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Accuracy of Digital Workflows and Reference Strategies for Full-Arch Implant Prostheses in Completely Edentulous Patients: A Narrative Review

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Abstract

Completely edentulous patients undergoing full-arch implant-supported prosthetic rehabilitation present significant challenges in achieving accurate transfer of implant positions and prosthetic information, particularly when using a fully digital workflow. The absence of stable and reproducible anatomical landmarks makes complete-arch intraoral scanning and accurate superimposition of digital datasets difficult, potentially affecting the accuracy, fit, and overall clinical performance of the resulting prosthesis prototypes. These challenges may become more pronounced when multiple digital datasets are acquired and subsequently aligned, as registration errors can influence the spatial relationship between the implant positions and the prosthetic surfaces. Double digital scanning (DDS) has been introduced as a method for integrating implant position with the contours and occlusal characteristics of an interim prosthesis, thereby facilitating the transfer of relevant prosthetic information into the digital workflow. However, the accuracy of this technique depends substantially on the reference strategy used for digital alignment and superimposition. Different approaches, including anatomical references such as palatal rugae, artificial reference markers such as glass beads, and customized scan bodies, have been proposed to improve the reliability and accuracy of digital superimposition. The effectiveness of these reference strategies may vary according to their geometric characteristics, distribution, detectability, and susceptibility to scanning errors. Therefore, systematic evaluation of these reference strategies and the software used for digital alignment is essential to determine their influence on registration accuracy and to establish accurate, reproducible, and predictable digital workflows for the fabrication of prosthesis prototypes in completely edentulous patients.

Keywords: Prosthesis, Double digital scanning, digital workflows

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1. Introduction

Complete edentulism remains a major oral health problem worldwide and may result from dental caries, periodontal disease, trauma, and other oral conditions. Tooth loss can negatively affect mastication, nutrition, speech, facial appearance, and oral health-related quality of life [1]. Progressive resorption of the residual alveolar ridge further complicates prosthetic rehabilitation and may compromise denture support and stability [2-3]. Complete dentures have traditionally been used to rehabilitate completely edentulous patients; however, limitations in retention, stability, and masticatory function may affect patient satisfaction. Implant-supported prostheses provide an alternative treatment option by improving retention, stability, function, and patient comfort. Full-arch implant-supported fixed prostheses have therefore become an established treatment modality for completely edentulous patients [4]. For predictable long-term outcomes, accurate transfer of the three-dimensional implant positions to the definitive prosthesis is essential. Inaccurate prosthetic fit may result in mechanical complications such as screw loosening and fracture, as well as unfavorable stress distribution at the implant–prosthesis and implant–bone interfaces. Therefore, achieving an accurate and passive prosthetic fit is considered an important factor in successful full-arch implant rehabilitation [5-7].

Traditionally, implant positions are transferred using conventional impression techniques. Open- and closed-tray techniques have been widely used, with the accuracy of resulting master cast influenced by impression material, impression technique, implant angulation and distribution, impression coping splinting, and operator-related factors [4]. These multiple clinical and laboratory procedures may introduce cumulative errors during fabrication of definitive prosthesis. The development of computer-aided design and computer-aided manufacturing (CAD/CAM) has introduced digital alternatives to conventional implant impressions. Intraoral scanners can directly acquire three-dimensional information from the oral cavity and transfer the digital data to CAD software for prosthetic design and manufacturing. Digital workflows may simplify clinical and laboratory procedures and reduce some of potential sources of error associated with conventional impressions [4-8]. Despite these advantages, scanning completely edentulous arches remains challenging because of the absence of stable anatomical landmarks and the large surface area that must be captured. These limitations may increase stitching errors and affect the accuracy of full-arch implant scans, particularly when multiple implants are distributed across arch [9]. Double digital scanning (DDS) has been introduced to facilitate the transfer of prosthetic information in completely edentulous patients [10-12].

This technique involves a first scan of the interim prosthesis and a second scan of the implant positions using scan bodies. The two Standard Tessellation Language (STL) datasets are subsequently superimposed to generate a combined digital dataset for prosthetic design [10]. The accuracy of this procedure depends largely on the availability of reliable reference points for accurate STL alignment [12]. Different reference strategies have been proposed to overcome the lack of anatomical landmarks in edentulous arches, including palatal rugae, artificial fiducial markers, and customized scan bodies. However, limited evidence is available regarding the comparative accuracy and precision of these approaches. Furthermore, software used for digital superimposition may influence the resulting alignment and consequently the accuracy of fabricated prosthesis prototype [9-10-13]. Therefore, evaluation of different reference strategies and digital alignment protocols is essential for establishing accurate and predictable full-arch digital workflows. Accurate assessment of implant positional deviations and prosthesis fit may help identify reliable methods for fabrication of digitally produced prosthesis prototypes in completely edentulous patients.

2. Digital Workflow in Full-Arch Implant Rehabilitation

Digital technology has progressively transformed implant prosthodontics by integrating intraoral scanning, computer-aided design, and computer-aided manufacturing into a single workflow. A digital workflow generally involves three main stages: acquisition of three-dimensional anatomical data using a scanner, processing and designing the prosthesis using CAD software, and manufacturing the designed restoration using milling or three-dimensional printing technology [10-14-15]. In implant-supported rehabilitation, intraoral scanners record the three-dimensional position of scan bodies connected to the implants. The acquired information is converted into a digital file, commonly in Standard Tessellation Language (STL) format, which can subsequently be imported into CAD software for prosthetic planning and design as shown in Figure 1. This approach eliminates several conventional impression and cast-fabrication procedures and facilitates rapid digital communication between the dental clinic and laboratory [16]. Digital workflows may provide several advantages, including reduced clinical and laboratory procedures, improved data storage and transfer, easier communication, and the possibility of integrating prosthetic and surgical information. However, the accuracy of the final prosthesis depends on the accuracy of each individual step, as errors introduced during scanning, data alignment, CAD processing, or manufacturing may accumulate and influence the final prosthetic fit [17-18].

3. Accuracy of Digital Impressions

The accuracy of an implant impression is essential for transferring the three-dimensional relationship between implants to the definitive prosthesis. Digital impression accuracy is commonly described using the concepts of trueness and precision. Trueness refers to the agreement between the acquired digital dataset and a reference dataset, whereas precision describes the reproducibility of repeated scans under the same conditions [19-21]. Several studies have compared digital and conventional implant impressions. Although the results vary according to the scanning system, implant configuration, and evaluation method, current evidence indicates that digital impressions can achieve clinically acceptable accuracy for full-arch implant-supported restorations [22-23]. Recent systematic reviews have reported that digital impressions may provide comparable or, in some circumstances, superior accuracy to conventional techniques, although the advantages are not consistent across all clinical situations [23-24].

4. Challenges of Digital Scanning in Completely Edentulous Patients

Complete-arch digital scanning is more challenging in completely edentulous patients than in partially dentate patients because natural teeth are absent and therefore cannot provide stable anatomical landmarks for image stitching and dataset alignment. The scanner must acquire a relatively large surface area, and the lack of distinct reference points may increase cumulative stitching errors during scanning [8-25]. The accuracy of full-arch implant scanning may also be affected by implant number, implant distribution, implant angulation, scan-body geometry, scanning technology, and operator experience. As the scanning distance increases, small errors introduced during successive image acquisition may accumulate and result in greater discrepancies in the final digital representation of implant positions [26]. Another important challenge is the transfer of prosthetic information from an interim prosthesis to the implant digital impression. The clinician must accurately combine the implant positions with the contours and occlusal information of the interim prosthesis. Therefore, reliable reference points are required to accurately superimpose the different digital datasets [27].

5. Double Digital Scanning Technique

Double digital scanning (DDS) was introduced to facilitate the transfer of prosthetic information during full-arch implant rehabilitation. The technique involves obtaining two separate digital scans. The first scan records the contours of the interim prosthesis and the available reference structures, whereas the second scan records the three-dimensional positions of the implants using scan bodies. The two resulting STL datasets are subsequently superimposed to combine the implant and prosthetic information into a single digital model as shown in Figure 2. The DDS technique provides a completely digital approach for transferring the relationship between implant positions and the interim prosthesis. The resulting dataset can be used for CAD-based prosthetic design and subsequent fabrication of a prototype or definitive restoration. This approach may reduce the number of conventional clinical and laboratory procedures required for full-arch implant rehabilitation [8-10]. Several clinical and in-vitro studies have demonstrated the feasibility of DDS for completely edentulous patients. However, the accuracy of the technique depends largely on the reliability of STL superimposition. Since completely edentulous arches lack natural teeth that can serve as common reference structures, different anatomical and artificial reference strategies have been investigated to improve the accuracy of digital alignment [11-28-29]. A modified double-scan technique has also been described for completely edentulous patients to improve the accuracy of digital data integration during implant planning. In this approach, three complementary digital surfaces are matched: a cone beam computed tomography (CBCT) scan of the patient wearing a complete denture containing radiopaque reference markers, an intraoral scan of the same denture, and a digital representation of the intaglio surface obtained from the relined denture. The radiopaque markers facilitate the registration of the CBCT and prosthetic datasets, while the additional surface information allows the mucosal anatomy to be incorporated into the digital workflow. The three matched surfaces are subsequently used to design a mucosa-supported stereolithographic surgical guide. This approach demonstrates the potential of combining multiple digital datasets and reference markers to overcome the lack of stable anatomical landmarks in completely edentulous patients [30].

6. Reference Strategies for Digital Superimposition

Accurate superimposition of the two STL datasets is a critical step in the DDS workflow. The absence of natural teeth in completely edentulous patients limits the availability of stable reference points, making the selection of an appropriate reference strategy particularly important. Several approaches have therefore been proposed to facilitate reliable alignment of the digital datasets.

A) Reference Points

To apply this reference-point technique for intraoral scanning of fully edentulous arches, the mucosa was first gently dried to facilitate pigment adhesion. A specialized mucosal marker was then used to create thin, clearly visible purple reference marks at selected areas of the maxillary and mandibular arches, providing distinct tracking landmarks. The scanner was initially positioned over these reference points to establish reliable image acquisition, followed by controlled scanning sweeps across the arch to maintain continuous software tracking and minimize stitching errors, as shown in Figure 3. Rapone [31] reported that digital impressions of completely edentulous arches remain challenging due to the absence of stable landmarks and variable soft tissues. They evaluated a modified scanning approach incorporating standardized reference points (1-mm diameter at 5-mm intervals) and systematic soft-tissue management, compared with conventional scanning protocols using iTero Element 5D and Trios 5 scanners. The modified approach significantly improved accuracy, reduced scanning time by 37%, and showed excellent reproducibility (ICC = 0.92), suggesting potential for more efficient and accurate digital impressions in edentulous patients.

B) Palatal Rugae

The palatal rugae are anatomical structures located on the anterior portion of the hard palate and may provide identifiable reference areas during digital scanning. Their use has the advantage of relying on naturally occurring anatomical structures without requiring additional markers. However, the visibility and scanability of the palatal rugae may vary depending on scanner technology, scanning conditions, and the morphology of the palatal tissues. Loumprinis [32] found no significant differences among best-fit, tooth-based, restoration-based, and palatal rugae registration methods, supporting palatal rugae as a reliable reference region. However, registration accuracy depends on the size and quality of the selected area. The quality of the palatal region captured by an intraoral scanner may also influence its usefulness as a registration reference. Elawady [33] evaluated the influence of palatal vault morphology on the accuracy and scanning time of IOS in completely edentulous patients with moderate, deep, and flat palatal vaults. Although palatal morphology significantly affected scanning time, no significant differences were found in scan trueness or precision among the three vault configurations. The study suggested that the palatal region can provide a reproducible surface for digital acquisition, although its clinical usefulness as a registration reference depends on adequate capture of the palatal anatomy.

C) Artificial Fiducial Markers

Artificial fiducial markers provide discrete, high-contrast geometric features that can facilitate software-based registration compared with the relatively smooth edentulous mucosa, as shown in Figure 4. Different materials, including gutta-percha, flowable composite, metallic spheres, and glass beads, have been investigated as artificial landmarks. These markers may improve the reliability of STL superimposition by providing fixed landmarks that are easily identified by the scanning and alignment software. Kanjanasavitree [34] evaluated artificial landmarks and scanning patterns in complete-arch implant scans. Liquid dam landmarks combined with quadrant scanning achieved the highest trueness and precision, highlighting the influence of both artificial landmarks and scanning strategies on scanning accuracy. Da Ressurreição [35] investigated different fiducial marker types and imaging modalities for edentulous arch registration. Registration accuracy varied according to both marker type and imaging modality, emphasizing the importance of appropriate fiducial marker selection. Farah [36] evaluated spherical fiducial markers attached to implant analogs for digital scan alignment in an edentulous mandibular model. The system achieved approximately 85 µm alignment accuracy, supporting the feasibility of geometrically defined fiducial markers for digital registration.

D) Customized Scan Bodies

Customized scan bodies represent another approach in which geometry of scan body itself provides additional reference information during digital alignment. Their customized design may provide more clearly defined three-dimensional reference structure and potentially reduce errors associated with the superimposition of separate STL files as shown in Figure 5.

Figure 1: Digital workflow for implant-supported prosthetics using an intraoral scanner.

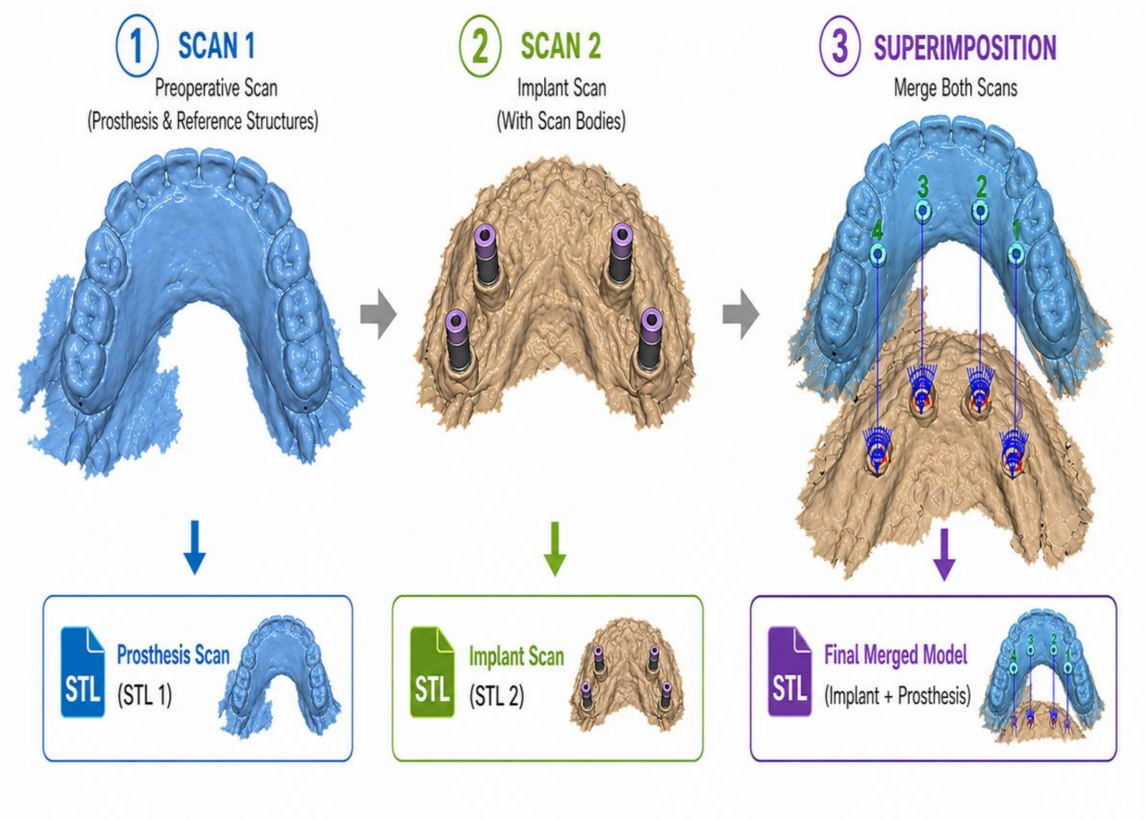

Figure 2: Double digital scanning (DDS) workflow for full-arch implant rehabilitation. The workflow involves two separate intraoral scans: (1) a preoperative scan recording the contours of the interim prosthesis and available reference structures; (2) a second scan with scan bodies in place to capture the three-dimensional implant positions and angulations; and (3) superimposition of the two STL datasets to integrate the prosthetic and implant information into a single digital model.

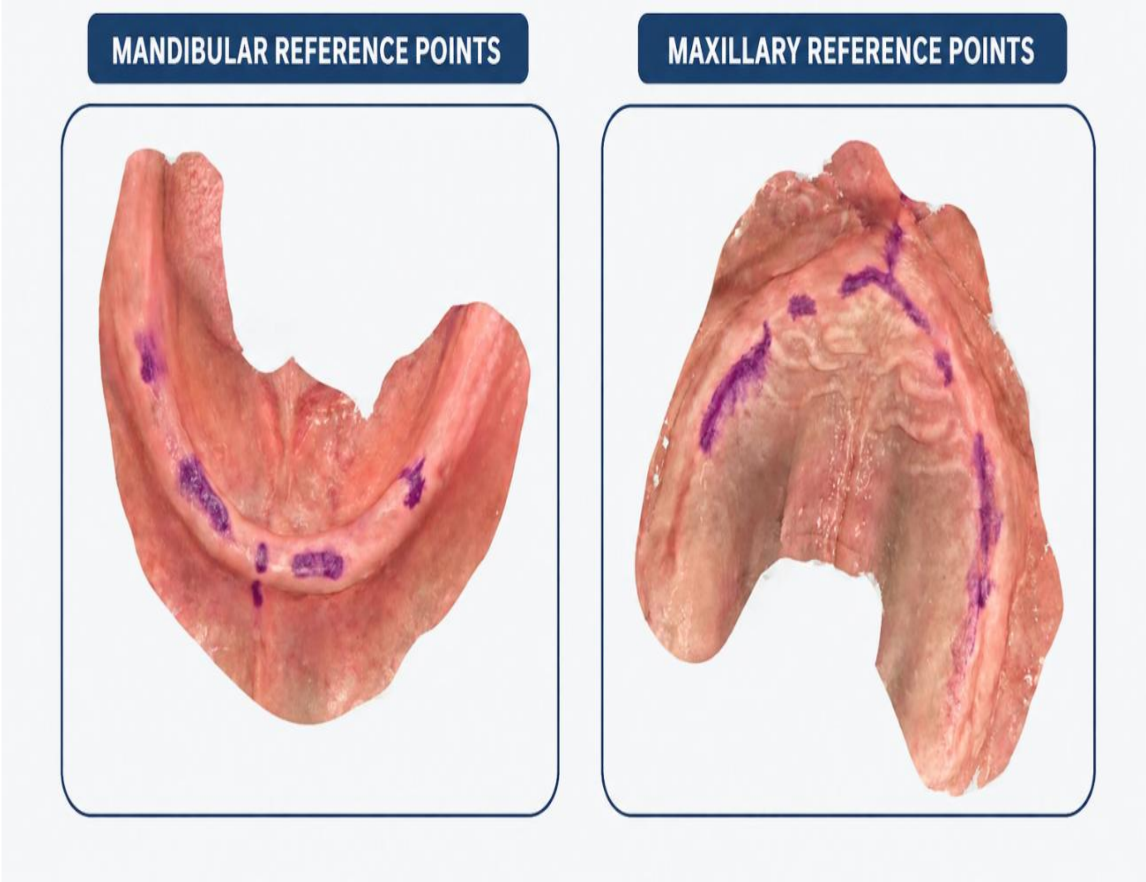

Figure 3: Reference-point technique

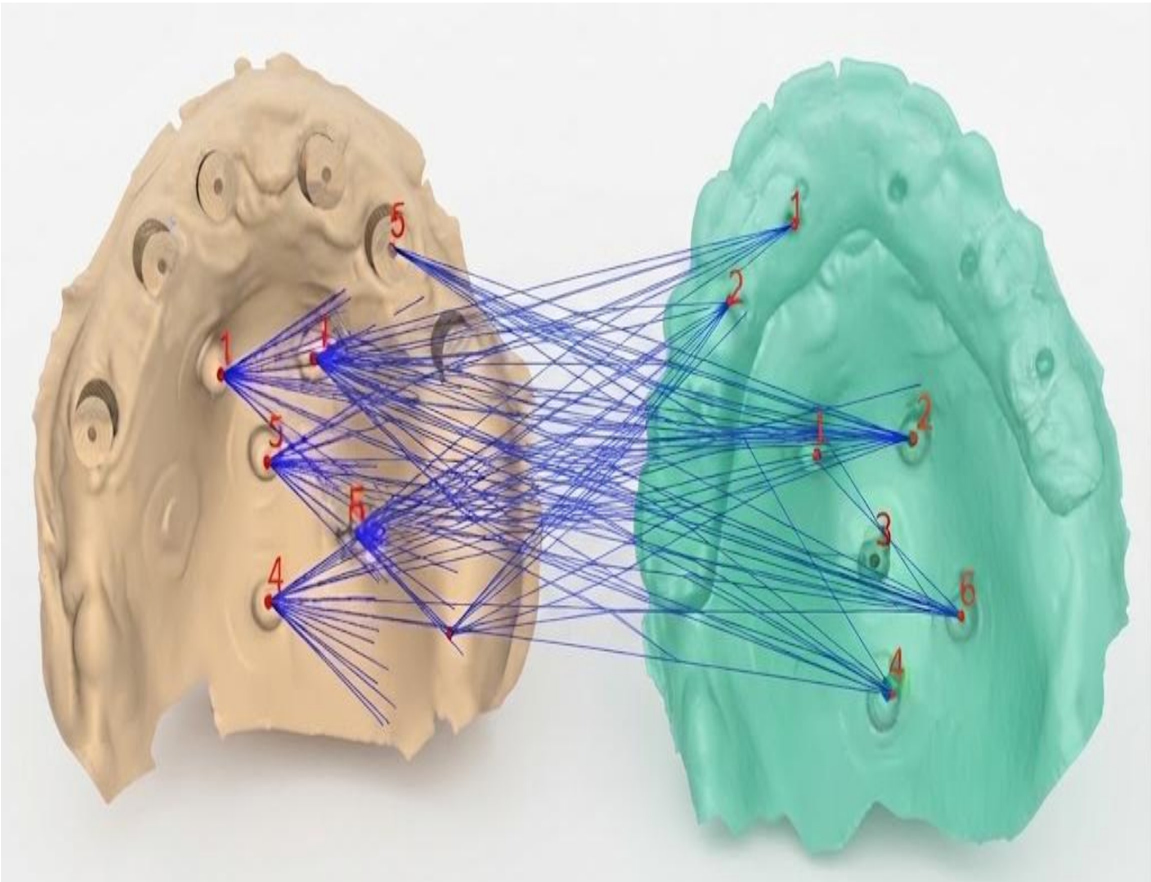

Figure 4: Artificial Fiducial Markers in scanning edentulous areas

Figure 5: Customized scan bodies

Huang [37] found that CAD/CAM scan body with an extended structure demonstrated significantly greater trueness and precision than the unmodified and non-extended designs. Similarly, Anwar [38] demonstrated that modified scan bodies together with a specially designed geometric device for maxillary complete-arch implant scanning facilitate scan registration in long edentulous arches by providing additional recognizable landmarks. Saaedi and Thabet [39] suggested that customized resin scan bodies with distinct geometries may improve landmark recognition and scanning continuity in maxillary full-arch implant scanning. However, Uzel [40] reported that excessive scan-body modification increased linear and angular deviations, indicating that modification does not necessarily improve scanning accuracy.

7. Accuracy Assessment of Digital Prosthesis Prototypes

Achieving an accurate and passive fit is a fundamental objective in fabrication of multi-unit implant-supported prostheses. A prosthesis that does not accurately adapt to the implant or abutment interfaces may generate internal stresses when the prosthetic screws are tightened, potentially contributing to mechanical complications and biological disturbances. However, passive fit has no universally accepted quantitative definition, and clinically acceptable degree of misfit remains debated. Importantly, prosthetic misfit should not be considered the result of a single clinical or laboratory procedure. Rather, it represents the cumulative effect of errors introduced throughout the prosthetic workflow, including implant-position recording, master-model or digital-model generation, CAD design, manufacturing, and final prosthesis assembly. Consequently, evaluating the fit of the completed prosthesis or prototype provides a clinically meaningful assessment of the accuracy achieved by the entire workflow [41-42]. The accuracy of digital full-arch implant workflows can be evaluated at both the digital and physical levels. Digital assessment is commonly performed by superimposing the test STL dataset onto a high-accuracy reference dataset using reverse-engineering software. The resulting deviations can be expressed as root mean square (RMS) values, linear deviations, angular deviations, and differences in inter-implant distances [43]. In addition to digital measurements, the accuracy of the fabricated prosthesis prototype can be evaluated by assessing its marginal discrepancy and passive fit. The one-screw or Sheffield test is commonly used to assess passive adaptation of implant-supported frameworks by tightening one terminal screw and evaluating the adaptation at the contralateral implant [44-45]. Microscopic and radiographic methods may also be used to quantify the discrepancy at the implant–prosthesis interface [46].

8. Clinical Considerations

- **Digital scanning**
  Accurate full-arch scanning requires an appropriate scanning protocol, suitable scanner, and standardized operator technique.
- **Reference strategy**
  Reliable anatomical or artificial reference points are essential for accurate STL superimposition in completely edentulous patients.
- **Scan-body design**
  Scan-body geometry may influence the accuracy of implant position transfer and should be considered

when selecting components for full-arch digital workflows.

- **Software alignment**
  The accuracy and reproducibility of the software used for STL superimposition should be considered during digital workflow planning.
- **Prototype fabrication**
  Printer type, material, printing parameters, and post-processing may influence the final dimensional accuracy and fit of the prosthesis prototype.
- **Accuracy assessment**
  Digital deviation measurements should ideally be combined with physical evaluation of marginal discrepancy and passive fit.

9. Conclusion

Digital workflows have become an increasingly important approach for the rehabilitation of completely edentulous patients with full-arch implant-supported prostheses. Intraoral scanning and CAD/CAM technology can simplify implant data acquisition and prosthetic fabrication; however, achieving accurate full-arch digital impressions remains challenging because of the large scanning area and the absence of stable anatomical landmarks in edentulous arches. Double digital scanning provides a promising approach for transferring both implant positions and prosthetic information, but its accuracy depends on reliable STL superimposition and appropriate reference strategies. Palatal rugae, artificial markers, and customized scan bodies may provide potential solutions for improving digital alignment. Therefore, further evaluation of these reference strategies and alignment software is essential to establish accurate, reproducible, and clinically predictable digital workflows for the fabrication of prosthesis prototypes in completely edentulous patients.

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