciences and Education*, *2*(2), 43–46. doi:10.51271/jdse-0032

Chapter

4

# DIGITAL BITE REGISTRATION SYSTEMS IN OCCLUSAL ASSESSMENT

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## INTRODUCTION

Dental occlusion is defined in the Glossary of Prosthodontic Terms as the static relationship between the incising or masticating surfaces of the maxillary and mandibular teeth or tooth analogues ("The Glossary of Prosthodontic Terms: Ninth Edition," 2017). Various studies have demonstrated a correlation between the number of occlusal contacts, the total contact area, and masticatory efficiency; these findings have indicated that the accurate and precise localization of occlusal contacts in clinical applications is determinant for functional rehabilitation (Dinçer et al., 2025). Occlusion plays a critical role in the function of the masticatory system, influencing chewing efficiency through occlusal units and contact areas (Jeong et al., 2020; Seth-Johansen & Gotfredsen, 2025).

The masticatory system includes components such as periodontal tissues, the neuromuscular system, muscles, the temporomandibular joint, and craniofacial bones in addition to teeth; its efficiency is proportional to the harmonious operation of these components, resulting from the balanced distribution of occlusal forces (Bostancıoğlu et al., 2022; Qadeer et al., 2018). Precise and detailed analysis of occlusal contacts is necessary for accurate detection of existing interferences during occlusal adjustments; failure to correct such interferences may adversely affect periodontal tissues, masticatory muscles, and the temporomandibular joint, leading to functional disorders (Dinçer et al., 2025). Furthermore, an unbalanced occlusion, far from an ideal force distribution, can lead to complications not only in biological tissues but also in prosthetic restorations; cracks may form in implants and implant-supported prostheses due to overload (Reich et al., 2025). From this perspective, occlusion plays a significant role in diagnosis and prosthetic treatment planning and is also predictive of treatment prognosis (Dinçer et al., 2025; Seth-Johansen & Gotfredsen, 2025).

To date, numerous methods have been employed for occlusion analysis. Occlusal analysis considers parameters such as occlusal contact area (OCA), occlusal contact number (OCN), and occlusal force (Zhao et al., 2023). The localisation of occlusal contact areas also plays an important role in clinical assessment (Rovira-Lastra et al.,). Conventional occlusal registration materials generally used in clinical practice for occlusal analysis include articulating papers, shim-stock foils, elastomeric impression materials, and occlusal wax plates. These materials, used as indicators of static occlusion, are unable to objectively determine the sequence of occlusal contacts during patient movements or measure the quantitative level of the applied force. Furthermore, factors such as thickness, mechanical strength, physical properties, and elastic structure can cause errors due to deformation within the oral environment; this significantly limits the accuracy and reliability of these methods (Qadeer, 2016).

With advances in dental technology, digital methods have been integrated with traditional materials, enabling more precise evaluation of occlusal contacts under static and dynamic conditions in dental applications (Manziuc et al., 2024). Computer-aided occlusal analysis systems, such as T-Scan, OccluSense, and Accura, and intraoral scanners are used for digital occlusal recording (Revilla-León et al., 2023). The aim of this section is to evaluate the performance of digital methods for interocclusal registration, which plays an important role in prosthetic treatment.

## 1. METHODS USED IN OCCLUSAL EVALUATION

### 1.1. CONVENTIONAL OCCLUSAL REGISTRATION METHODS

Materials such as articulating papers, waxes, silicone-based impression materials, silk ribbons, metal plates, occlusal sprays, transillumination, and occlusal sonography have long been used to obtain occlusal records via conventional methods. Traditional recording methods, which are based on determining occlusal contacts and relationships through recording materials placed between dental arches, frequently utilize the patient's feedback regarding the sensation of occlusal contact. However, factors such as patient cooperation and the subjective interpretations of the evaluating clinician can significantly affect the accuracy and reproducibility of these methods (Bostancıoğlu et al., 2022; Seth-Johansen & Gotfredsen, 2025).

#### 1.1.1. Articulating Papers

Articulating paper is an occlusal registration material that has been used for many years, distinguished by its cost-effectiveness and ease of use. Articulating papers are used as a result of their dye content which provides color transfer. It is a method that stains the contact areas between opposing teeth with this dye to detect occlusal contacts (Reich et al., 2025; Rovira-Lastra et al., 2024). Despite their widespread use, articulating papers have various limitations. The permanence and effectiveness of the dye depend on various factors. Upon contact with saliva, the dye dissolves and disperses, preventing clear evaluation of occlusal contacts. Additionally, staining efficiency is low on polished ceramic or metal surfaces in prosthetic restorations with low surface roughness (Esposito et al., 2024; Reich et al., 2025).

The durability and elasticity of articulating papers are affected by the mechanical properties of the material used, such as paper, silk, and polyester, and its thickness, which can vary between 8–200 µm. Silk's superior tear resistance and elasticity, compared to paper's limited elasticity, reduce the risk of inaccurate staining and tearing during occlusal contact assessment. However, both methods rely on subjective evaluation and clinical expertise. Mark intensity should not be interpreted as a quantitative measure of occlusal force (Bozhkova et al., 2021; Reich et al., 2025). While color differences in articulating papers, which can be of various colors and thicknesses, aim to clarify the difference between static and dynamic contacts, the difference in material thickness is effective in distinguishing the surface area of occlusal contact marks. Thus, the clinician can select articulating paper suitable for the prosthetic restoration, whether prepared with tooth, implant, or soft-tissue support, and for the requirements of the preferred occlusal concept (Malta Barbosa et al., 2018).

### 1.1.2. Wax-Based Registration Materials

In this method, where occlusal records are taken by placing wax plates between opposing teeth, it shows the maxillomandibular relationship in static occlusion; these records are utilized in transferring the interocclusal record to the laboratory and mounting models onto the articulator. Tears, perforations, or the size of translucent areas on the wax indicate potential contact areas but do not provide reliable information about the magnitude of force or contact sequencing. Quantitative force values cannot be derived from these marks; they are subjective data subject to the clinician's interpretation. It has been reported that perforations in the wax do not occur at regions of actual contact but rather result from patient-dependent variations in closing force (Qadeer et al., 2021; Reich et al., 2025).

Rapid application, ease of use, and low cost of thermoplastic waxes have been reported as significant advantages; furthermore, their intraoral verifiability and reshaping have been recognised as clinically beneficial features. In clinical practice, the wax material, which exhibits a soft property and flexible character in the patient's mouth when heated, becomes harder after cooling. It may be the case that the wax used for occlusal registration does not exhibit a homogeneous structure throughout its mass. Consequently, the material, which may harbor internal differences in terms of thickness and hardness, may also show variability in heating and cooling rates. Even after the occlusal record is taken, wax is not resistant to external forces; it may deform under pressure, and distortion may be observed. Wax is a material with limited reliability for recording the maxillomandibular relationship and transferring it to the laboratory, due to its structural properties, which can alter the record (Qadeer et al., 2021; Reich et al., 2025). Although the use of wax for occlusal registration is common in clinical practice, few studies have investigated the accuracy of wax. The literature has also noted that clinical recording and data transfer using wax materials are limited by the material's lack of precision and the difficulties encountered during application (Sharma et al., 2013).

### 1.1.3. Silicone-Based Impression Materials

The features that highlight silicone-based impression materials in occlusal registration are their high flowability and the advantage of having almost no thickness in the contact area (Ando et al., 2007). Consequently, when these materials are injected between opposing teeth to localise occlusal contacts, they are displaced in areas of tooth contact, allowing for evaluation (Qadeer, 2016). As with occlusal wax, perforations and areas adjacent to perforations observed in PVS materials represent only potential contact regions and do not provide information about the magnitude or timing of force. Scientific literature supporting the effectiveness of polyvinyl siloxane in occlusal evaluation, which involves physical parameters such as dimensional stability, tear strength, flowability, and elastic deformation, is quite limited. This situation creates serious uncertainties regarding the force-sensing ability of the materials in question, the level of accuracy that depends on their physical properties, and issues related to the clinician's skill in clinical applications (Qadeer et al., 2021).

### 1.1.4. Clinical Accuracy and Reproducibility in Conventional Occlusal Registration Methods

In conventional occlusal registration methods, there are differences in the physical properties of the materials used, such as thickness, durability, and elasticity, and these materials are affected by saliva. Consequently, the accuracy and reliability of the obtained record are affected by these factors. Traditional methods of determining occlusal contacts have been criticized in the literature from various aspects. These criticisms include subjectivity in the evaluation process, low reproducibility of contact points, the negative effect of saliva on marking accuracy, and the effect of tooth surface characteristics on results. Furthermore, in clinical practice, it has been assumed that traditional indicators provide quantitative information on the magnitude of occlusal forces, with wider contact marks indicating higher forces. However, existing scientific data have not confirmed a significant relationship between marking width and applied occlusal forces (Beninati & Katona, 2019; Carey et al., 2007; Popa & Ahlers, 2024; Saraçoğlu, 2002). The occlusal surface morphology and the physical thickness of the paper or ribbon material used for marking are more effective in determining the size and shape of contact marks than the applied occlusal force (Sutter, 2018).

## 1.2. DIGITAL OCCLUSAL ANALYSIS METHODS

### 1.2.1. The Concept of Digital Occlusal Analysis

Digital workflow has recently come to the forefront in dentistry, paving the way for the widespread adoption of advances in digital technologies across disciplines and areas of dentistry (Spagnuolo & Sorrentino, 2020). One of these developments emerges through innovations in dental analysis systems. These systems have secured a place in the digital workflow through software that enables the examination of parameters such as surface area, distance measurement, and error analysis (Zhao et al., 2023). Using digital occlusal analysis has accelerated the interocclusal registration process in clinical practice and enabled more precise quantification of occlusal contacts (Reich et al., 2025).

Digital occlusal analysis methods used in this context include intraoral scanners (Revilla-León et al., 2023), the T-Scan system (Tekscan Inc., South Boston, MA, USA) used in the evaluation of occlusal contacts (Bozhkova et al., 2021), and OccluSense (Bausch, Cologne, Germany), a hybrid system that enables the recording of contacts via an electronic sensor foil and simultaneous staining (Popa & Ahlers, 2024).

### 1.2.2. Working Principles of Digital Occlusal Registration Methods

Digital occlusal analysis methods rely on software-based processing of data obtained from two- or three-dimensional models, thereby enabling detailed evaluation of the number of occlusal contacts, contact surfaces, and the magnitude of applied occlusal forces (Popa et al., 2024). Digital occlusal indicators differ in their structural configurations, functional capabilities, and fundamental operating principles (Seth-Johansen & Gotfredsen, 2025). T-Scan and Dental Prescale are examples of early applications in computer-aided occlusal registration systems. These systems aim to quantitatively express the relative distribution of occlusal forces and contact areas. Systems such as Dental Prescale II (DP2, GC Corp.) enable the evaluation of bite force throughout the entire dentition with numerical data, and from these data, the patient's masticatory function can be analyzed. However, the inability of these systems to determine the temporal sequencing of occlusal contacts constitutes a significant limitation for clinical applications (Huang, 2022; Shiga et al., 2020).

In contrast, the T-Scan system offers a dynamic occlusal analysis. This sensor-based technology displays the timing of contacts formed during the process from the first contact of opposing teeth to maximum intercuspation and the occlusal force with real-time data (Huang et al., 2021). In subsequent years, newer systems, such as Accura and OccluSense, were introduced for dental use. Similar to T-Scan, these systems use sensor-based technologies and aim to acquire additional information on occlusal contacts by integrating articulating paper into the digital recording mechanism. It has been reported that the Accura (Dmetec Co., Ltd.) system was developed to be cost-effective and user-friendly (Lee et al., 2022). The integration of computer-aided design/computer-aided manufacturing (CAD/CAM) systems and intraoral scanners (IOS) into occlusal analysis workflows allows clinicians to digitally evaluate and optimize occlusion during the design phase of restorations (Chinam et al., 2023; Solaberrieta et al., 2016). Intraoral scanners provide digital impressions and occlusal bite registration by aligning virtual models created after scanning the maxillary and mandibular arches. In this way, it is possible to transfer the maxillomandibular relationship to the virtual environment (Renne et al., 2017; van der Meer et al., 2012).

### 1.2.3. Digital Bite Registration Systems

#### 1) Computer-Aided Occlusal Analysis Systems

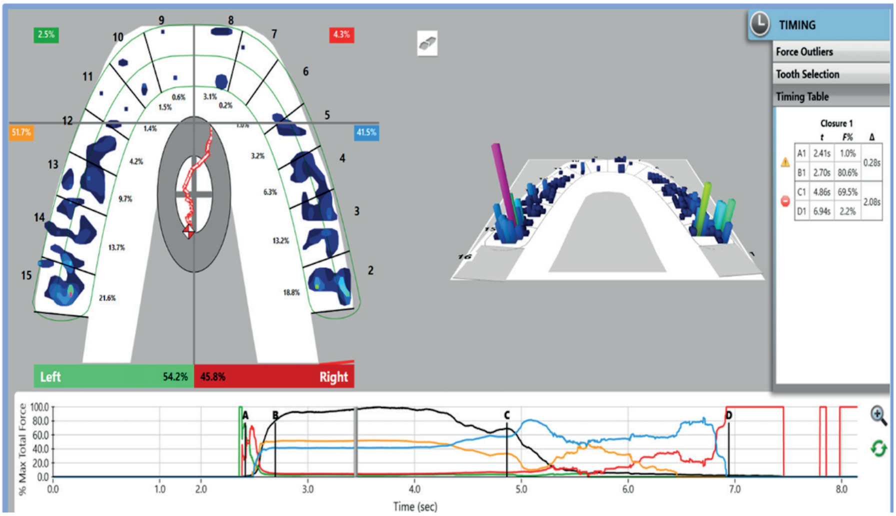
In the literature, various computer-based occlusal analysis systems are defined that can analyze the pressure distribution on occlusal surfaces depending on time and reveal the formation sequence of occlusal contacts.

#### a) T-Scan

The T-Scan system, developed in 1984 by Prof. Dr. William L. Maness and engineers from the Massachusetts Institute of Technology (MIT), has developed new versions by acquiring different features over time. Following the initial T-Scan 1, the Windows-based T-Scan II in 1995, T-Scan III with turbo recording features in 2004, and the most current version, T-Scan v10, in 2018 were presented for use for digital occlusal registration (Jeong et al., 2020; Kerstein et al., 2006).

*Figure 1: T-Scan system components (Sutter, 2019)*

The T-Scan system consists of an arch-shaped pressure-measurement sensor placed between opposing teeth forming the occlusion and a recording unit that houses the sensor. This recording unit can be integrated into a laptop or a Windows-based computer via a USB connection. Thus, occlusal forces detected by the pressure sensor are rendered and evaluated as 2D and 3D graphics in real time (Afrashtehfar & Qadeer, 2016; Koos et al., 2010) (Figure 1).



Closure 1

|  |  | t | F% | Δ |
|---|---|---|---|---|
| ⚠ | A1 | 2.41s | 1.0% | 0.28s |
|  | B1 | 2.70s | 80.6% |  |
| ⛔ | C1 | 4.86s | 69.5% | 2.08s |
|  | D1 | 6.94s | 2.2% |  |

*Figure 2: T-Scan occlusal analysis with left and right sides and time correlation (Sutter, 2019)*

The working principle of the pressure-sensitive sensor is essentially based on electrical changes. The sensor is in a structure consisting of conductive lines, and there are areas named 'sensels' sensitive to pressure on these lines. In the presence of bite force on the sensor, a drop in electrical resistance occurs in the sensels. As the applied occlusal force increases, the change in resistance across the sensels increases, whereas changes are more limited at low forces. These resistance changes caused by different occlusal contacts are recorded by the system at real-time intervals, and as a result of processing these changes by the software, they are visualized by becoming digital data (Cerna, 2015; Afrashtehfar & Qadeer, 2016; Kerstein, 2016).

Creating a balanced occlusion is critical for the balanced distribution of occlusal forces in treatment plans in which natural teeth and implant-supported prostheses coexist, as in every treatment. Since implants do not possess a periodontal ligament (PDL), unlike natural teeth, while natural teeth can intrude approximately 25-100 microns apically under load, this value is limited to 3-5 microns in osseointegrated implants (Misch, 2008). This causes most of the occlusal force to be transmitted to the implants via the PDL during maximal occlusion, as natural teeth intrude. This excessive load transmitted to the implants can lead to bone loss in the neck region of the implant and screw loosening. To prevent this adverse situation, with 'timed occlusal adjustment' performed under T-Scan guidance, implants contact the opposing arch milliseconds after natural teeth during tight closure, preventing occlusal overloading of the implant (Kerstein, R. B, 2015).

Optimizing the disclusion time in Temporomandibular Disorder (TMD) treatment is of great importance in preventing excessive loading on masticatory muscles. Findings by Kerstein and Radke (2006) indicate that, by determining the contact duration of posterior teeth that continue to contact during eccentric movements under T-Scan guidance, posterior interferences are ground down. It shows that this 'Disclusion Time Reduction' (DTR) protocol provides distinct success in the remission of clinical symptoms by minimizing bioelectric activity (EMG) in masseter and anterior temporal muscles (Kerstein & Radke, 2006).

The most efficient use of the T-Scan system in the clinic involves certain combinations. Primarily, T-Scan is used by placing the sensor in the patient's mouth to detect contact timing and determine occlusal forces during closure, followed by marking the contacts with thin articulating paper. Combining these two datasets enables more accurate occlusal adjustment by locating problematic contact areas, identified under T-Scan guidance and schematized on a computer, within the mouth using articulating paper markings (Qadeer et al., 2021).

In more detailed terms, occlusal analysis and equilibration with T-Scan include the following steps:

**Data Acquisition:** In the first stage of the protocol, the patient bites on the ultra-thin (100 µm) pressure-sensitive sensor in the Maximum Intercuspation (MIP) position. Additionally, for evaluating dynamic occlusion, right/left lateral and protrusive eccentric movements are recorded, along with their timings, until the MIP position is reached (Chowdhary & Sonnahalli, 2024).

**Center of Force (COF) Analysis:** T-Scan technology standardizes the vector sum of occlusal loads distributed along the dental arch with the 'Center of Force' (COF) parameter. In a biomechanically ideal occlusion, this dynamic projection is expected to coincide with the first molars in the sagittal plane and with the midline of the dental arch in the coronal plane (Beninati & Katona, 2019; Mitchem et al., 2017; Kerstein, 2015).

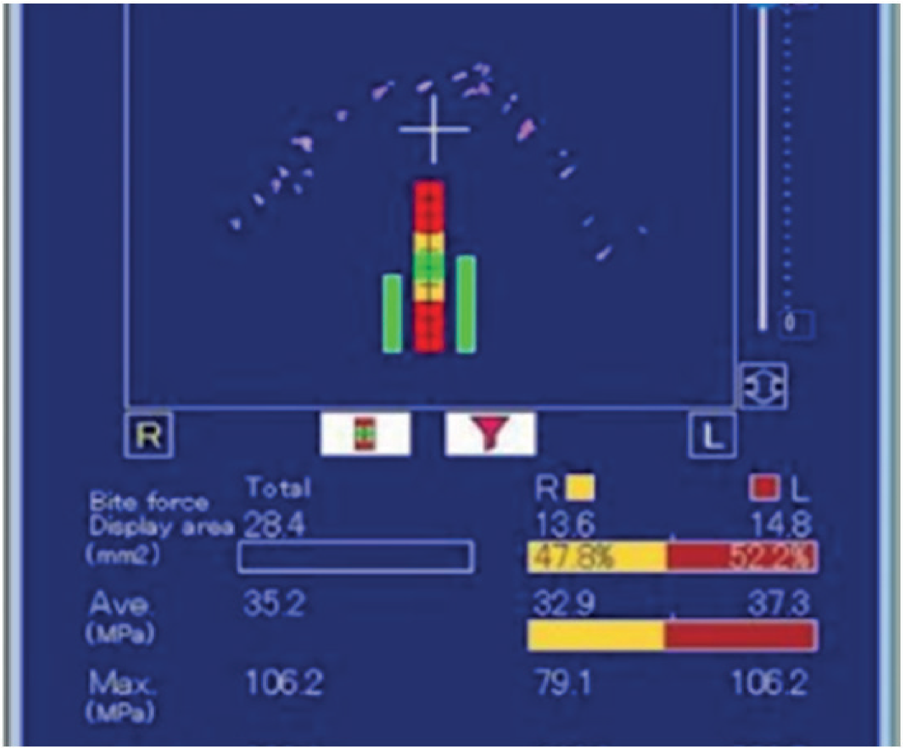
**Force Distribution:** T-Scan analysis evaluates the force distribution between the right and left arches via percentage values, expressing occlusal asymmetries with quantitative data. Deviations from the force-balanced condition in the right and left arches, commonly used as an indicator of ideal occlusion, indicate excessive load areas within the system's 3D window. This visualization ensures the objective localization of premature contacts that clinically require correction (Afrashtehfar & Qadeer, 2016; Liu et al., 2015) (Figure 2).

**Occlusal Timing Analysis:** It evaluates the closure phase of the dental arch by dividing it into phases with microsecond precision. This process is tracked via A (first contact), B (MIP start), C (maximum force), and D (start of excursive movement) reference points. With this analysis, a balanced force distribution across the arch ensures that all teeth enter occlusion simultaneously, thereby making it possible to minimize the risk of occlusal trauma (Abutayyem et al., 2023; Koos et al., 2010).

**Guided Adjustment Technique:** The correlation of T-Scan data with static markings obtained from articulating paper forms the basis of the 'Guided Adjustment' protocol. In this process, intervention is limited to points detected as high force (red/pink columns) on the digital screen that overlap with articulating paper intraorally. This approach prevents accidental grinding of areas stained by the paper but carrying low occlusal force (false positives), thereby preserving healthy tooth tissue (Abutayyem et al., 2023; Qadeer et al., 2021).

**b) Dental PreScale and PreScale II**

The Dental Prescale System (Fujifilm Co., Tokyo, Japan) is a method for simultaneously measuring occlusal contact area, average occlusal pressure, and total bite force, providing objective data (Adachi, 2020). Prescale is a system that works on the principle of transferring the data received by a horseshoe-shaped pressure-sensitive film layer as a result of bite force inside the mouth to a colored image receiver analyzer called 'Occluzer' to make it examinable.



| | Total | R | L |
|---|---|---|---|
| Bite force Display area (mm2) | 28.4 | 13.6<br>47.8% | 14.8<br>52.2% |
| Ave. (MPa) | 35.2 | 32.9 | 37.3 |
| Max. (MPa) | 106.2 | 79.1 | 106.2 |

*Figure 3: Dental PreScale II system quantative force analysis (Huang, 2022)*

This film has a matrix consisting of microcapsules placed between polyethylene terephthalate (PET) based layers. As a result of the reaction between microcapsules of different sizes and the bite force, red-stained contact areas suitable for these emerge on the film. The color intensity in these areas is directly attributable to occlusal pressure.

In the Dental Prescale II system, these data examined with the occluzer in the Prescale system are evaluated using advanced analysis software and converted into force values in Newtons (Adachi, 2020; Suzuki et al., 1997) (Figure 3).

In the literature, studies investigating the reliability and reproducibility of the PreScale system report that it is an objective, nonrelative method that generates quantitative data. Hattori et al. conducted in vitro and in vivo evaluations of the system and reported that it is an objective method that produces quantitative data. Furthermore, this study reports a linear relationship between occlusal force and the system's measurements (Hattori et al., 1994). In a study addressing the effect of intraoral humidity and temperature changes on measurement accuracy of the pressure-sensitive film layers used in the Prescale system, it was reported that these factors did not have a result that would affect the accuracy of the record on the film layers. Suzuki et al. focused on occlusal force; when colourations resulting from forces applied for 1, 5, and 10 seconds were compared, no statistically significant difference was found between 1 and 5 seconds, whereas force applied for 10 seconds produced a more pronounced colouration. As a result of the study, it was reported that the effect of force application speed and duration on color formation on the film layer was at a negligible level.

Although the Dental Prescale system provides important data for occlusal analysis, occlusal contact areas and force values in the posterior region may be recorded as higher than their true values. This issue arises from the rigidity and thickness of the pressure-sensitive sensor, a known limitation of the method, as highlighted in the literature. In this photo-occlusion based technique, the film must be analysed using an 'Occluzer' after the patient bites; studies have described these steps as complex and time-consuming. Additionally, some research emphasises that the Prescale method has a low reproducibility. It should also be noted that measurements in systems that rely on pressure-sensitive sensors may be influenced by the condition of the masticatory muscles and dental health. However, the most fundamental structural shortcoming of the system is its lack of dynamic data, especially when compared with digital occlusion analysis (T-Scan) (Adachi, 2020; Qadeer et al., 2021).

**c) OccluSense**

The OccluSense system (Dr. Jean Bausch GmbH & Co. KG, Cologne, Germany), introduced to the dental market in 2019, is a hybrid occlusal analysis platform combining the physical marking advantage of traditional articulating papers with the objective data of digital recording technology (Figure 4). Thus, while pressure distribution under static and dynamic occlusion is measured, simultaneous staining is applied to the teeth. Beside static occlusion, a dynamic record of the closure sequence until reaching the MIP position is also taken. The system consists of a wireless handheld scanner (BK 5000), single-use, sensitive sensors, and an iPad application that analyses and visualises data in real time (The Future of Occlusion Control).

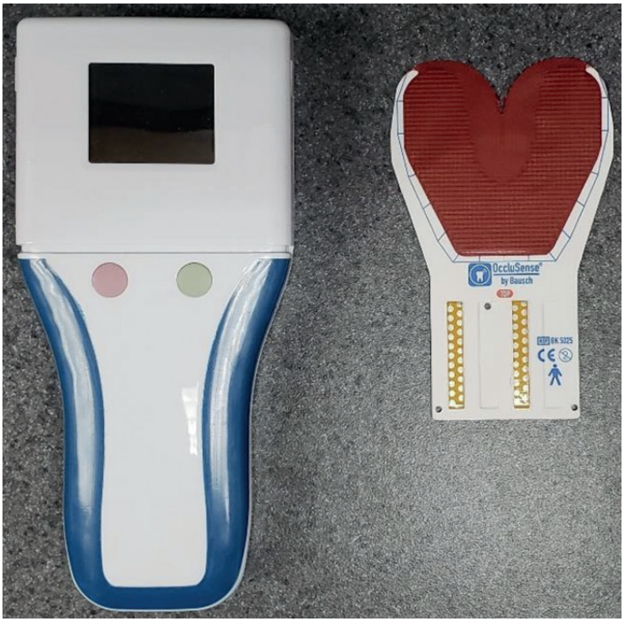
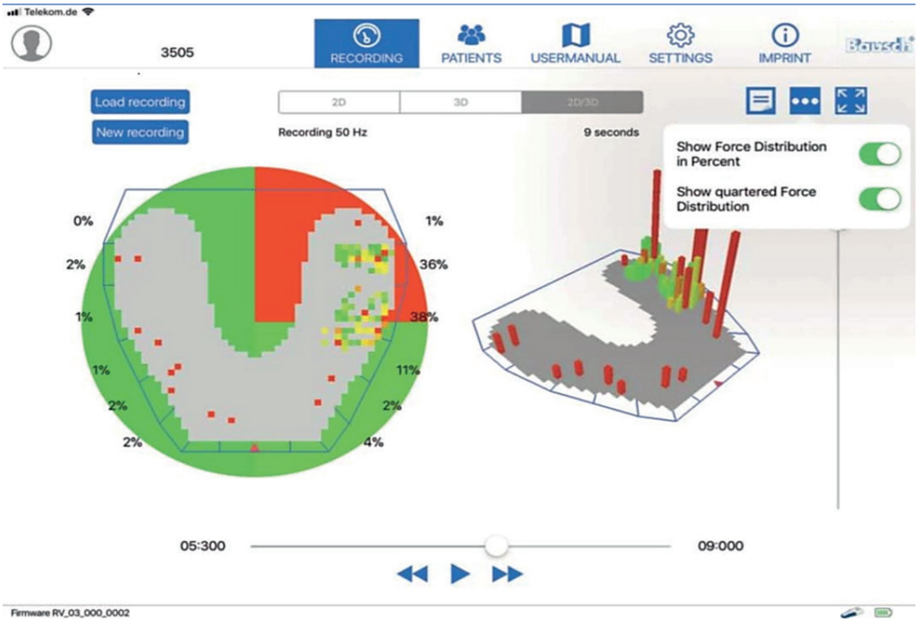


*Figure 4: OccluSense hybrid analysis sensor that combining with the articulating paper (Sutter, 2019)*



Show Force Distribution in Percent ●
Show quartered Force Distribution ●

*Figure 5: OccluSense bite force analyzis with 2D and 3D colorized graphics (Sutter, 2019)*

The sensor, which is the distinguishing feature of the OccluSense system, is thin compared to other digital occlusal registration methods, with a thickness of approximately 60 microns and can process occlusal forces at different pressure levels.

Both sides of these sensors, offered as single-use for each patient, are coated with a red articulation dye; this ensures intraoral localization by physically marking contact points on the teeth during the creation of digital pressure data.

Data generated by the sensor's bite-force measurement is transmitted to the iPad application via Wi-Fi. Here, it is schematized as 2D and 3D graphics with color codes varying from green to red (maximum pressure: red; minimum pressure: blue/green) according to detected pressure levels (Figure 5). However, the arch shape in this scheme is a standard template that does not vary depending on the patient. It cannot be adjusted based on tooth positions, alignment, deficiencies, or arch shape. This may result in occlusal forces being observed in different positions or on the wrong teeth, in various forms (Popa & Ahlers, 2024; Schütze et al., 2025).

Limitations of the OccluSense system outside the standard arch form are also reported in the literature. Although the 60-micron-thin sensor creates less material thickness between teeth, this thin structure causes it to become more sensitive to forces. It can be perforated in repetitive bites in clinical use. Furthermore, it has been reported that the coloration created by the sensor on the teeth is more difficult to distinguish when compared to traditional articulating paper. Besides this, it has also been observed that the system, which uses Wi-Fi connection to transfer data to the digital environment and application, causes delays in workflow during disruptions here (Schütze et al., 2025; Sutter, 2019).

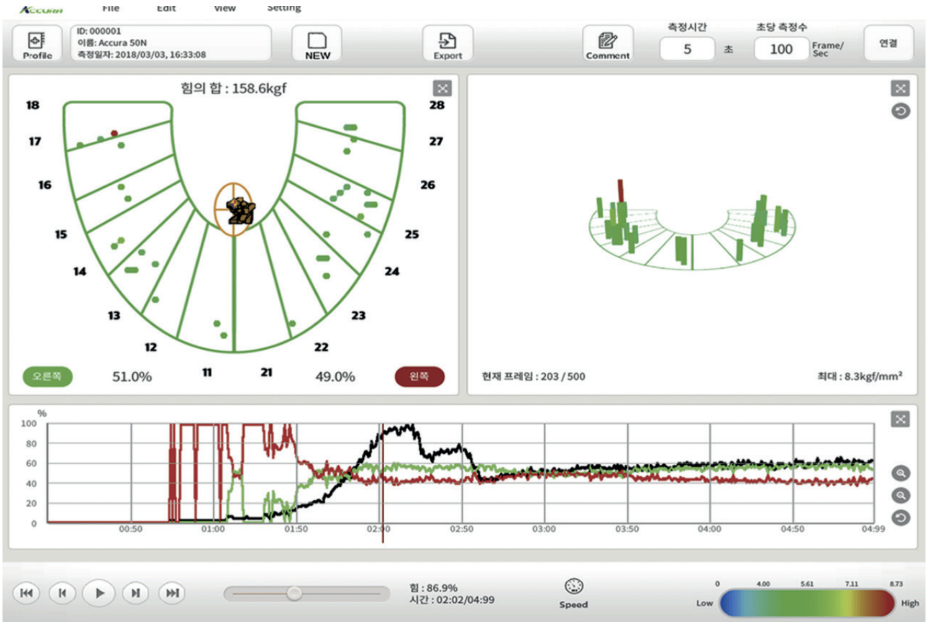
### d) Accura

The Accura Occlusal Analysis System (Dmetec Co., Ltd., Seoul, South Korea) is a sensor-based digital diagnostic device developed to measure the distribution and temporal sequence of occlusal forces. Sharing a similar mechanical principle with T-Scan technology, Accura distinguishes itself from other systems on the market according to manufacturer data by its ability to measure occlusal forces as absolute values (Lee et al., 2022). The system consists of an ergonomic hand unit with a rechargeable battery, interchangeable sensor film heads suitable for different arch widths (e.g., S, M), a film positioning guide, and integrated software for data processing; the data obtained is transferred to the computer via a Wi-Fi connection (Figure 6). Records are taken by placing Accura's pressure-sensitive sensor, which is 160 microns thick and made of polyimide material in a hard structure, onto the occlusal plane with the film positioning guide and having the patient bite. Subsequently, the software converts these records into 2D and 3D graphics, where the time variable can also be examined (Figure 7).

*Figure 6: Main device of T-scan Novus and Accura with film sensor attached (Lee et al., 2022).*

This sensor, a prominent feature of the system, imposes significant limitations. A sensor of this thickness and hardness can affect tooth contact when bitten during occlusal registration. Applied pressure cannot be fully detected, particularly in anterior teeth, resulting in the system yielding different accuracy values in the anterior and posterior regions. In the literature, in a study conducted by Jeong et al., it was reported that the system gave better accuracy results in the posterior but its effectiveness decreased in the anterior.

Sensel spatial resolutions were also reported for the Accura system, compared with T-Scan, in the same study. It was stated that sensels are effective in the more precise measurement of pressure and one of the sources of difference between the two devices might be T-Scan's sensel spatial resolution value of 400 sensels/in$^2$ compared to Accura's 361 sensels/in$^2$ (Jeong et al., 2020).



ID: 000001
이름: Accura 50N
측정일자: 2018/03/03, 16:33:08
측정시간 5 초
초당 측정수 100 Frame/Sec
힘의 합 : 158.6kgf
51.0%
49.0%
현재 프레임 : 203 / 500
최대 : 8.3kgf/mm²
힘 : 86.9%
시간 : 02:02/04:99

*Figure 7: Accura occlusal analysis software (Lee et al., 2022).*

## 2) Intraoral Scanners

While the occlusal relationship in data transferred to the technician for the design of prosthetic restorations in traditional dentistry is usually obtained physically using wax or silicone-based (PVS) registration materials, in the digital workflow, these records can proceed entirely digitally via 'virtual interocclusal record' (VIR) protocols using intraoral scanners. In this method, the mandibular and maxillary dental arches are first scanned separately; the jaws are then brought to maximum intercuspation, and additional scans of the buccal surfaces of the lower and upper jaw teeth are performed in this position (Michelinakis et al., 2020; Sandeep et al., 2025). Recorded scan data is used by the software's advanced best-fit alignment algorithms to align the lower and upper jaw models in the virtual environment. Thus, occlusion reconstruction in the digital environment is ensured (Ries et al., 2022).

The literature reports numerous factors affecting the accuracy of lower- and upper-jaw models and maxillomandibular relationships obtained with intraoral scanners. In addition to the IOS technology and software hardware utilized, choices dependent on scanning application such as the scanner head being of a size suitable for the mouth, calibration having been performed, and the applied scanning distance and angle are important. Environmental conditions such as light, heat, and humidity are also situations that should not be ignored. Besides these, intraoral conditions that can be termed patient-dependent factors such as the shape, position, alignment of teeth, structure of the arch, saliva, existing restorations, position and angle of implants, scanbody differences, and edentulous areas also affect the accuracy of the device (Gehrke et al., 2024; Revilla-León, Gohil, Barmak, et al., 2023).

The scanning protocol used in intraoral scanners also directly affects the accuracy of the resulting occlusal record. Scanning can include a specific segment or half jaw as a short arch, or it can be in a way to record the entire arch. In the literature, occlusal registration accuracy for short-arch (quadrant) scans has been reported to be very high. However, potential errors that may occur during the merging of image data from full-arch scans are noted. Consequently, it has been reported that open bite or premature contact errors may occur.

Many variables have also been identified as affecting the accuracy of static articulation in the matching of virtual models created from intraoral scans. In particular, arch size, the position and size of edentulous spaces, the scanner technology used, and the articulation technique are directly effective. Furthermore, characteristics such as the number of virtual occlusal records, the area they cover, and the region from which they are taken play a decisive role in the system's precision (Revilla-León, Kois, & Kois, 2023). Studies support that buccal records taken bilaterally give better results than unilateral scanning. With these records taken from the right and left sides, cross-arch stability is provided and canting error is prevented. The number of teeth included in bilateral records also affects the record. In the literature, bilateral records covering 4 teeth have been shown to achieve substantially higher accuracy than records with fewer teeth. In light of these data, it is recommended to include at least 4 teeth from the right and left sides in the bite registration (Revilla-León, Kois, Zeitler, et al., 2023).

The presence of the periodontal ligament provides teeth with a limited movement capability of 100 microns. Lower and upper arch scans are performed when teeth are not in contact or under any load, but since the bite scan is performed in maximum intercuspation, interpenetrations may occur on occlusal surfaces between opposing teeth. This situation stems from differences in tooth position arising from the periodontal ligament's stretching capacity. This condition, termed 'Mesh interpenetration,' leads to insufficient volume in the prosthetic restoration and loss of contact with the opposing tooth. Software capable of detecting and removing these interpenetrations exists in some IOS and CAD (computer-aided design) programs, but its effect on maxillomandibular relationship accuracy is not definitely known (Revilla-León, Kois, Zeitler, et al., 2023; Stavness et al., 2016).

## 2. COMPARATIVE EVALUATION OF DIGITAL OCCLUSAL ANALYSIS SYSTEMS: ADVANTAGES, DISADVANTAGES, AND LIMITATIONS

### 2.1. T-Scan (Tekscan Inc.)

It is the most cited analysis system in the literature, distinguished by its exstensively researched reliability and reproductibility and particularly noted for its dynamic analysis capabilities (Andrus et al., 2019; Qadeer et al., 2021).

· **Advantages:**

o Time Resolution*:* Records occlusion in 0.003-second increments, measuring premature contacts and disclusion time with millisecond precision (Kerstein & Radke, 2006) (Vlăduțu et al., 2023)

o Force Distribution*:* Dynamically monitors Right/Left arch balance and Center of Force (Liu et al., 2015).

o Scientific Evidence: Treatment protocols such as DTR (Disclusion Time Reduction) and implant-protective occlusion concepts are built upon this device (Kerstein & Radke, 2006).

· **Disadvantages:**

o Lack of Marking*:* The sensor does not stain teeth. It requires the additional use of articulating paper (correlation) for intraoral localization of the problematic region (Afrashtehfar & Qadeer, 2016).

· **Limitations:**

o The thickness of the sensor (~100 μm) is a point of criticism, and studies have observed that it influences electromyographic (EMG) activity. Furthermore, numerous factors may affect the extent to which an indicator accurately and reliably demonstrates tooth contacts. Consequently, the selection and clinical application of the material to be utilized necessitate rigorous analysis and careful clinical judgment (Cao et al., 2023; Forrester et al., 2011).

### 2.2. OccluSense (Bausch)

It is a hybrid system combining traditional articulating paper usage with digital data (The Future of Occlusion Control).

· **Advantages:**

o Hybrid Structure: The sensor records digital pressure data and simultaneously physically stains the teeth thanks to the red coating on it; this feature facilitates localization (Popa & Ahlers, 2024).

o Thinness: With its 60 μm thick sensor, it has the lowest thickness value among available electronic sensors (Schütze et al., 2025) .

o Ergonomics: Wireless (Wi-Fi) operation and tablet integration provide clinical ease of use (Schütze et al., 2025).

· **Disadvantages:**

o Sensor Deformation: Sensors may deform in a single use due to the color coating; it has been reported that data consistency decreases in multiple bites when compared with T-Scan (Sutter, 2019).

o Timing Analysis: Although it has dynamic analysis capability and the timing graphs offered by the software are not as detailed as T-Scan (Sutter, 2019).

### 2.3. Dental Prescale II (Fujifilm)

It is a chemical-based static analysis system focused on measuring the "magnitude" of occlusal force and "contact area" (Shiga et al., 2020).

· **Advantages:**

o Total Force (Newton): It is the most reliable method capable of numerically measuring the patient's Maximum Bite Force and occlusal contact area (Hattori et al., 2015).

o Muscle Function: Ideal for evaluating the strength and efficiency of masticatory muscles (e.g., pre- and post-prosthesis).

o Reliability: The clinical reproducibility of the new generation Prescale II system has been found to be high (ICC > 0.9) (Adachi et al., 2020).

· **Disadvantages:**

o Static Data: Measures only "instantaneous" peak force. Cannot show the equence of contacts or timing of premature contacts (Suzuki et al., 1997).

o Workflow: The film must be scanned in a scanner after the biting process; it cannot perform real-time imaging(Suzuki et al., 1994).

· **Limitations:**

o Its solitary use in precise occlusal adjustments is not recommended due to its rigid structure and risk of "overestimation" (measuring force higher than actual) (Suzuki et al., 1994)

### 2.4. Accura (Dmetec)

It is a cost-focused digital analysis alternative using piezoresistive sensor technology (Lee et al., 2022).

· **Advantages:**

o Economical: Device and consumable costs are more accessible compared to T-Scan (Lee et al., 2022).

o Dynamic Data: Provides superiority over static methods by offering force-time graphs and left/right balance analysis similar to T-Scan (Jeong et al., 2020).

· **Disadvantages:**

o Software Depth: Analysis software does not possess advanced modules such as "Center of Force" trajectory or implant loading warnings (Jeong et al., 2020).

### 2.5. Intraoral Scanners (IOS)

These are systems analyzing occlusion not with a physical sensor but with geometric algorithms (virtually) (Revilla-León, Kois, & Kois, 2023).

· **Advantages:**

o Virtual Simulation: Systems like 3Shape can record the patient's mandibular movements and perform dynamic simulation (Patient Specific Motion) (Jirajariyavej et al., 2025).

· **Disadvantages:**

o Does Not Measure Force: Colors in occlusion maps indicate "virtual penetration depth" (distance), not force (Revilla-León, Kois, Zeitler, et al., 2023).

o PDL Fallacy (Biomechanical Limitation): Digital models are rigid (inflexible). While teeth actually intrude within the PDL, the scanner cannot simulate this. Therefore, it tends to show contact areas as wider (overestimation) and more forceful than they are (Revilla-León, Kois, Zeitler, et al., 2023; Stavness et al., 2016).

## 3. TECHNICAL REVIEW OF DIGITAL OCCLUSAL ANALYSIS SYSTEMS: DATA COLLECTION, SENSOR, AND SOFTWARE FEATURES

### 3.1. T-Scan (Tekscan Inc., USA)

As a pioneering force in digital occlusion, T-Scan stands out with its dynamic data collection capacity (Andrus et al., 2019; Qadeer et al., 2021).

· **A. Data Collection Format**

o Method: Real-Time dynamic recording.

o Process: When the patient bites the sensor, the system records data not as a static "photograph" but as a continuous "movie".

o Sampling Rate: Works with a scanning speed of approximately 300-500 Hz. This means recording occlusion by dividing it into 0.003-second time frames. This speed is critical for capturing neuromuscular reflexes and early contacts (Sutter, 2019).

· **B. Sensor Features**

o Type: Ultra-thin, flexible, piezoresistive sensor (Novus HD Sensor).

o Structure: Conductive ink grid printed between two polyester (Mylar) layers.

o Thickness: Approximately 100 µm.

o Durability: Resistant to repetitive loading and provides high data reproducibility (Sutter, 2019)(Cerna et al., 2016).

- **C. Pressure-Force Sensing Mechanism**

o Principle: Piezoresistive Effect (Pressure-Dependent Resistance Change).

o Operation: When the sensor is unloaded, its electrical resistance is high. When teeth compress the sensor, conductive rows and columns approach each other, and resistance drops at the contact point. The system converts this resistance drop into voltage change.

o Data: Output is "Relative Force" percentage, not absolute force (Newton) (Fraile et al., 2022)(Cerna et al., 2016)

· **D. Software Features**

o Analysis: Force vs. Time Graph, Center of Force trajectory, and A-B-C-D timing analysis (Abutayyem et al., 2023).

o Feature: Automatically calculates premature contacts and disclusion time (Kerstein & Radke, 2006).

### 3.2. OccluSense (Dr. Jean Bausch GmbH, Germany)

A handheld wireless system where traditional and digital hybridize.

· **A. Data Collection Format**

o Method: Wireless (Wi-Fi) dynamic recording and physical marking.

o Process: Data is transferred from the handheld device to the application on the iPad. It creates both a digital graph and a physical dye mark on the tooth.

o Capacity: Although it can perform dynamic recording, data flow speed and processing capacity are not as high frequency as T-Scan.

· **B. Sensor Features**

o Type: Piezoresistive sensor + Color Coating.

oThickness: 60 µm (The thinnest electronic sensor on the market).

o Structure: The pressure-sensitive electronic layer is coated with a red food dye-based pigment (Bausch, 2019).

· **C. Pressure-Force Sensing Mechanism**

o Hybrid Mechanism:

1. Electronic: Under pressure, the sensor's electrical resistance changes, and this data is transferred to the tablet as 256 pressure levels.

2. Physical: The same pressure ensures the transfer of red pigment on the sensor surface to tooth enamel.

o Limitation: Color coating may deform in multiple bites and reduce data consistency by affecting electronic conductivity .

· **D. Software Features**

o Interface: iPad App-based user-friendly interface.

o Visualization: 2D and 3D pressure distribution graphs. Detailed "timing manipulation" or "Center of Force" analysis as in T-Scan is limited (Schütze et al., 2025; Sutter, 2019).ö

### 3.3. Dental Prescale II (Fujifilm, Japan)

A static system where occlusal force is measured via chemical reaction (Suzuki et al., 1997).

· **A. Data Collection Format**

o Method: Static (One-time) Recording.

o Process: The patient bites the film (Clench), the film is removed from the mouth and analyzed with a special Scanner or mobile application.

o Timing: There is no dynamic process; it collects only the peak data at the moment of maximum clenching (MIP).

· **B. Sensor Features**

o Type: Pressure Sensitive Chemical Film.

o Structure: Microcapsule layer and color developer layer on PET base.

o Thickness: Approximately 98 µm (Type 50H).

· **C. Pressure-Force Sensing Mechanism**

o Principle: Microcapsule breakage and color reaction.

o Operation: When occlusal pressure is applied, microcapsules burst. The colourless agent (colour-former) inside combines with the developer agent to form a red color (Suzuki et al., 1997).

o Measurement: Color Density is directly proportional to applied pressure (MPa). The scanner reads this density and converts it to absolute force in Newtons (N) (Hattori et al., 2015).

· **D. Software Features**

o Analysis: Occlusal contact area, Average Pressure (MPa), and Maximum Bite Force (N).

o Usage: Specialized software for masticatory efficiency and muscle strength analysis (Shiga et al., 2020).

### 3.4. Intraoral Scanners (3Shape, Dentsply Sirona, Medit, etc.)

"Virtual" analysis systems not using physical sensors (Jirajariyavej et al., 2025).

- **A. Data Collection Format**

o Method: Optical Scanning and Buccal Bite Scan.

o Process: Upper and lower jaws are scanned separately; two models are matched in digital space with the image taken from the cheek side while the patient closes (Michelinakis et al., 2020).

o Dynamics: Some systems (3Shape, Medit) can record the patient's jaw movements (Motion), but contact analysis is mathematical (Jirajariyavej et al., 2025).

· **B. Sensor Features**

o Physical Sensor: None. No material enters between teeth during occlusion (Sensorless Analysis) (Ender & Mehl, 2013).

· **C. Pressure-Force Sensing Mechanism**

o Principle: Virtual Penetration (Virtual Intermesh).

o Operation: Software superimposes upper and lower digital models. The depth at which teeth intersect is calculated.

o Absence of Force: The system does not measure a real force (N) or pressure (MPa). "Red" areas indicate not high force, but only "0 mm" distance or virtual overlap (Fraile et al., 2018).

· **D. Software Features**

o Visualization: Color-coded occlusion maps.

o Limitation: Since it cannot calculate the stretching of the periodontal ligament (intrusion), it tends to show contact areas wider than they are (Overestimation) (Revilla-León, Kois, Zeitler, et al., 2023; Stavness et al., 2016).

| Technical Parameter | T-Scan (Tekscan) | OccluSense (Bausch) | Accura (Dmetec) | Dental Prescale II (Fujifilm) | Intraoral Scanners (IOS) |
|---|---|---|---|---|---|
| Recording Method | Dynamic / Real-Time (Video) | Dynamic / Wireless Transmission | Static / Semi-Dynamic (Digital) | Static / Single-Use (Chemical) | Static Geometric Alignment (Virtual) |
| Sensor Type | Piezoresistive (Novus HD) | Piezoresistive + Color Pigment | Conductive Film Sensor | Pressure-Sensitive Chemical Film | Optical Sensor (CMOS/CCD) |
| Sensor Thickness | ~100 µm | ~60 µm (Thinnest) | ~160 µm (Rigid Structure) | ~98 µm (Type 50H) | (Sensorless) |
| Output Unit | Relative Force (%) and Time (s) | Pressure Level (256 Levels) | Absolute Force (Newtons) + Pressure | Absolute Force (Newtons) | Distance / Contact Map (mm) |
| Timing Analysis | Very High (Millisecond precision) | Moderate | Low | None | None |
| Premature Contact Detection | Excellent (Sequential formation) | Good (Pressure intensity) | Moderate (Force intensity) | Poor (Peak moment only) | Moderate (Virtual penetration) |
| Reproducibility | High (With calibration) | Moderate (Risk of deformation) | High | Very High (Single-use) | Variable (Dependent on scanning strategy) |
| Primary Indication | Occlusal Timing & Implant Balance | Routine Control & Physical Marking | Bite Force Measurement (Diagnosis) | Masticatory Performance & Research | Prosthetic Design & Virtual Articulation |
| Limitation | Does not measure absolute force (N) | Sensor coating prone to abrasion | Sensor thickness (Proprioceptive interference) | Does not provide dynamic data | Does not measure actual force (Virtual) |

*Table 1: Comparision of digital occlusal registration systems.*

## 4.PERFORMANCE ASSESSMENT CRITERIA FOR OCCLUSAL REGISTRATION SYSTEMS

Accuracy is defined by the integration of precision and trueness (Figure 8). Precision reflects the consistency of repeated measurements; the higher the precision, the more predictable the outcomes. Trueness, on the other hand, quantifies the extent to which a measurement deviates from the object's actual dimensions. High trueness ensures that results closely align with, or are identical to, the true dimensions of the measured subject (Ender & Mehl, 2013).

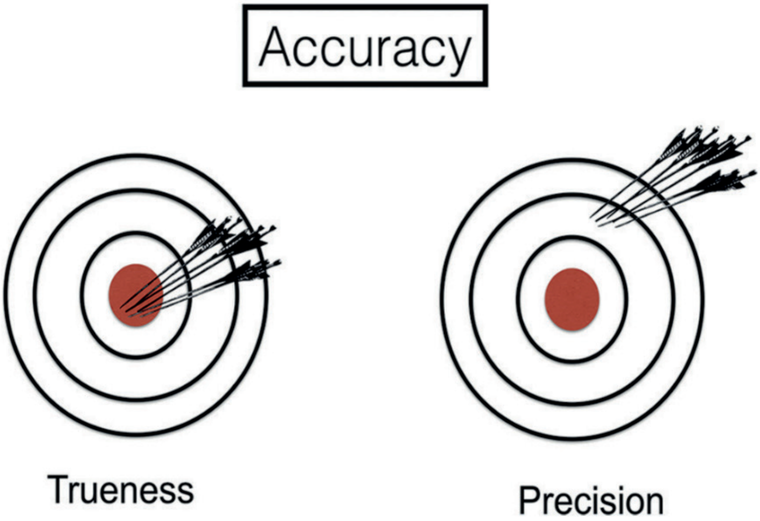


*Figure 8: Accuracy components (Renne et al., 2017).*

### 1. Trueness: Anatomical Alignment vs. Functional Loading

· **Intraoral Scanners (Geometric Alignment):** In the field of digital dentistry, intraoral scanners (IOS) interpret occlusion primarily as a geometric superimposition of two volumetric entities in virtual space rather than a biodynamic interaction. The spatial orientation of the maxillary and mandibular arches relies on "best-fit" algorithms executed through buccal bite registrations. However, this virtual modeling paradigm fails to incorporate the microscopic mobility of the periodontal ligament under functional load or the physiological tension exerted by the masticatory musculature. To comprehensively evaluate the intricate nature of occlusion and its impact on the stomatognathic system, IOS data must be supplemented with digital analyzers based on high-sensitivity physical pressure sensors, such as T-Scan or OccluSense (Ender et al., 2016; Zimmermann et al., 2020).

· **Sensor-Based Systems (Functional Analysis):** Dynamic analysis platforms like the T-Scan are recognized as the primary benchmark for evaluating the temporal progression and proportional load distribution of dental occlusion. Unlike static imaging, these technologies provide a millisecond-by-millisecond breakdown of contact sequences and calculate bilateral force symmetry using relative percentage metrics—biometric insights that remain beyond the reach of conventional intraoral scanners. In addition to temporal tracking, pressure-sensitive technologies, such as the Dental Prescale II, provide an additional diagnostic advantage. By converting color intensity into precise Newton values, these systems bridge the gap between subjective observation and objective biomechanical measurement, ensuring a more predictable standard of rehabilitative care (Kerstein & Radke, 2013; Sutter, 2019; Suzuki et al., 2020).

## 2. Precision and Material Interaction

· **Intraoral Scanners (Non-Invasive Registration):** A distinct clinical advantage of IOS is the ability to record occlusion without interposing any physical material between the teeth (sensor-free registration). The theoretical "zero-micron" clearance allows for the capture of the Maximum Intercuspal Position (MIP) without triggering proprioceptive deviations. However, optical precision remains susceptible to environmental variables such as ambient lighting, salivary contamination, and surface reflectivity (Revilla-León et al., 2023).

· **Sensor Systems (Thickness-Dependent Deviation):** The physical thickness of sensors used for digital analysis (approximately 100 µm for T-Scan and 160 µm for Prescale) can induce shifts in mandibular positioning or alter closure patterns due to a "foreign body" sensation. The OccluSense system was developed with a 60-micron profile, aiming to provide contact precision comparable to traditional articulating foils while minimizing proprioceptive interference (Bausch, 2019; Qadeer et al., 2016). However, despite this reduction in sensor thickness, current literature suggests that the reliability of static occlusal measurements remains a subject of debate, particularly in specific malocclusions such as deep bite (Schütze et al., 2025).

## 3. Repeatability and Data Consistency

Repeatability assesses the consistency of data obtained from multiple measurements taken under identical conditions.

· **Intraoral Scanners:** The consistency of digital impressions is heavily dependent on the operator's scanning strategy (scan path). Particularly in full-arch scans, cumulative errors during the image stitching process increase the risk of arch distortion (warpage). This can lead to the spatial displacement of occlusal contact points in sequential scans of the same patient, thereby compromising repeatability (Flügge et al., 2016; Renne et al., 2017).

· **Sensor Systems:** Single-use technologies, such as the Dental Prescale II, eliminate the variable of material fatigue, ensuring high repeatability standards for each measurement. Conversely, multi-use sensors such as the T-Scan may experience surface deformation due to repetitive biting forces. However, when strict calibration protocols are adhered to, the reliability of the dynamic data is well-supported by the literature (Koos et al., 2010; Ohyama et al., 2019).

## 4. Clinical Indication and Workflow Integration

The efficacy of these technologies relies on their application within the appropriate clinical context. Contemporary consensus suggests these systems are not mutually exclusive but are complementary components of a "holistic digital workflow."

· **Design and Manufacturing (IOS):** Intraoral scanners are the cornerstone of the fabrication process, essential for ensuring the marginal fit of restorations, capturing anatomical morphology, and enabling movement simulations on virtual articulators.

· **Functional Adjustment and Diagnosis (Sensors):**

**o T-Scan:** Is critical for optimizing occlusal timing, particularly in implant prosthodontics, to ensure implants engage in function slightly later than natural teeth (delayed contact) to prevent overload.

**o Prescale/Accura:** Is utilized for diagnostic-centric processes, such as the objective evaluation of masticatory performance, monitoring the efficacy of masseter muscle treatments, and assessing the retention of complete dentures (Solaberrieta et al., 2017; Sierpinska et al., 2020).

## 5. COMPARATIVE ANALYSIS OF CONVENTIONAL AND DIGITAL OCCLUSION METHODS

| **Comparison Parameter** | Conventional Analysis (Articulating Paper/Foil) | Conventional Registration (Wax / PVS Silicone) | Digital Analysis (T-Scan / Prescale / OccluSense) | Digital Registration (Intraoral Scanner - IOS) |
|---|---|---|---|---|
| **Data Nature** | Subjective / Qualitative | Physical / Volumetric: Negative replica of the interdental space (Analog mold). | Objective / Quantitative: Force (Newton or %), time (seconds), and surface area data. | Virtual / Geometric: Mathematical alignment of point clouds (Best-fit algorithm). |
| **Force Measurement Capability** | Mark size does not consistently indicate high force (approx. 20% accuracy). | Only locks tooth position; does not quantify force magnitude. | Presents force distribution and intensity via numerical data. | Does not measure force; visualizes "virtual penetration" magnitude via a color map. |

| | | | | |
|---|---|---|---|---|
| **Dynamic Motion Recording** | Static Mark: Displays contacts during jaw movement as “smear marks”; differentiation is difficult. | Static Position: Captures only the locked position (MIP or CR) at a single moment. | Real-Time (4D): Records the precise onset and offset of contact (e.g., T-Scan). | Simulation: Typically simulates patient movement via software algorithms. |
| **Material Thickness & Proprioception** | Variable (12μm - 200μm): Thick papers may induce mandibular deviation due to proprioceptive reflexes. | High: Patients may lose the sensation of full intercuspation when material is interposed. | Sensor-Dependent (60μm - 160μm): Thin sensors allow near-natural occlusion but are not entirely imperceptible. | None (Contactless): No material enters the interdental space. Facilitates the most natural occlusal reflex. |
| **Sources of Error (Limitations)** | False Positives: Saliva presence, surface morphology, and paper tearing can result in erroneous marks. | Deformation: Thermal shrinkage of wax or distortion of silicone during mounting. | Sensor Fatigue: Reduced sensor sensitivity after multiple bites (requires calibration). | Software Error: Stitching errors in full-arch scans or artifacts from reflective surfaces. |
| **Archiving & Communication** | Not permanent unless photographed; physical paper cannot be efficiently archived. | Physical Storage: Subject to degradation and space requirements. | Digital Archiving: Storable proprietary data files. | Digital Integration: Stored in STL/PLY formats for seamless CAD/CAM integration. |
| **Clinical Indication** | Routine try-ins, simple adjustments, gross detection of high spots. | Transferring models to the laboratory, bite registration for prosthesis fabrication. | Implant loading, TMJ analysis, treatment of occlusal instability, bruxism management. | Digital prosthesis design, virtual articulation, orthodontic planning. |

*Table 2: Comparative analysis of conventional and digital occlusion methods.*

## 6. DEVELOPMENTS AND ADVANCEMENTS

The findings examined in this review demonstrate a fundamental paradigm shift in occlusal registration and analysis methods. Although traditional techniques, such as articulating papers and wax records, have constituted the foundation of dentistry for over a century, they remain insufficient in meeting the standards of contemporary "Precision Dentistry." Current literature reveals that combining the geometric accuracy of Intraoral Scanners (IOS) with the functional data power of Digital Occlusal Analysis Systems (e.g., T-Scan, Prescale, and OccluSense) may enhance diagnostic consistency and provide a more comprehensive understanding of occlusal dynamics (Zimmermann et al., 2020). However, this technological integration is not a final destination, but rather the commencement of the "4th Dimension" revolution in dentistry.

1. Evolution from Static Model to "4D Virtual Patient"

The most salient trend of the coming decade is the transformation of occlusion from a static "moment" into a dynamic simulation that incorporates temporal elements. The "Virtual Patient" concept aims to integrate Cone Beam Computed Tomography (CBCT) for bone, Face Scanning for soft tissue, IOS for dentition, and Jaw Motion Tracking data into a single coordinate system (Joda et al., 2018; Lepidi et al., 2019). Through this integration, the patient's masticatory cycles can be simulated in a virtual environment before the restoration is fabricated, enabling detection of potential occlusal interferences prior to production. Consequently, the field is entering an era of "zero-error production," although clinicians must remain cognizant of current hardware limitations in specific malocclusions, such as deep bite, where sensor sensitivity may still vary (Schütze et al., 2025).

2. Artificial Intelligence (AI) and Autonomous Occlusal Design

The "Big Data" collected by intraoral scanners and digital sensors serves as an excellent training ground for Artificial Intelligence algorithms. Future CAD/CAM software will not only select anatomical tooth forms from a library but will also autonomously design the occlusal surface morphology—specifically cusp inclinations and fossa depths—tailored to the individual's functional requirements. This design process will be driven by the patient's specific bite force pattern and neuromuscular activity. These AI-supported systems will generate "smart occlusion" profiles, creating designs that are biomechanically more resistant for bruxist patients or load-distributing for implant-supported prostheses (Revilla-León et al., 2020; Ding et al., 2023).

3. Clinical Guidance with Augmented Reality (AR)

From a future perspective, digital data is expected to transcend computer screens and be projected directly into the patient's mouth via Augmented Reality (AR) glasses. When viewing the patient, the clinician can visualise colour-coded force maps holographically superimposed on the teeth, enabling real-time tracking of which micron-level point requires adjustment.

This technology represents the ultimate reflection of the vision of "making the invisible visible" in clinical practice, bridging the gap between virtual planning and physical execution (Farronato et al., 2019).

## 7. CONCLUSION

The precise analysis of occlusal contacts remains a cornerstone of successful dental treatment, directly influencing masticatory efficiency, the longevity of prosthetic restorations, and the stability of implant-supported rehabilitations. As demonstrated in this section, while conventional methods such as articulating papers and wax records are deeply ingrained in clinical practice due to their accessibility, they are inherently limited by their subjectivity and inability to provide quantitative data regarding force magnitude and contact sequencing. These static indicators are susceptible to distortion by intraoral factors such as saliva and material thickness, which can lead to interpretive errors that may compromise the functional harmony of the stomatognathic system.

The advent of digital occlusal analysis systems has revolutionized this domain by introducing objective metrics into the diagnostic workflow. Sensor-based technologies, particularly the T-Scan system, have addressed the critical need for dynamic analysis by quantifying the timing of occlusal contacts and the distribution of forces in real-time. Similarly, the Dental Prescale system provides reliable data on maximum bite force and contact area, making it a valuable tool for evaluating muscle function. Although intraoral scanners (IOS) have streamlined the digital design process, their reliance on virtual algorithms rather than physical pressure sensors currently limits their ability to accurately simulate the complex biomechanics of the periodontal ligament under load.

In contemporary practice, digital and conventional methods should not be viewed as mutually exclusive but rather as complementary. The most robust clinical results are achieved through a synergistic approach: utilizing digital systems to identify force imbalances and timing errors, while employing traditional articulating papers for the precise physical localization of these contacts on the tooth surface. As digital dentistry continues to evolve, the integration of quantitative analysis tools into routine protocols will be essential to move beyond subjective estimation toward a predictable, data-driven standard of care in occlusal rehabilitation.

## REFERENCES

Abutayyem, H., M Annamma, L., Desai, V. B., & Alam, M. K. (2023). Evaluation of occlusal bite force distribution by T-Scan in orthodontic patients with different occlusal characteristics: a cross sectional-observational study. BMC Oral Health, 23(1). https://doi.org/10.1186/s12903-023-03544-4

Adachi, K., (2020). reproducebility of the newly developed dental prescale 2 system and bite force analyzer for occlusal measurements.

Afrashtehfar, K. I., & Qadeer, S. (2016). Computerized occlusal analysis as an alternative occlusal indicator. Cranio - Journal of Craniomandibular Practice, 34(1), 52–57. https://doi.org/10.1179/2151090314Y.0000000024

Ando, K., Kurosawa, M., Fuwa, Y., Kondo, T., & Goto, S. (2007). A Study on Measuring Occlusal Contact Area Using Silicone Impression Materials: an Application of this Method to the Bite Force Measurement System Using the Pressure-sensitive Sheet. In Dental Materials Journal (Vol. 26, Number 6).

Andrus R, Qian F, Schneider R, Huber L, Kerstein RB. Comparison of results of traditional occlusal adjustment technique with computer-aided occlusal adjustment technique. Adv Dent Tech. Published online September 7, 2019:43-53..

Beninati, C. J., & Katona, T. R. (2019). The combined effects of salivas and occlusal indicators on occlusal contact forces. Journal of Oral Rehabilitation, 46(5), 468–474. https://doi.org/10.1111/joor.12772

Bostancıoğlu, S. E., Toğay, A., & Tamam, E. (2022). Comparison of two different digital occlusal analysis methods. Clinical Oral Investigations, 26(2), 2095–2109. https://doi.org/10.1007/s00784-021-04191-1

Bozhkova, T., Musurlieva, N., & Slavchev, D. (2021). Comparative Study Qualitative and Quantitative Techniques in the Study of Occlusion. BioMed Research International, 2021. https://doi.org/10.1155/2021/1163874

Cao, R., Xu, H., Lin, J., & Liu, W. (2023). Evaluation of the accuracy of T-scan system and Cerec Omnicam system used in occlusal contact assessment. Heliyon, 9(2). https://doi.org/10.1016/j.heliyon.2023.e13476

Carey, J. P., Craig, M., Kerstein, R. B., & Radke, J. (2007). Determining a Relationship Between Applied Occlusal Load and Articulat-ing Paper Mark Area. In The Open Dentistry Journal (Vol. 1). Bentham Science Publishers Ltd.

Cerna M, Ferreira R, Zaror C, Navarro P, Sandoval P. In vitro evaluation of T-Scan®III through study of the sensels. Cranio. 2015 Oct;33(4):299-305. doi: 10.1080/08869634.2015.1097332.

Chinam, N., Bekkali, M., Kallas, M., & Li, J. (2023). Virtual occlusal records acquired by using intraoral scanners: A review of factors that influence maxillo-mandibular relationship accuracy. In Journal of Prosthodontics (Vol. 32, pp. 192–207). John Wiley and Sons Inc. https://doi.org/10.1111/jopr.13787

Chowdhary, R., & Sonnahalli, N. K. (2024). Clinical applications of the T-Scan quantitative digital occlusal analysis technology: a systematic review. International Journal of Computerized Dentistry, 27(1), 49–86. https://doi.org/10.3290/j.ijcd.b3945153

Dinçer, G., Nogueira Chamma-Wedemann, C., Reis, I. N. R. dos, da Silva, E. V. F., Çakmak, G., Yılmaz, B., & Sesma, N. (2025). Comparison of digital technologies for occlusal analysis in dentate arches: A systematic review. In Journal of Dentistry (Vol. 163). Elsevier Ltd. https://doi.org/10.1016/j.jdent.2025.106114

Ding H, Wu J, Zhao W, Matinlinna JP, Burrow MF, Tsoi JKH. Artificial intelligence in dentistry-A review. Front Dent Med. 2023 Feb 20;4:1085251. doi: 10.3389/fdmed.2023.1085251.

Esposito, R., Masedu, F., Cicciù, M., Tepedino, M., Denaro, M., & Ciavarella, D. (2024). Reliabilty of recording occlusal contacts by using intraoral scanner and articulating paper - A prospective study. Journal of Dentistry, 142. https://doi.org/10.1016/j.jdent.2024.104872

Farronato M, Maspero C, Lanteri V, Fama A, Ferrati F, Pettenuzzo A, Farronato D. Current state of the art in the use of augmented reality in dentistry: a systematic review of the literature. BMC Oral Health. 2019 Jul 8;19(1):135. doi: 10.1186/s12903-019-0808-3.

Forrester, S. E., Presswood, R. G., Toy, A. C., & Pain, M. T. G. (2011). Occlusal measurement method can affect SEMG activity during occlusion. Journal of Oral Rehabilitation, 38(9), 655–660. https://doi.org/10.1111/j.1365-2842.2011.02205.x

Fraile, C., Ferreiroa, A., Romeo, M., Alonso, R., & Pradíes, G. (2022). Clinical study comparing the accuracy of interocclusal records, digitally obtained by three different devices. Clinical Oral Investigations, 26(2), 1957–1962. https://doi.org/10.1007/s00784-021-04174-2

Gehrke, P., Rashidpour, M., Sader, R., & Weigl, P. (2024). A systematic review of factors impacting intraoral scanning accuracy in implant dentistry with emphasis on scan bodies. International Journal of Implant Dentistry, 10(1). https://doi.org/10.1186/s40729-024-00543-0

Hattori, Y., Okugawa, H., & Watanabe, M. (1994). Occlusal Force Measurement Using Dental Prescale. Nihon Hotetsu Shika Gakkai Zasshi, 38, 835-841.

Huang, Y. F., Liu, S. P., Muo, C. H., & Chang, C. T. (2021). The impact of occluding pairs on the chewing patterns among the elderly. Journal of Dentistry, 104. https://doi.org/10.1016/j.jdent.2020.103511

Huang YF, Wang CM, Shieh WY, Liao YF, Hong HH, Chang CT. The correlation between two occlusal analyzers for the measurement of bite force. BMC Oral Health. 2022 Nov 5;22(1):472. doi: 10.1186/s12903-022-02484-9.

Jeong, M. Y., Lim, Y. J., Kim, M. J., & Kwon, H. B. (2020). Comparison of two computerized occlusal analysis systems for indicating occlusal contacts. Journal of Advanced Prosthodontics, 12(2), 49–54. https://doi.org/10.4047/

jap.2020.12.2.49

Jirajariyavej, B., Ounvorawong, P., Pornprasertsuk-Damrongsri, S., Visuttiwattanakorn, P., Sriyarun, S., & Petchmedyai, P. (2025). Accuracy of individual mandibular motion records using intraoral scanner for fixed implant- supported prosthesis designs: a comparative study. BMC Oral Health, 25(1). https://doi.org/10.1186/s12903-025-06282-x

Joda T, Gallucci GO, Wismeijer D, Zitzmann NU. Augmented and virtual reality in dental medicine: A systematic review. Comput Biol Med. 2019 May;108:93-100. doi: 10.1016/j.compbiomed.2019.03.012.

Kerstein, R. B. (2015). Handbook of Research on Computerized Occlusal Analysis Technology Applications in Dental Medicine (2 Vols.). Hershey, PA: Medical Information Science Reference (IGI Global). ISBN 978-1-4666-6587-3.

Kerstein, R. B. (2016). History of the T-scan system development from 1984 to the present day. In Medical Imaging: Concepts, Methodologies, Tools, and Applications (pp. 1–36). IGI Global. https://doi.org/10.4018/978-1-5225-0571-6.ch001

Kerstein, R. B., Lowe, M., Harty, M., & Radke, J. (2006). A force reproduction analysis of two recording sensors of a computerized occlusal analysis system. Cranio - Journal of Craniomandibular and Sleep Practice, 24(1), 15–24. https://doi.org/10.1179/crn.2006.004

Kerstein RB, Radke J. The effect of disclusion time reduction on maximal clench muscle activity levels. Cranio. 2006 Jul;24(3):156-65. doi: 10.1179/crn.2006.026.

Koos B., Godt, A., Schille, C., & Göz, G. (2010). Präzision eines instrumentellen Analyseverfahrens der Okklusion und ihrer resultierenden Kraftverteilung im Zahnbogen. Journal of Orofacial Orthopedics, 71(6), 403–410. https://doi.org/10.1007/s00056-010-1023-7

Lee, W., Kwon, H. B., Kim, M. J., & Lim, Y. J. (2022). Determination of the reliability and repeatability of a quantitative occlusal analyzer by using a piezoelectric film sensor: An in vitro study. Journal of Prosthetic Dentistry, 127(2), 331–337. https://doi.org/10.1016/j.prosdent.2020.07.024

Lepidi L, Chen Z, Ravida A, Lan T, Wang HL, Li J. A Full-Digital Technique to Mount a Maxillary Arch Scan on a Virtual Articulator. J Prosthodont. 2019 Mar;28(3):335-338. doi: 10.1111/jopr.13023.

Liu, C. W., Chang, Y. M., Shen, Y. F., & Hong, H. H. (2015). Using the T-scan III system to analyze occlusal function in mandibular reconstruction patients: A pilot study. Biomedical Journal, 38(1), 52–57. https://doi.org/10.4103/2319-4170.128722

Malta Barbosa, J., Urtula, A. B., Hirata, R., & Caramês, J. (2018). Thickness evaluation of articulating papers and foils. Journal of Esthetic and Restorative Dentistry, 30(1), 70–72. https://doi.org/10.1111/jerd.12343

Manziuc, M. M., Savu, M. M., Almăşan, O., Leucuţa, D. C., Tăut, M., Ifrim, C., Berindean, D., Kui, A., Negucioiu, M., & Buduru, S. (2024). Insights into Occlusal Analysis: Articulating Paper versus Digital Devices. Journal of Clinical Medicine, 13(15). https://doi.org/10.3390/jcm13154506

Michelinakis, G., Apostolakis, D., Tsagarakis, A., Kourakis, G., & Pavlakis, E. (2020). A comparison of accuracy of 3 intraoral scanners: A single-blinded in vitro study. Journal of Prosthetic Dentistry, 124(5), 581–588. https://doi.org/10.1016/j.prosdent.2019.10.023

Misch, C. E. (2007). Contemporary implant dentistry-e-book: Contemporary implant dentistry-e-book. Elsevier Health Sciences.

Mitchem, J. A., Katona, T. R., & Moser, E. A. S. (2017). Does the presence of an occlusal indicator product affect the contact forces between full dentitions? Journal of Oral Rehabilitation, 44(10), 791–799. https://doi.org/10.1111/joor.12543

Popa, A. D., Vlăduțu, D. E., Turcu, A. A., Târtea, D. A., Ionescu, M., Păunescu, C., Stan, R. S., & Mercuț, V. (2024). Aspects of Occlusal Recordings Performed with the T-Scan System and with the Medit Intraoral Scanner. Diagnostics, 14(13). https://doi.org/10.3390/diagnostics14131457

Popa, S., & Ahlers, M. O. (2024). Contact point marking with the OccluSense system—an in vitro study on reliability and validity. Journal of Oral Rehabilitation, 51(9), 1662–1674. https://doi.org/10.1111/joor.13774

Qadeer, S. (2016). The limitations of traditional non-digital occlusal indicators when compared to the t-scan computerized occlusal analysis technology. In Medical Imaging: Concepts, Methodologies, Tools, and Applications (pp. 1528–1555). IGI Global. https://doi.org/10.4018/978-1-5225-0571-6.ch065

Qadeer, S., Abbas, A. A., Sarinnaphakorn, L., & Kerstein, R. B. (2018). Comparison of excursive occlusal force parameters in post-orthodontic and non-orthodontic subjects using T-Scan® III. Cranio - Journal of Craniomandibular Practice, 36(1), 11–18. https://doi.org/10.1080/08869634.2016.1259785

Qadeer, S., Özcan, M., Edelhoff, D., & Vanpelt, H. (2021). Accuracy, Reliability and Clinical Implications of Static Compared to Quantifiable Occlusal Indicators. European Journal of Prosthodontics and Restorative Dentistry, 29(3), 130–141. https://doi.org/10.1922/EJPRD_2202Qadeer12

Reich, K. M., Tatzber, V., Skolka, A., Piehslinger, E., Lettner, S., Kundi, M., & Sagl, B. (2025). A comparative study of digital and conventional occlusal indicators: accuracy and reliability of the T-Scan Novus, wax occlusogram, and articulating silk in clinical application. Journal of Dentistry, 156. https://doi.org/10.1016/j.jdent.2025.105695

Renne, W., Ludlow, M., Fryml, J., Schurch, Z., Mennito, A., Kessler, R., & Lauer, A. (2017). Evaluation of the accuracy of 7 digital scanners: An in vitro analysis based on 3-dimensional comparisons. Journal of Prosthetic Dentistry, 118(1), 36–42. https://doi.org/10.1016/j.prosdent.2016.09.024

Revilla-León, M., Gohil, A., Barmak, A. B., Gómez-Polo, M., Pérez-Barquero, J. A., Att, W., & Kois, J. C. (2023). Influence of ambient temperature changes on intraoral scanning accuracy. Journal of Prosthetic Dentistry, 130(5), 755–760. https://doi.org/10.1016/j.prosdent.2022.01.012

Revilla-León, M., Kois, D. E., & Kois, J. C. (2023a). A guide for maximizing the accuracy of intraoral digital scans. Part 1: Operator factors. In Journal of Esthetic and Restorative Dentistry (Vol. 35, Number 1, pp. 230–240). John Wiley and Sons Inc. https://doi.org/10.1111/jerd.12985

Revilla-León, M., Kois, D. E., & Kois, J. C. (2023b). A guide for maximizing the accuracy of intraoral digital scans: Part 2—Patient factors. In Journal of Esthetic and Restorative Dentistry (Vol. 35, Number 1, pp. 241–249). John Wiley and Sons Inc. https://doi.org/10.1111/jerd.12993

Revilla-León, M., Kois, D. E., Zeitler, J. M., Att, W., & Kois, J. C. (2023). An overview of the digital occlusion technologies: Intraoral scanners, jaw tracking systems, and computerized occlusal analysis devices. In Journal of Esthetic and Restorative Dentistry (Vol. 35, Number 5, pp. 735–744). John Wiley and Sons Inc. https://doi.org/10.1111/jerd.13044

Ries, J. M., Grünler, C., Wichmann, M., & Matta, R. E. (2022). Three-dimensional analysis of the accuracy of conventional and completely digital interocclusal registration methods. Journal of Prosthetic Dentistry, 128(5), 994–1000. https://doi.org/10.1016/j.prosdent.2021.03.005

Rovira-Lastra, B., Khoury-Ribas, L., Flores-Orozco, E.-I., Ayuso-Montero, R., Chaurasia, A., & Martinez-Gomis, J. (2024). Accuracy of digital and conventional systems in locating occlusal contacts: A clinical study. Retrieved http://www.randomization.com

Sandeep, C., Afreen, S., Kumar, V. B., Srujana, P. L. N., Guntupalli, S., & Adavikatla, S. (2025). Evaluation and Comparison of Interocclusal Registration Accuracy Using Digital Intraoral Scanners and Conventional Methods: An In Vivo Study. Cureus. https://doi.org/10.7759/cureus.89266

Saraçoğlu A, Ozpinar B. In vivo and in vitro evaluation of occlusal indicator sensitivity. J Prosthet Dent. 2002 Nov;88(5):522-6. doi: 10.1067/mpr.2002.129064.

Schütze, P., Beuer, F., & Bumann, A. (2025). 373 SCIENCE OccluSense: reliability, influencing factors, and limitations. International Journal of Computerized Dentistry, 28(4), 373–379. https://doi.org/10.3290/j.ijcd.b5951419

Seth-Johansen, C., & Gotfredsen, K. (2025). Validity and reliability of digital occlusal analyzing methods in Dentistry. A systematic review. In Journal of Dentistry (Vol. 163). Elsevier Ltd. https://doi.org/10.1016/j.jdent.2025.106124

Sharma, A., Rahul, G. R., Poduval, S. T., Shetty, K., Gupta, B., & Rajora, V. (2013). History of materials used for recording static and dynamic occlusal contact marks: A literature review. Journal of Clinical and Experimental Dentistry, 5(1). https://doi.org/10.4317/jced.50680

Shiga, H., Komino, M., Uesugi, H., Sano, M., Yokoyama, M., Nakajima, K., & Ishikawa, A. (2020). Comparison of two dental prescale systems used for the measurement of occlusal force. Odontology, 108(4), 676–680. https://doi.

org/10.1007/s10266-020-00509-9

Solaberrieta, E., Garmendia, A., Brizuela, A., Otegi, J. R., Pradies, G., & Szentpétery, A. (2016). Intraoral Digital Impressions for Virtual Occlusal Records: Section Quantity and Dimensions. BioMed Research International, 2016. https://doi.org/10.1155/2016/7173824

Stavness, I. K., Hannam, A. G., Tobias, D. L., & Zhang, X. (2016). Simulation of dental collisions and occlusal dynamics in the virtual environment. Journal of Oral Rehabilitation, 43(4), 269–278. https://doi.org/10.1111/joor.12374

Sutter, B. (2019). Digital Occlusion Analyzers: A Product Review of T-Scan 10 and Occlusense.

Sutter, B. A. (2018). A digital poll of dentists testing the accuracy of paper mark subjective interpretation *. Cranio - Journal of Craniomandibular Practice, 36(6), 396–403. https://doi.org/10.1080/08869634.2017.1362786

Suzuki T, Kumagai H, Watanabe T, Uchida T, Nagao M. Evaluation of complete denture occlusal contacts using pressure-sensitive sheets. Int J Prosthodont. 1997 Jul-Aug;10(4):386-91.

The Future of Occlusion Control. https://www.pantelides-dental.gr/userfiles/files/BauschEN.pdf

The Glossary of Prosthodontic Terms: Ninth Edition. (2017). The Journal of Prosthetic Dentistry, 117(5), e1–e105. https://doi.org/10.1016/j.prosdent.2016.12.001

van der Meer, W. J., Andriessen, F. S., Wismeijer, D., & Ren, Y. (2012). Application of intra-oral dental scanners in the digital workflow of implantology. PLoS ONE, 7(8). https://doi.org/10.1371/journal.pone.0043312

Vlăduțu, D. E., Ionescu, M., Noveri, L., Manolea, H. O., Scrieciu, M., Popescu, S. M., Turcu, A. A., Ştefârță, A., Lăzărescu, G., & Mercuț, V. (2023). Aspects of Dental Occlusion Assessed with the T-Scan System among a Group of Romanian Dental Students in a Cross-Sectional Study. International Journal of Environmental Research and Public Health, 20(6). https://doi.org/10.3390/ijerph20064877

Zhao, Z., Wang, Q., Li, J., Zhou, M., Tang, K., Chen, J., & Wang, F. (2023). Construction of a novel digital method for quantitative analysis of occlusal contact and force. BMC Oral Health, 23(1). https://doi.org/10.1186/s12903-023-02899-y