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Digital Innovations in Dentistry

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1

3D-PRINTED ZIRCONIA MATERIALS FOR FIXED PROSTHODONTICS

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INTRODUCTION

Advances in dental materials have improved restorative dentistry. Zirconia, a notable example, combines esthetics, durability, and biocompatibility. Its high strength, wear resistance, and biocompatibility are advantageous (Kelly, 2008). Digital workflows such as CAD/CAM enhance the application of zirconia, enabling precise fabrication of crowns, improving fit, and improving patient outcomes (Mosaddad et al., 2025).

In line with the development of digital dentistry, additive manufacturing (AM)—commonly known as three-dimensional (3D) printing—has become a transformative technology. Unlike subtractive milling (SM), which creates restorations by removing material from pre-sintered blocks, AM constructs restorations by depositing material layer by layer. While SM depends on reductive processes that restrict geometric complexity and produce substantial waste, AM uses constructive processes that allow for intricate geometries and reduce material loss. This contrast highlights the complementary strengths of both methods. SM delivers restorations with consistent accuracy, established protocols, and proven long-term clinical reliability. Conversely, AM offers greater design freedom, reproducibility, and sustainability, aligning with the wider move toward personalised and environmentally responsible dentistry. Together, these approaches represent two distinct yet converging paths in the advancement of restorative technologies. This technological shift has sparked considerable interest, though questions remain regarding whether printed zirconia can match the accuracy, fit, and durability of milled crowns (Revilla-León et al., 2020). Recent systematic reviews and meta-analyses have sought to answer these questions. Mosaddad et al. (2025) concluded that although printed crowns demonstrated greater precision, milled crowns outperformed in trueness and marginal fit, both of which are crucial for clinical longevity. Cai et al. (2025), in one of the first randomised controlled trials, confirmed that printed crowns were clinically acceptable, although they exhibited more minor defects than milled controls. These findings underscore both potential and limitations.

The distinctive properties of zirconia ceramic as a restorative dental material, together with rising patient demand for aesthetic and metal-free restorations, have attracted considerable attention in the dental profession. Zirconia restorations are widely used owing to their biocompatibility, chemical stability, exceptional mechanical properties, and favourable optical properties (Piconi, 1999). Full-contour zirconia restorations have become the preferred option for rehabilitating posterior dentition worldwide (Makhija, 2016). With improvements in translucency and advances in coloring procedures, monolithic zirconia restorations have been gaining popularity. Their mechanical advantages also include minimal tooth preparation and the elimination of the risk of veneer chipping in porcelain-fused-to-zirconia restorations (Pereira, 2018).

Therefore, the core research question is whether additive manufacturing of zirconia crowns can match the accuracy, fit, and clinical performance of subtractive manufacturing. Answering this necessitates examining zirconia's material properties, AM technology mechanics, and comparative laboratory and clinical findings.

1. Zirconia: Composition, Phases, and Microstructure

Zirconia (ZrO_2) exists in three crystallographic phases: monoclinic, tetragonal, and cubic. Pure zirconia is monoclinic at room temperature, transforming to tetragonal and cubic phases at higher temperatures. These transformations are accompanied by volume changes that can compromise structural integrity. To stabilize the tetragonal phase at room temperature, zirconia is doped with oxides such as yttria (Y_2O_3), resulting in yttria-stabilized tetragonal zirconia polycrystalline (Y-TZP) (Chevalier et al., 2009).

The most widely used dental zirconia is 3Y-TZP, containing approximately 3 mol% yttria. This composition balances mechanical strength with acceptable translucency, making it suitable for posterior crowns where load-bearing capacity is paramount (Denry & Kelly, 2014). More recent zirconia formulations, such as 4Y-PSZ and 5Y-PSZ, incorporate higher yttria concentrations, which increase the proportion of the cubic phase and thereby enhance translucency. This improvement in optical properties, however, is accompanied by a reduction in fracture toughness, reflecting the inherent trade-off between esthetics and mechanical resilience (Zhang & Lawn, 2018). Microstructural characteristics, including grain size and distribution, play a critical role in determining zirconia's performance. Fine-grained microstructures improve strength and resistance to low-temperature degradation (LTD), while larger grains enhance translucency but may reduce mechanical resilience. Oh et al. (2024) demonstrated that printed zirconia exhibited slightly larger grain size and porosity than milled blocks, which affected flexural strength. This suggests that the fabrication method directly influences microstructural outcomes.

In the context of manufacturing, milling typically produces restorations from pre-sintered zirconia blocks, followed by sintering to achieve final density and strength. Printing, by contrast, introduces additional variables, such as layer thickness, build angle, and post-processing protocols, that can influence microstructural homogeneity and phase distribution (Mosaddad et al., 2025). These differences underscore the importance of understanding zirconia's fundamental material science when evaluating the comparative outcomes of additive and subtractive manufacturing.

2. Entry of 3D Printing Technology into Dentistry

Charles W. Hull patented the first 3D printer in 1986, marking the beginning of 3D printing's rapid expansion as an industrial technology over the past four decades (Della Bona, 2021). AM technologies have recently gained traction in dentistry, offering new possibilities for zirconia crown fabrication. Stereolithography (SLA), digital light processing (DLP), inkjet printing, and lithography-based ceramic manufacturing (LCM) are among the most studied techniques. Each method differs in resolution, build-angle sensitivity, and post-processing requirements, influencing the accuracy and fit of the final restoration (Revilla-León et al., 2020).

AM utilizes diverse materials like composites, polymers, metal alloys, and ceramics (Peng, 2018; Kihara, 2021). 3D printing is gaining prominence for customized dental restorations (Kirsch, 2017). However, 3D-printed zirconia for dental applications remains relatively nascent, with ongoing research comparing its performance to CAD/CAM counterparts. Evaluating its potential for widespread use in dentistry and clinical applications is crucial. Despite increasing research on AM dental zirconia, a comprehensive assessment is still needed.

The advantages of AM include reduced material waste, the ability to fabricate complex geometries, and enhanced reproducibility. However, limitations such as dimensional inaccuracies, shrinkage during sintering, and variability in post-processing remain significant challenges. Nezir et al. (2025) reported that printed crowns exhibited clinically acceptable adaptation but greater variability in marginal fit compared to milled crowns. This variability is often attributed to differences in printer technology and parameter settings.

Recent systematic reviews have highlighted these issues. Mosaddad et al. (2025) found that printed crowns demonstrated higher precision but lower trueness compared to milled crowns. Cai et al. (2025) confirmed these findings in a clinical trial, noting that while printed crowns survived one year without catastrophic fracture, minor defects were more frequent. These results suggest that while printing is reproducible, it may not yet achieve the dimensional fidelity of milling.

Therefore, the adoption of 3D printing in dentistry presents both opportunities and challenges. While the technology offers sustainability and design freedom, its clinical adoption will depend on overcoming current limitations in accuracy and fit. Continued research into printer technologies, parameter optimization, and post-processing protocols is essential to realize the full potential of additive manufacturing in zirconia crown fabrication.

3. Mechanical Properties of 3D-Printed Zirconia

The microstructure of a material influences its physical and chemical properties. In zirconia, toughness is closely linked to microscopic phase composition. Additively manufactured (AM) zirconia, similar to milled zirconia, is composed predominantly of the tetragonal phase with evenly distributed particles approximately 0.6 μm in size. Digital light processing (DLP) zirconia exhibits no significant differences in grain size or crystalline phase structure compared to milled zirconia (Lu, 2020).

Yttrium oxide stabilizes the high-temperature tetragonal phase of Y-TZP zirconia at room temperature. The tetragonal phase (t) provides high strength, and stress can induce transformation to the monoclinic phase (m), resulting in a 3–5% volume expansion known as transformation toughening. However, in humid environments, the tetragonal phase can spontaneously transform to the monoclinic phase, leading to intergranular microcracking—a phenomenon referred to as aging, hydrothermal degradation, or low-temperature degradation (LTD)—which compromises mechanical properties (Zhai, 2021). While LTD does not significantly affect surface roughness, it alters the material's polarity and surface energy, potentially impacting biocompatibility (Pandoleon, 2019; Yang, 2021). Recent studies indicate that aged DLP zirconia exhibits a higher monoclinic phase content than subtractively milled (SM) zirconia, potentially due to compositional differences prior to aging. Furthermore, zirconia produced via SLA demonstrates a significantly faster tetragonal-to-monoclinic transformation rate compared to conventionally manufactured SM zirconia (Zhai, 2021).

Surface roughness of dental zirconia is critical for clinical success. Rough surfaces promote plaque accumulation, potentially leading to secondary caries and periodontitis (Hao, 2018). A roughness value below 0.58 μm is generally considered acceptable (Zhang, 2015). However, 3D-printed zirconia often exhibits roughness exceeding this threshold (up to 0.71 μm; Xiang, 2021), likely due to the inherent stepping effect of the printing process. Micro pores ranging from 196 nm to 3.3 μm (Branco, 2020), common in additively manufactured zirconia, can compromise mechanical properties, esthetics, and surface quality. Pore formation is typically attributed to weak interlayer bonding and uneven slurry distribution, while thicker slurries promote agglomerate formation (Harrer, 2017).

Mechanical performance remains the cornerstone of clinical success for zirconia crowns. CAD/CAM-milled zirconia consistently demonstrates flexural strengths exceeding 900 MPa, with fracture toughness values sufficient to resist occlusal loading in both anterior and posterior regions (Denry & Kelly, 2014). The dense, uniform microstructure of milled zirconia blocks contributes to this reliability, minimizing porosity and internal defects. In contrast, printed zirconia often exhibits lower flexural strength, typically ranging between 600–800 MPa depending on printing technology and post-processing protocols (Oh et al., 2024).

Experimental evaluations of 3D-printed zirconia have reported Vickers hardness values reaching 13.4 ± 0.2 GPa. This metric, indicative of material strength and toughness, was found to be load-dependent, as evidenced by proportional specimen resistance in apparent and true hardness measurements. Both apparent and true hardness values of 3D-printed zirconia were lower than those of milled zirconia. Moreover, Vickers hardness was strongly influenced by pore size and porosity, as observed in experimental studies (Mei, 2021).

Recent comparative investigations highlight these differences. Cai et al. (2025), in a randomized controlled trial, reported that nanoparticle jetting-printed crowns survived one year of clinical service without catastrophic fracture, though minor chipping was more frequent compared to milled controls. SLA-based additive manufacturing of zirconia crowns has been widely investigated as an alternative to conventional CAD/CAM milling. Hassan et al. (2025) reported that SLA-printed zirconia crowns exhibited significantly lower fracture resistance compared to milled crowns, attributing this to increased surface roughness and microstructural heterogeneity. Similarly, Refaie A. et al. (2023) demonstrated that under cyclic loading, milled crowns consistently outperformed printed ones, emphasizing the role of porosity and anisotropic structures in reducing mechanical strength. In contrast, Alharbi et al. (2016) found that although SLA-printed zirconia showed inferior fracture resistance, the values remained within clinically acceptable thresholds, suggesting potential for clinical application with optimized post-processing. Revilla-León et al. (2020) further highlighted that additive manufacturing introduces unique defects such as layer delamination, which compromise fracture resistance compared to the dense, homogeneous microstructure of milled zirconia. Collectively, these studies indicate that while SLA-based 3D printing of zirconia crowns offers efficiency and sustainability benefits, conventional milling remains superior in terms of fracture resistance and long-term reliability. Nevertheless, the consistent observation that SLA crowns fall within acceptable clinical ranges suggests that ongoing improvements in printing parameters, sintering protocols, and surface finishing could narrow the mechanical gap between the two fabrication methods.

Manufacturing parameters exert a critical influence on mechanical outcomes. Layer thickness, build orientation, and sintering shrinkage directly affect performance. Nezir et al. (2025) demonstrated that reducing layer thickness improved flexural strength in printed crowns, though variability remained higher than in milled restorations. Milling, by contrast, benefits from standardized industrial protocols that ensure consistent mechanical properties across restorations.

Most studies report no significant difference in fracture toughness between 3D-printed and CAD/CAM zirconia (Marsico, 2020), although some indicate lower fracture toughness for 3D-printed zirconia (Harrer, 2017). Alumina-toughened zirconia exhibits higher fracture toughness than zirconia alone (Wu, 2019). Aging studies on 3D-printed zirconia (SLA and DLP) show increased monoclinic phase content with aging time, but no significant decrease in mechanical properties, suggesting material stability (Zhai, 2021). Chewing simulations with cyclic temperature fluctuations revealed no discernible difference in bending moment after fatigue, indicating long-term durability of AM implants. Mechanical fatigue in water at 90°C resulted in significantly larger fracture stress and bending moment. Combined mechanical wear and aging in a chewing simulator with water at 90°C caused a tetragonal-to-monoclinic phase transformation in %31 volume of t-ZrO_2 at the surface (Zhang, 2022).

Therefore, although printed zirconia crowns can achieve clinically acceptable mechanical performance, milling remains superior in strength and toughness. Future research should focus on optimizing printing parameters and post-processing techniques to close this gap, particularly for posterior crowns where load-bearing demands are greatest. Solid loading, printing parameters, debinding, and sintering processes significantly affect final product performance. Higher solid loading generally improves mechanical properties. Studies show that build orientation impacts indentation fracture resistance, with a 45° inclination of layer lines to the indentation direction yielding enhanced performance (Marsico, 2020). Inadequate temperature control during sintering can result in high product porosity (Branco, 2020). A study comparing the biaxial flexural strength of milled and 3D-printed 3Y-TZP and 4Y-TZP zirconia demonstrated that 3D-printed 4Y-TZP had significantly higher strength than milled 4Y-TZP, exceeding the 800 MPa ISO 6872 threshold. While 3D-printed 3Y-TZP exhibited lower strength than milled 3Y-TZP, it remained clinically adequate. X-ray diffraction confirmed a predominantly tetragonal phase in all groups. Weibull analysis indicated greater reliability in milled 3Y-TZP and reduced variability in 3D-printed 4Y-TZP. These findings suggest that 3D printing of 4Y-TZP offers both sufficient mechanical performance and improved translucency, making it a promising alternative to milling for zirconia restorations (Kyung, 2024).

4. Optical Properties of 3D-Printed Zirconia

Esthetics are a decisive factor in restorative dentistry, particularly for anterior crowns. Milled zirconia blocks, especially those with higher yttria content (4Y-TZP,5Y-TZP), provide controlled translucency and shade stability, enabling predictable esthetic outcomes (Zhang & Lawn, 2018). In contrast, printed zirconia often suffers from light scattering due to layer interfaces and surface roughness, reducing translucency and compromising shade matching (Nezir et al., 2025).

Clinical evaluations have shown that 3D-printed crowns exhibit acceptable esthetics but lower translucency compared to milled controls, particularly under natural light conditions. Cai et al. (2025) reported that patients rated the esthetics of printed crowns as satisfactory, although clinicians noted subtle differences in shade uniformity. These findings suggest that while printed crowns are esthetically acceptable, milling remains superior for demanding anterior cases.

Minimizing layer visibility is crucial for esthetic success in 3D-printed dental applications. Studies demonstrate varying results depending on the printing technique. SLA printing yields a smooth, slightly depressed layer texture (Revilla-León & Husain, 2022), whereas robocasting produces a "stair-stepped" surface with drying-related cracks (Silva, 2011). MJ printing results in a smooth surface without stair steps (Özkol, 2012), while DLP printing followed by sintering eliminates the interlayered structure in dental crowns (Kim, 2020; Li, 2020).

Applying glass veneers, a common practice for esthetic enhancement, typically conceals the layered structure, reducing its clinical significance. Nevertheless, the choice of printing technology significantly impacts the final esthetic outcome and the extent of required post-processing. SLA can produce relatively smooth surfaces; though subtle layer depressions may remain perceptible in areas with complex geometries or shallow angles. Robocasting, with its pronounced stair-stepping and cracking issues, often necessitates extensive post-processing such as polishing or coating. MJ printing appears to offer the most advantageous surface finish directly from the printer, potentially reducing the need for manual intervention. The DLP-sintering approach, while promising for complete layer elimination, may involve a more complex and costly workflow.

The reliance on glass veneers as a masking strategy underscores the inherent limitations of certain 3D printing techniques in achieving a truly homogeneous surface and highlights the continued importance of traditional esthetic restorative methods in conjunction with additive manufacturing. Further research is required to fully characterize the long-term esthetic stability of these approaches, particularly with respect to staining, wear, and potential layer delamination.

Advances in printing technology are narrowing the gap. NPJ printing has demonstrated improved optical homogeneity by reducing layer interfaces, resulting in translucency values closer to milled zirconia (Oh et al., 2024).

However, variability in printer settings and post-processing protocols continues to affect outcomes. Milling, by contrast, benefits from standardized block compositions and established finishing techniques, ensuring consistent esthetic performance.

Thus, while printed zirconia crowns can achieve satisfactory esthetics, milling remains the preferred method for anterior restorations where translucency and shade stability are critical. Continued innovation in printing technologies is required to achieve parity with milling in optical properties.

5. Additive Manufacturing Parameters, Sintering, and Post-Processing

The accuracy of printed zirconia crowns is highly dependent on manufacturing parameters. Layer thickness, build angle, and support material influence dimensional fidelity, while post-processing steps such as debinding and sintering introduce shrinkage and microstructural changes (Mosaddad et al., 2025). SLA printing at 25 µm has been shown to achieve better dimensional accuracy than DLP at 50 µm, though variability remains higher than in milled crowns (Nezir et al., 2025).

Layer thickness strongly influences product performance and quality. Z-direction resolution, which exhibits the greatest variability, is affected by photoinitiator quantity, particle characteristics, and exposure parameters (wavelength, laser power, beam size, speed, and exposure time) (Stansbury, 2016; Revilla, 2022). Smaller layer heights promote complete polymerization, reducing porosity and delamination. While layer line defects can cause failures in DLP-printed zirconia, their impact diminishes under favorable loading directions. Further research is needed to optimize algorithms for calculating the ideal build angle prior to printing (Marsico, 2020; Kim, 2022).

Oh et al. (2024) demonstrated that reducing layer thickness improved accuracy but increased printing time, highlighting trade-offs between efficiency and fidelity. Cai et al. (2025) emphasized the need for standardized post-processing protocols to minimize shrinkage and dimensional variability. Advances in printer technology, such as NPJ and hybrid systems, may further enhance outcomes.

Recent studies underscore the importance of parameter optimization. Oh et al. (2024) reported that reducing layer thickness improved trueness but increased printing time, while Cai et al. (2025) found that build angle significantly affected marginal fit, with vertical orientations producing greater discrepancies. These findings highlight the complexity of parameter selection in additive manufacturing.

SLA and DLP are recommended for fabricating dense ceramics. Horizontal printing yields superior dimensional accuracy and fracture toughness compared to vertical printing. However, vertical printing results in higher relative density, improved semi-transparency, wettability, and flexural strength. Printing direction also affects surface roughness, and optimal zirconia powder proportions vary depending on orientation (Nakai, 2021). Exposure energy and layer thickness significantly impact product performance and quality. Factors such as photoinitiator quantity, particle size and shape, and exposure parameters (wavelength, laser power, beam size, speed, and exposure time) influence Z-direction resolution, where the greatest variation occurs. Small layer heights promote full polymerization, minimizing porosity and delamination at layer boundaries. Layer line defects in DLP-printed zirconia can lead to failure, though this effect diminishes under favorable loading conditions (Miura, 2022; Hada, 2022).

Efforts have also focused on improving control of the debinding and sintering processes, which are essential for reducing product defects. After curing, debinding removes dispersants, solvents, and the polymer network from the green body. The ceramic microparticles are then densified at high temperature by surface energy to form a dense component. Compared with conventional CAD/CAM products, 3D-printed parts require more complex post-processing. Sintering influences porosity, surface roughness, and asynchronous densification (Li, 2021). Accordingly, many studies have optimized debinding and sintering, including two-stage sintering and slow temperature-gradient sintering (Osman, 2017). Secondary shaping can be enhanced using high-temperature porous polymer molds to precisely control geometry, while cold isostatic pressing reduces interlayer defects (Zhang, 2019). Post-print annealing also improves mechanical performance; annealed composites show higher heat resistance and compressive strength than unannealed ones. Grain size increases with sintering temperature, and the optimal sintering temperature varies depending on zirconia translucency (Too, 2021).

Post-processing introduces additional challenges in additive manufacturing (AM). Shrinkage during sintering can exceed 20%, complicating dimensional accuracy. Inconsistent debinding protocols further contribute to variability in fit, whereas standardized sintering procedures have been shown to improve outcomes. Milling avoids these variables by relying on established sintering protocols that ensure consistent accuracy and fit.

Dimensional shrinkage in AM not only affects component dimensions but can also induce cracking, thereby degrading mechanical performance. Minimizing shrinkage is therefore crucial for producing high-quality AM restorations. Strategies to mitigate shrinkage include increasing ceramic particle content while maintaining acceptable rheology, incorporating expanding particles to offset sintering shrinkage, and lowering sintering temperature provided that sufficient density and structural integrity are retained (Galante, 2019). Lowering sintering temperature has been reported to reduce shrinkage. Valenti (2024), however, found similar discrepancies between AM and SM restorations, though the study grouped all prosthetic materials together. Larger discrepancies in 3D-printed restorations may stem from accumulated errors during fabrication (Revilla, 2020; Refaie, 2023).

In AM, loosely stacked zirconia particles undergo debinding and sintering post-printing, resulting in volume reduction, shrinkage, and distortion (Meng, 2022). Consequently, AM's additional heat treatment phases lead to greater thermal shrinkage compared to SM. In SLA, metal particle settling within suspension layers can exacerbate shrinkage, reduce sintering efficiency, and compromise marginal fit (Xiang, 2021). Furthermore, the larger discrepancy observed at chamfer finish lines in AM may be attributed to the curved axiogingival line angle, which increases the risk of stair-stepping errors during layer printing.

By contrast, SM employs bur-cutting orientations to create milling lines on interparallel planes, which can be adjusted by the number of machine axes, bur tip geometry, and milling line width (Tapie, 2015). Post-polymerization in AM can increase shrinkage, which cannot be corrected by adding layers. Printing supports also compromise cusp replication accuracy in 3D printing. AM accuracy is further influenced by polymerization beam width and layer thickness; narrower beams and thinner layers yield higher accuracy (Choi, 2019).

Therefore, while additive manufacturing offers flexibility and sustainability, its dimensional accuracy remains highly dependent on parameter optimization and post-processing protocols. Milling continues to demonstrate superior fidelity, but advances in printing technology and the development of standardized workflows may eventually bridge this gap.

6. Surface Treatments, Aging, and Low-Temperature Degradation (LTD)

Surface integrity plays a decisive role in the long-term success of zirconia crowns. Both printed and milled zirconia are susceptible to low-temperature degradation (LTD), a phenomenon involving the gradual transformation of tetragonal grains into monoclinic under humid oral conditions. This transformation is accompanied by microcracking, surface roughening, and eventual loss of mechanical strength (Chevalier et al., 2009). Milled zirconia, with its refined microstructure and reduced porosity, demonstrates greater resistance to LTD compared to printed zirconia, which often exhibits microstructural heterogeneity due to layer interfaces (Oh et al., 2024).

Recent studies have highlighted differences in surface roughness between the two fabrication methods. Nezir et al. (2025) reported that printed zirconia crowns exhibited higher baseline roughness compared to milled crowns, increasing the risk of antagonist enamel wear. However, polishing and glazing significantly reduced this discrepancy, suggesting that surface finishing protocols can mitigate the limitations of printed zirconia.

Aging studies further underscore these differences. Cai et al. (2025) observed that printed crowns subjected to accelerated aging tests exhibited greater monoclinic phase transformation compared to milled crowns, resulting in reduced flexural strength. Conversely, milled restorations maintained more stable phase distribution, preserving mechanical resilience under aging conditions. These findings suggest that while both methods are clinically viable, milling offers superior long-term stability.

SLA is favored for dental applications due to its superior accuracy, resolution, and surface finish (Della Bona et. al., 2021). Several studies have investigated the physical and mechanical properties of additively manufactured zirconia relevant to dentistry. Revilla-León et al. (2021) reported that SLA-printed zirconia bars exhibited lower flexural strength compared to milled zirconia. Simulated mastication aging further reduced flexural strength and fracture resistance in both AM and milled zirconia groups, though the AM group demonstrated a more pronounced degradation.

Other research has explored the impact of printing parameters and post-processing techniques on the mechanical strength of SLA-printed zirconia. Optimized laser power and scanning speed during printing, combined with appropriate sintering protocols, have been shown to improve density and reduce porosity, thereby enhancing mechanical performance (Revilla-León, 2021). The long-term clinical performance of SLA-printed zirconia restorations remains under investigation, with studies focusing on resistance to wear, chipping, and fracture in vivo. Revilla-León and Husain (2021) found that artificial aging (8000 cycles, 5–55 °C) decreased flexural strength by 12% in SLA-produced 3Y-TZP and by 37% in SM-produced samples. Zhai et al. (2021) aged SLA, DLP, and SM zirconia samples (134 °C, 0.2 MPa, 5–15 h). Aging up to 15 h affected only SLA samples, initially increasing flexural strength from 776.7 MPa to 1010.3 MPa after 5 h, then decreasing to 913.1 MPa and 814.3 MPa at 10 h and 15 h, respectively. DLP and SM samples maintained flexural strengths around 800 MPa and above 1200 MPa, respectively, before and after aging. DLP samples exhibited zirconia grain fragmentation, while SLA samples showed grain pullout; monoclinic phase content increased with aging time in both. Wu et al. (2019) hydrothermally treated DLP-produced alumina-toughened zirconia (ATZ) implants (134 °C, steam, 5–40 h) and observed a lower aging rate and reduced tetragonal-to-monoclinic phase transformation compared to 3Y-TZP.

Therefore, surface treatments are essential for both printed and milled zirconia crowns, but particularly critical for printed restorations. Optimized polishing, glazing, and sintering protocols can enhance the durability of printed crowns, reducing LTD susceptibility and improving clinical longevity. Milling remains superior in baseline resistance, but advances in additive manufacturing may progressively narrow this gap.

7. Marginal Fit of 3D-Printed Zirconia

Marginal adaptation is one of the most critical determinants of restoration survival. Poor marginal fit can lead to cement dissolution, microleakage, secondary caries, and periodontal inflammation, ultimately compromising the longevity of crowns (Mosaddad et al., 2025). CAD/CAM-milled zirconia crowns consistently demonstrate superior marginal accuracy, with mean gaps reported between 60–80 μm, values well within clinically acceptable thresholds. In contrast, 3D-printed zirconia crowns often exhibit larger marginal discrepancies, averaging 90–120 μm, although they remain within acceptable ranges. This difference underscores the reliability of milling in producing restorations with precise margins.

Zirconia's inertness complicates durable resin–ceramic adhesion, impacting restoration outcomes. Dimple formation at interfaces, attributed to stress-induced ceramic cracking, has been hypothesized to represent strong bonding and superior adhesion in 3D-printed zirconia (Moon, 2022). However, Schwickerath adhesion tests on DLP zirconia copings demonstrated similar adhesive performance between printed and CAD/CAM zirconia (Lu, 2020). This suggests that dimple formation, while indicative of interfacial stress concentration and potential micro-mechanical interlocking, may not be the sole determinant of long-term adhesive success.

Accuracy is crucial for evaluating additive manufacturing (AM) performance, particularly in dental applications where further enhancement is needed. ISO defines accuracy as the agreement between a measured and true value, encompassing trueness (deviation from the true value) and precision (consistency of repeated measurements) (Braian, 2016). Improved fabrication precision leads to better prosthetic fit, minimizing clinical adjustments, reducing operative damage, and improving product quality. Inaccurate restorations, for example, can cause plaque accumulation, gingival inflammation, and microleakage (Chopra, 2022).

To assess the trueness of 3D-printed crowns, researchers analyze inner and outer surfaces, focusing on intaglio surface characteristics and cement space volume and thickness. Crowns are typically divided into marginal, axial, and occlusal areas. Using visible-light scanning and micro-CT, 3D data are compared against the original CAD design to evaluate cement space volume, surface characteristics, manufacturing flaws, and crown–preparation adaptation.

Intaglio marginal-area accuracy may distinguish 3D printing from milling. Milled and 3D-printed crowns have shown opposing results for intaglio occlusal surface, intaglio surface, and marginal area accuracy, with 3D printing exhibiting superior external surface accuracy, although these differences were not statistically significant (Wang 2019, Abualsaud 2022, Moon 2022). Other studies reported contrasting findings: the accuracy of AM monolithic crowns was lower than that of SM crowns, but only in the marginal areas.

The split zirconia crown, a two-piece design intended to better mimic the structure of enamel and dentin, has been evaluated for accuracy. Both the trueness of CAD/CAM crowns and AM split zirconia crowns were found to be clinically acceptable. Understanding fabrication precision, systematic and random errors, and limitations affecting restoration outcomes is essential. Printing technique and parameters also influence accuracy; reduced layer height can improve accuracy (Li, 2019), possibly due to the surface stepping phenomenon inherent to AM (Kim, 2022).

Similar findings were observed in a four-unit bridge study, where DLP demonstrated lower accuracy than SLA (Lüchtenborg, 2022). Porosity also impacts accuracy and should be controlled through optimized sintering (Revilla, 2022). Specialized processes, such as the use of designed porous polymer molds, allow for accurate shaping of flexible 3D-printed products to specific curvatures. Shrinkage prediction models and methods can further improve dimensional control (Zhang, 2019). Finally, tooth type and construction angle have been shown to affect product accuracy.

8. Cementation of 3D-Printed Zirconia

Cementation protocols for 3D-printed zirconia require a surface-specific strategy that reconciles the material's polycrystalline, glass-free microstructure with manufacturing-induced surface features, prioritizing micromechanical and chemical coupling over silica-based approaches. Because zirconia lacks a silica phase, hydrofluoric acid etching and silanization are ineffective. Instead, controlled alumina airborne-particle abrasion (≈50 µm, 1–2 bar, 10–15 s, ~10 mm) followed by an MDP-containing primer or universal adhesive yields durable adhesion. The 10-methacryloyloxydecyl dihydrogen phosphate (MDP) monomer chelates zirconium oxide while copolymerizing via its methacrylate group, forming a hydrolysis-resistant interphase that maintains bond strength after aging (Inokoshi, 2014; Kern, 2015; Zhang, 2018).

For additively manufactured zirconia, careful post-sinter finishing, management of sintering shrinkage, and elimination of residual defects are essential. A standardized sequence—finish/polish, controlled air-abrasion, ultrasonic decontamination to remove embedded particles, MDP priming, and selection of self-adhesive or conventional resin cements with MDP when retention allows, or a full adhesive protocol with dual-cure resin cement for short or compromised abutments—optimizes retention and marginal integrity (Inokoshi, 2014; Özcan, 2015). Salivary contamination should be removed by phospholipid removal (e.g., a sodium hypochlorite rinse or dedicated zirconia-cleaning pastes) before re-priming to restore surface energy and re-establish chemical coupling. Tribochemical silica coating may further enhance micromechanical retention, though MDP chemistry remains indispensable for bonding to the oxide lattice, including in high-strength, high-translucency 3Y-TZP and 4Y-PSZ variants produced via 3D printing (Matinlinna, 2018; Özcan, 2015).

Clinical studies have begun to confirm these laboratory findings. Cai et al. (2025), in a randomised controlled trial, observed that both printed and milled crowns maintained acceptable marginal integrity after one year of service. However, printed crowns showed marginally higher rates of cement line discolouration, indicating increased microleakage risk. Nezir et al. (2025) also reported greater variability in marginal fit among printed crowns, attributing discrepancies to build angle and layer thickness. Milling, by contrast, produced consistently accurate margins across different cases, reinforcing its clinical reliability. Intaglio fit, which influences retention and stability, has shown no significant difference between printed and milled crowns. Both fabrication methods achieved clinically acceptable internal adaptation, ensuring adequate seating and cementation. While marginal fit favored milling, intaglio fit was comparable, suggesting that printing can achieve reliable internal adaptation when parameters are optimized. This finding is particularly relevant for clinical cementation protocols, as internal adaptation directly affects crown retention and resistance to dislodgement.

Precision and reproducibility further differentiate the two methods. Printed crowns often demonstrate higher precision, meaning repeated fabrications yield consistent results. However, trueness—the degree to which the restoration matches the intended CAD design—remains superior in milled crowns. This distinction highlights the trade-off between reproducibility and dimensional fidelity. Clinically, milling continues to provide restorations with more accurate margins, while printing offers sustainability and reproducibility but requires further refinement to ensure long-term marginal integrity.

9. Clinical Evidence and Failure Modes: Printed vs. CAD/CAM

Clinical evidence remains the ultimate benchmark for restorative technologies. CAD/CAM-milled zirconia crowns have been extensively studied, with survival rates exceeding 95% over five years (Denry & Kelly, 2014). Failures typically involve marginal discrepancies, secondary caries, or occlusal overload. Printed zirconia crowns, by contrast, have limited clinical data, with most evidence derived from in vitro studies (Mosaddad et al., 2025).

Recent randomized controlled trials provide encouraging results. Cai et al. (2025) reported that nanoparticle jetting (NPJ)-printed crowns survived one year of service without catastrophic fracture, though minor chipping was more frequent compared to milled controls. Nezir et al. (2025) observed similar findings, noting that printed crowns exhibited acceptable survival but greater variability in marginal integrity. These outcomes suggest clinical viability but highlight differences in failure modes. While clinically acceptable, 3D-printed crowns show distinct failure patterns, such as surface defects, compared to milled crowns, which have well-established long-term success (Cai et al., 2025). This necessitates specific protocols and further investigation.

Failure mechanisms differ between the two methods. Milled crowns typically fail due to bulk fracture or marginal leakage, whereas printed crowns more often exhibit surface defects, microcracks, or chipping. Research emphasizes that these differences reflect underlying microstructural variability introduced during printing. Understanding these distinct failure modes is essential for tailoring clinical protocols (Hassan, 2025). Thus, while printed zirconia crowns are clinically acceptable, milling remains superior in long-term predictability. Continued trials with larger sample sizes and extended follow-up are needed to confirm equivalence and guide clinical adoption of additive manufacturing.

10. Conclusions and Future Directions

The comparative evidence highlights both the promise and current limitations of additive manufacturing (AM) in zirconia crown fabrication. While AM zirconia demonstrates comparable phase composition to subtractive manufacturing (SM) counterparts and clinically acceptable accuracy, its mechanical properties and marginal fit remain slightly inferior. Nevertheless, AM offers unique advantages in precision, reproducibility, sustainability, and design flexibility, enabling complex geometries and reducing material waste.

Despite these advances, AM zirconia lags behind the maturity of metal and polymer printing. Key challenges include optimizing raw materials, refining printing parameters, and improving mechanical reliability and dimensional fidelity. Porosity, interlayer defects, and shrinkage during sintering continue to hinder performance compared to the dense, homogeneous microstructure achieved by milling. Accuracy—particularly trueness and marginal fit—remains the domain where milling excels, ensuring predictable long-term stability.

Future research must prioritize:

- Optimization of printing parameters (layer thickness, build angle, support strategies) to minimize errors.

- Refinement of post-processing protocols (debinding, sintering, polishing) to reduce porosity and enhance durability.

- Long-term randomized controlled clinical trials, especially in posterior regions with high load demands, to validate printed zirconia crowns beyond short-term studies.

- Standardized testing frameworks to ensure reproducibility and comparability across different AM technologies.

- Exploration of novel approaches, including functionally graded materials, hybrid AM–SM workflows, and advanced ceramic printing techniques for improved esthetics and color matching.

Clinical evidence to date suggests that printed crowns are viable, though they exhibit distinct failure modes such as surface defects and minor chipping, whereas milled crowns provide predictable outcomes supported by extensive long-term data. Establishing robust clinical protocols tailored to the unique properties of AM restorations will be essential for their widespread adoption.

In summary, milling remains the gold standard for zirconia crown fabrication, offering superior trueness, marginal fit, and long-term reliability. However, additive manufacturing represents a promising alternative that, with continued innovation and rigorous validation, may eventually achieve parity—or even surpass milling—in certain applications. The convergence of advanced materials science, improved printing technologies, and comprehensive clinical research has the potential to reshape digital dentistry, delivering sustainable, customizable, and high-performance zirconia restorations for the future.

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Chapter
2

DIGITAL IMPRESSION OF EDENTULOUS ARCHES: PROS AND CONS

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Introduction

Complete edentulism continues to represent a significant health concern among older adults and affects function, comfort, quality of life, and clinical decision-making in removable prosthodontics. Although advances in preventive dentistry and restorative treatments have significantly reduced tooth loss in younger populations, complete edentulism remains highly prevalent, particularly among aging and socioeconomically disadvantaged populations. Rather than being a direct consequence of aging, complete edentulism reflects the accumulated effects of oral disease, social determinants of health, and access to dental care, as demonstrated by population-based investigations and systematic reviews reporting a marked increase in prevalence with advancing age, particularly beyond 65 years (Douglass, Shih, & Ostry, 2002; Linn, Khaohoen, Thu, & Rungsiyakull, 2024; Petersen & Yamamoto, 2005; Roberto et al., 2019).

Beyond its functional effects, complete tooth loss has been linked to decreased oral health–related quality of life, nutritional restrictions, limited social interactions, and psychological distress. Large-scale epidemiological studies show significant links between edentulism, depressive symptoms, and poor self-rated general health, emphasising the multidimensional impact of tooth loss on overall well-being (Linn et al., 2024; Tyrovolas et al., 2016; Zarb, Hobkirk, Eckert, & Jacob, 2012). Moreover, the prevalence of edentulism varies notably across socioeconomic and geographic groups, with higher rates seen in patients with lower education levels, reduced income, and limited access to preventive dental care. Gender differences have also been observed, with higher prevalence among older women in several populations, possibly reflecting disparities in life expectancy, historical access to care, and health-seeking behaviours (Roberto et al., 2019; Tyrovolas et al., 2016). Overall, these findings stress the importance of prosthodontic rehabilitation strategies that are both clinically effective and adaptable to different population needs and healthcare systems.

From a public health perspective, the World Health Organization (WHO) has identified oral health in older adults as a priority, underscoring the importance of preventive strategies, accessible prosthodontic care, and rehabilitation approaches that support healthy aging (Petersen & Yamamoto, 2005).

Despite the growing availability of implant-supported treatment options, conventional complete dentures remain the most widely used and economically accessible modality for the rehabilitation of edentulous patients worldwide, particularly among older adults with medical or financial limitations (G. E. Carlsson & Omar, 2010; Douglass et al., 2002). Accordingly, impression procedures continue to represent a critical step in complete denture fabrication, as errors introduced at this stage cannot be fully compensated for during subsequent clinical or laboratory procedures and may adversely affect denture retention, stability, and long-term patient satisfaction (Carlsson, Örtorp, & Omar, 2013; Zarb et al., 2012).

In recent years, digital technologies have been increasingly incorporated into removable prosthodontics to improve clinical efficiency, reproducibility, and digital data management. However, the application of digital impression techniques in edentulous arches remains controversial, largely due to the distinctive anatomical and functional characteristics of the edentulous oral environment, including the absence of stable anatomical landmarks and the predominance of mobile soft tissues (Bidra, Taylor, & Agar, 2013; Wang et al., 2024).

In this context, the chapter aims to present a clinically oriented overview of digital impression techniques for edentulous arches. Conventional impression principles are first discussed to establish a biological and functional basis, after which digital impression technologies are critically examined with respect to their advantages, limitations, and the evolving role of hybrid digital–conventional workflows in complete denture fabrication.

Anatomical and Functional Complexity of the Edentulous Oral Environment

After tooth loss, a series of gradual anatomical and functional changes occur within the edentulous oral environment, collectively increasing the complexity of creating complete dentures. Residual ridge resorption, along with alterations in ridge shape and age-related reductions in soft tissue thickness, show significant variability between individuals and may differ between the maxilla and mandible. These changes directly impact denture-bearing tissues and impression techniques. Generally, resorptive patterns vary between the jaws, with the maxilla tending to resorb upward and inward, while the mandible usually resorbs downward and outward. These contrasting patterns lead to a gradual decrease in the available denture-bearing area and may negatively influence prosthesis retention and stability, especially in the mandible (Carlsson, 1998; Pietrokovski, Harfin, & Levy, 2003; Zarb et al., 2012).

Beyond osseous alterations, the biomechanical behavior of denture-bearing mucosa is a key determinant of complete denture function. Keratinized mucosa over the ridge crest provides relatively stable support, whereas the non-keratinized mucosa of vestibular and peripheral regions exhibits greater resilience and is more susceptible to functional displacement. Muscle attachments and dynamic movements during mastication, speech, and swallowing define the physiological limits of denture extension and should be appropriately considered and integrated during impression procedures (Zarb et al., 2012).

Conventional complete denture impression techniques were developed to address these anatomical and functional challenges. Through the application of selective pressure, border molding, and physiologic impression principles, such techniques aim to record denture-bearing tissues under functional conditions. The posterior palatal seal (PPS) exemplifies this biologically driven approach, in which controlled compression of posterior palatal tissues is intentionally incorporated to compensate for material shrinkage and functional movement, thereby enhancing maxillary denture retention (Carlsson, 1998; Zarb et al., 2012).

Conventional Impression Techniques for Edentulous Arches

Conventional impression techniques for edentulous arches form the biological and clinical foundation of complete denture prosthodontics. These techniques are designed to accommodate the anatomical and functional characteristics of denture-bearing tissues to achieve optimal retention, stability, and patient comfort. Although digital technologies have expanded contemporary prosthodontic workflows, conventional impression principles remain widely regarded as the benchmark for functional tissue recording in complete denture fabrication (Zarb et al., 2012).

Impression Materials and Techniques

Conventional impression techniques utilise a variety of impression materials chosen based on specific clinical goals and the biological features of denture-bearing tissues. Commonly used materials include impression compounds, zinc oxide–eugenol (ZOE) pastes, irreversible hydrocolloids, and elastomeric materials such as polyvinyl siloxane (PVS) and polyether. Each material has distinct properties related to flow, viscosity, setting behaviour, and tissue displacement, which directly affect impression accuracy. In clinical practice, primary impressions are usually taken using irreversible hydrocolloids to create an initial record of the denture-bearing area and to aid in fabricating custom trays. Final impressions are then made using zinc oxide–eugenol pastes or elastomeric materials, depending on the chosen impression approach and clinical needs (Zarb et al., 2012) (Figure 1).

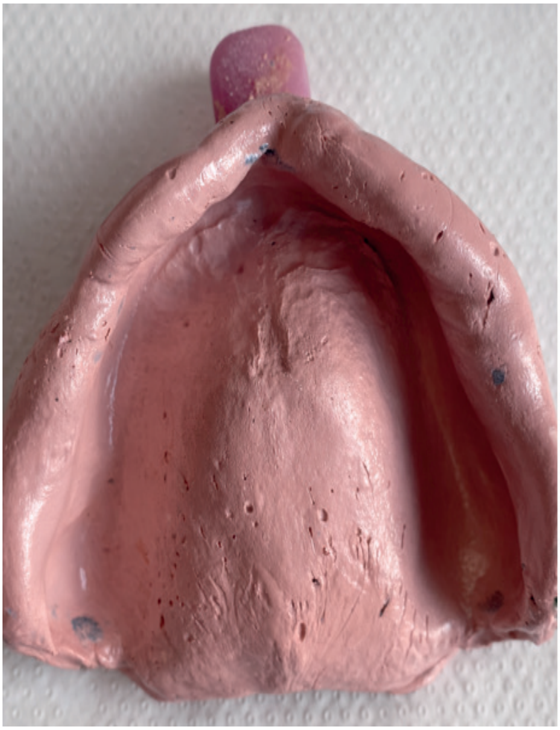


Figure 1. *Definitive complete denture impression of a completely edentulous maxillary arch obtained with zinc oxide–eugenol (ZOE) impression material following border molding procedures.*

Selective pressure impression techniques are employed to modulate occlusal force distribution by applying controlled compression to stress-bearing regions while minimizing application to non–stress-bearing tissues. Conversely, mucostatic impression techniques aim to document the denture-bearing tissues in an undisturbed, resting state. Functional impression techniques, on the other hand, are intended to record tissue behavior under functional loading conditions. In clinical practice, elements of these impression methodologies are often integrated to optimize retention, stability, and patient comfort (Zarb et al., 2012).

Border Molding Procedures

Border molding is a critical step in conventional complete denture impression procedures, as it establishes the functional extent of denture borders and directly affects denture retention and stability. The primary objective of border molding is to achieve appropriate border extension that allows normal functional movements without impingement of movable tissues.

Clinically, border molding is performed through the incremental shaping of impression tray borders using materials such as modeling compound or elastomeric border molding materials, while the patient is guided through functional movements including smiling, speaking, swallowing, and targeted muscle activations. This approach allows controlled displacement of vestibular tissues and establishes a physiologically acceptable relationship between the denture borders and surrounding anatomical structures.

Figure 2. *Border molding performed using modeling compound (Kerr Corp., Orange, CA, USA) on a custom impression tray, demonstrating functional extension of the denture borders.*

Accurate border moulding helps create an effective peripheral seal, which is vital for denture retention. Insufficient border extension can weaken the peripheral seal, while overextension may cause tissue irritation, discomfort, and instability of the denture. Therefore, border moulding is considered a highly technique-sensitive process that requires both clinical experience and a thorough understanding of functional anatomy (Zarb et al., 2012) (Figure 2).

<u>Posterior Palatal Seal Concept</u>

The Posterior Palatal Seal (PPS) is a critical determinant of maxillary complete denture retention and constitutes a fundamental element of conventional impression procedures. It is intentionally recorded under controlled tissue compression to compensate for polymerization shrinkage of denture base materials and to maintain a continuous seal during function.

Conventional impression techniques focus on accurately identifying the vibrating line and applying controlled pressure to the posterior palatal tissues during impression making. Proper PPS design improves denture retention while ensuring patient comfort, whereas too little or too much compression can reduce retention or cause discomfort. Overall, the PPS concept embodies the biologically driven approach of traditional complete denture impressions, where functional tissue behaviour is systematically integrated into prosthesis design (Zarb et al., 2012).

Technique Sensitivity and Sources of Error

While the clinical importance of impression accuracy in complete denture fabrication is well established, the technique-sensitive nature of conventional impression procedures becomes particularly apparent when the cumulative effects of multistep workflows are considered. Clinical outcomes are influenced by multiple interrelated factors, including custom tray design, impression material properties, border molding execution, impression pressure, clinician experience, and patient cooperation.

Errors introduced during impression-taking cannot be fully compensated for in subsequent clinical or laboratory stages and may result in compromised border extension, inadequate tissue adaptation, and reduced denture retention and stability, ultimately affecting patient satisfaction and long-term clinical outcomes. In addition, the multistep nature of conventional workflows, including impression making, cast pouring, and model handling, introduces additional sources of dimensional change and cumulative errors that cannot be fully corrected later. Collectively, these factors help explain the pronounced technique sensitivity of conventional impression procedures for edentulous arches (Carlsson, 1998; Paulino, Alves, Gurgel, & Calderon, 2015; Zarb et al., 2012)

In the context of increasing demands for efficiency, reproducibility, and patient-centered care in modern dental practice, these limitations have stimulated growing interest in alternative and digitally assisted approaches to impression making.

Digital Technologies and Workflows in Complete Denture Fabrication

Digital dentistry has substantially transformed contemporary prosthodontic practice by enhancing precision, streamlining clinical and laboratory workflows, and improving digital data management. Although these advances were initially established in fixed prosthodontics and implant dentistry, digital technologies have increasingly been integrated into removable prosthodontics, particularly in complete denture fabrication, with applications in denture design, manufacturing, and clinical record acquisition aimed at improving standardization and reproducibility (Bidra et al., 2013; Goodacre, Goodacre, & Baba, 2021).

IOS enables the direct digital capture of oral structures and facilitates seamless integration with computer-aided design and manufacturing (CAD/CAM) workflows. Reported advantages of IOS include improved patient comfort, elimination of conventional impression materials, digital data storage, and enhanced communication between clinicians and dental laboratories. These features have contributed to growing interest in the use of IOS in edentulous patients, particularly within fully digital and hybrid complete denture workflows (AlRumaih, 2021; Bidra et al., 2013; Goodacre et al., 2021).

Nevertheless, the application of IOS technology to complete denture fabrication remains clinically challenging. The anatomical and functional characteristics of edentulous arches differ fundamentally from those of dentate conditions, raising ongoing concerns regarding the accuracy and clinical validity of IOS when used as definitive records. Accordingly, these challenges highlight the need for a critical evaluation of IOS technologies within the context of complete denture workflows (AlRumaih, 2021; Bidra et al., 2013; Goodacre et al., 2021; Mohamedin, Komiha, Aboelroos, Mosaad, & Swelem, 2025).

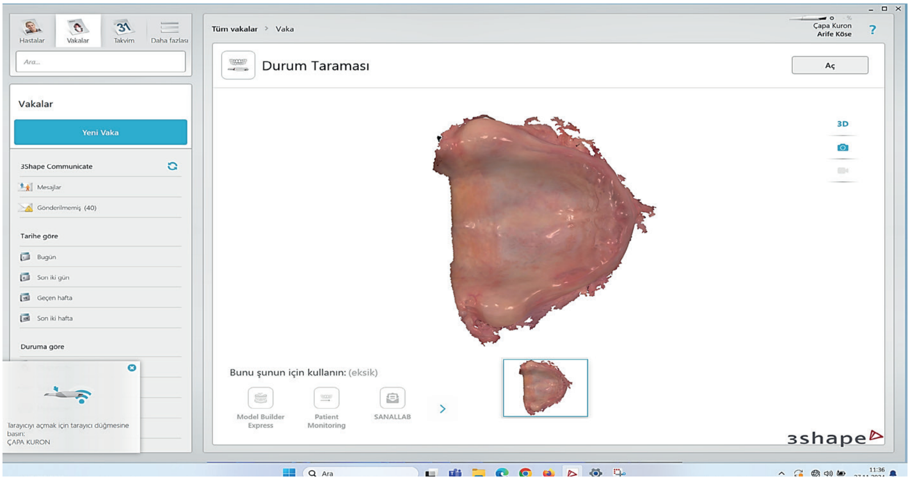
Intraoral Scanning Technologies in Complete Denture Fabrication

IOS systems generate three-dimensional (3D) digital representations of oral tissues by optically capturing surface data and reconstructing virtual models through sequential image acquisition and software-based processing. Current IOS platforms operate using different optical principles, such as confocal microscopy, optical triangulation, and active wavefront sampling. Although scanner designs and reconstruction algorithms vary among systems, IOS is inherently characterized by a contact-free and non-compressive mode of data acquisition. This characteristic distinguishes IOS from conventional complete denture impression techniques, which are based on deliberate and controlled displacement of denture-bearing tissues (Ender & Mehl, 2013; Logozzo, Zanetti, Franceschini, Kilpelä, & Mäkynen, 2014).

In contrast to dentate arches, where rigid tooth structures provide stable reference landmarks for image alignment, edentulous arches consist primarily of smooth, continuous, and compressible soft tissues. As a result, the performance of IOS reported under dentate conditions cannot be directly extrapolated to complete denture applications, particularly when extensive edentulous surfaces are scanned (Al Hamad & Al-Kaff, 2022; Hack et al., 2020; Patzelt, Bishti, Stampf, & Att, 2014; Russo et al., 2020).

Scanning Strategies and Data Acquisition Challenges in Edentulous Arches

In complete denture applications, IOS accuracy is influenced by both scanner-specific characteristics and operator-related factors, particularly the chosen scanning approach and data-acquisition workflow. In edentulous arches, these factors become critical, as the lack of stable anatomical reference structures makes complete-arch registration more vulnerable to cumulative alignment discrepancies and surface distortion, particularly when scan coverage is incomplete (Figure 3).



Tarayıcıyı açmak için tarayıcı düğmesine basın:
ÇAPA KURON

Figure 3. *Intraoral scan of an edentulous maxillary arch*

In dentate arches, stable tooth surfaces provide well-defined reference points that facilitate reliable image alignment during sequential scanning. By contrast, edentulous arches consist largely of relatively featureless and deformable soft tissues, providing limited geometric information for accurate image matching. Consequently, minor deviations introduced during data capture may progressively compound throughout the scanning sequence, resulting in distortion of the reconstructed virtual surface, particularly across extensive edentulous regions (Ender & Mehl, 2013; Kontis, Güth, & Keul, 2025; Nedelcu, Olsson, Nyström, Rydén, & Thor, 2018).

Scanning path selection plays a central role in minimizing these limitations. Continuous, unidirectional scanning strategies have been suggested to reduce stitching errors by maintaining consistent overlap between sequential images, whereas fragmented or interrupted scanning paths may increase the risk of misalignment. Peripheral regions, including vestibular extensions and border areas, are particularly prone to distortion due to soft-tissue mobility and the lack of surface texture (Kontis et al., 2025;

Nedelcu et al., 2018; Wang et al., 2024). However, optimal scanning paths are not universal and should be adapted to the specific intraoral scanner system and manufacturer-recommended acquisition protocols.

From a clinical perspective, notable differences exist in the way digital data are acquired from maxillary and mandibular edentulous arches. The maxilla typically provides a wider, more continuous denture-bearing foundation, which can support more stable image matching during scanning procedures. However, variations in palatal anatomy and the presence of displaceable posterior palatal tissues may still lead to localized deviations, particularly along peripheral borders. In contrast, digital capture of mandibular edentulous arches is inherently more demanding.

Limited anatomical extension, advanced ridge resorption, and the dynamic behavior of adjacent soft tissues, such as the floor of the mouth and tongue, reduce scan stability and compromise overlap reliability. As a result, cumulative stitching inaccuracies and geometric distortions are more likely to occur during complete-arch mandibular scanning, which may explain the consistently lower accuracy and reproducibility reported for mandibular edentulous scans in complete denture workflows (Braian & Wennerberg, 2019; Mohamedin et. al., 2025; Sawangsri et al., 2025) (Figure 4).

Figure 4. *Representative IOS strategies for edentulous maxillary and mandibular arches, illustrating recommended scanning paths across denture-bearing surfaces (courtesy of Prof. Dr. Lo Russo).*

In contrast to conventional impression techniques that intentionally capture tissues under controlled functional displacement, IOS records denture-bearing tissues in a static, non-compressed state. While such recordings may enhance scan reproducibility, they do not adequately capture functional border dynamics, especially in peripheral regions. Consequently, modifications in scanning strategy alone cannot fully substitute for functional tissue registration within current IOS-based complete denture workflows (Bidra et al., 2013; Nedelcu et al., 2018; Wang et al., 2024).

Trueness and Precision of Intraoral Scans in Edentulous Arches

Scan reliability in intraoral digitization depends on the interaction between trueness and precision. Trueness reflects how closely a digital scan represents the actual surface geometry, whereas precision refers to the consistency of repeated scans obtained under identical conditions. While dentate arches provide rigid reference structures that facilitate stable image registration, edentulous arches lack comparable anatomical guidance. As a result, the relatively smooth and deformable nature of denture-bearing soft tissues imposes intrinsic limitations on precise data acquisition.

Available evidence suggests that scanning inaccuracies in complete-arch edentulous conditions may accumulate, primarily affecting trueness, while factors such as scanning execution, intraoral environment, and operator performance are more closely related to precision. Compared with dentate conditions, these limitations become more pronounced in edentulous arches, resulting in greater inter-scan variability and reduced reproducibility of digital impressions. Accordingly, intraoral scan data obtained from edentulous patients should be interpreted with caution, particularly when such datasets are intended for definitive complete denture fabrication, where both geometric accuracy and repeatability are critical (Al Hamad & Al-Kaff, 2022; Ender & Mehl, 2013; Nedelcu et al., 2018).

Clinical Challenges of IOS in Edentulous Arches

Absence of Stable Anatomical Landmarks and Cumulative Errors

The clinical performance of IOS in edentulous arches is influenced by the limited presence of stable anatomical reference landmarks. In dentate patients, rigid teeth facilitate accurate image alignment and data stitching. By contrast, structures such as the alveolar ridge crest and palatal vault offer relatively limited geometric detail, thereby increasing vulnerability to registration inconsistencies and stitching-related errors during complete-arch scanning (Hack et al., 2020; Wang et al., 2024).

As scanning progresses across extensive edentulous surfaces, minor alignment inaccuracies introduced early in the scan sequence may accumulate, leading to region-dependent deviations. Clinical and experimental studies consistently report acceptable trueness in localized areas, particularly along the alveolar ridge crest, with progressively reduced accuracy toward peripheral regions (Alehaideb, Lin, Levon, Chu, & Yang, 2025; Kontis et al., 2025; Nedelcu et al., 2018; Russo et al., 2020).

Influence of Mobile Mucosa and Static Record

Edentulous denture-bearing tissues exhibit varying degrees of resilience and mobility, particularly in the vestibular and posterior palatal regions. Conventional impression techniques are intended to accommodate this tissue behavior by selectively compressing or displacing the mucosa. By contrast, IOS captures soft tissues under static, mucostatic conditions without functional loading (Alrumaih, 2021; Zarb et al., 2012).

This fundamental difference in recording approach contributes to measurable discrepancies between digital and conventional impressions, particularly in regions critical for denture retention and stability. As a result, impressions obtained by IOS may underestimate the functional extent of denture borders in patients with mobile or resilient mucosa (Alehaideb et al., 2025; Paulino et al., 2015; Zarb et al., 2012).

Peripheral Borders and Posterior Palatal Seal

Accurate recording of peripheral borders is essential for achieving effective denture retention and stability. Conventional border molding procedures are designed to register functional tissue displacement occurring during speech and mastication. By contrast, IOS captures peripheral tissues under static conditions, thereby limiting its capacity to reproduce functional border extensions with consistent accuracy (Lee, 2021; Wang et al., 2024).

3D superimposition analyses consistently reveal greater deviation values in the vestibular and border regions compared to the central denture-bearing areas (Russo et al., 2020; Wang et al., 2024). These inaccuracies appear to be predominantly independent of the scanner system employed and are primarily attributable to inherent limitations within the digital acquisition process in mobile soft tissue environments (Kontis et al., 2025; Nedelcu et al., 2018). Similar constraints have been observed in the posterior palatal seal region. In numerous digital workflows, the formation of the posterior palatal seal (PPS) relies on virtual design rather than direct functional recording, potentially compromising biological fidelity and introducing operator-dependent variability (Lee, 2021).

Clinical Applications and Indications of IOS in Edentulous Patients

IOS is increasingly used in removable prosthodontics; however, its clinical value in edentulous patients depends largely on appropriate indication and case selection. Current evidence does not support the routine use of IOS as a replacement for conventional functional impression techniques in complete denture fabrication. Instead, IOS should be regarded as an adjunct method within selected clinical scenarios (AlRumaih, 2021; D'Arienzo et al., 2020; Wang et al., 2024).

The most commonly reported clinical applications of IOS in edentulous patients include preliminary impressions, diagnostic records, duplication of existing dentures, and digitally assisted workflows combined with conventional impression principles. Systematic and narrative reviews indicate that IOS demonstrates more predictable performance when functional tissue displacement and border molding are not required (D'Arienzo et al., 2020; Wang et al., 2024). In these clinical scenarios, IOS facilitates efficient data acquisition while avoiding limitations associated with static recording of mobile mucosa.

IOS-based duplication techniques represent a well-supported clinical indication. Scanning the existing dentures or record bases enables preservation of established occlusal relationships and prosthesis contours, while allowing targeted refinement through conventional or hybrid approaches (Alehaideb et al., 2025; Oyamada, Yonezawa, & Kondo, 2021). These workflows are particularly advantageous for patients who are satisfied with their existing dentures but require replacement due to wear, fracture, or material degradation.

Overall, the clinical role of IOS in edentulous patients is best defined by appropriate indication and case selection, rather than indiscriminate use.

When selectively integrated into suitable workflows, IOS can provide clinical benefits without compromising functional accuracy.

Advantages of IOS in Edentulous Arches

In carefully selected clinical situations, intraoral scanning (IOS) offers several practical advantages in managing edentulous patients. Notably, improved patient comfort is frequently reported. The avoidance of traditional impression trays and materials through digital workflows can reduce patient discomfort and gag reflex responses, which is especially beneficial for elderly patients with systemic conditions. Current clinical evidence indicates that IOS is generally better tolerated than conventional impression methods, particularly for preliminary and diagnostic purposes (AlRumaih, 2021; Jafarpour, Haricharan, & de Souza, 2024).

IOS can also improve workflow efficiency in certain clinical settings. The immediate access to digital scan data allows clinicians to assess scan quality chairside, identify incomplete areas, and, if needed, acquire additional data during the same appointment, thus reducing the chances of impression remakes and additional patient visits. In addition, IOS reduce the need for material handling, setting time, and disinfection procedures, which may shorten chairside time in experienced operators. However, efficiency improvements still depend on operator experience and scanning strategy (Le Texier, Nicolas & Batisse, 2024).

An additional advantage of IOS relates to digital data storage and reproducibility. IOS files (typically exported in STL format) can be archived indefinitely without the distortion or degradation associated with conventional stone casts, enabling reliable long-term data retrieval, remanufacturing, and duplication of prostheses (D'Arienzo et al., 2020; Saponaro et al., 2016). This feature is particularly valuable in complete denture therapy, where replacement or reproduction of prostheses is frequently required over time.

Finally, IOS integrates seamlessly with CAD/CAM manufacturing workflows, including both milling and 3D-printing. Digital design environments support standardized workflows, virtual modifications, and reproducible denture fabrication, thereby reducing variability related to manual laboratory procedures (Al-Kaff & Al Hamad, 2024; Goodacre, Goodacre, Baba, & Kattadiyil, 2016). Although these advantages do not compensate for limitations in functional tissue recording, they provide substantial benefits when IOS is applied within its appropriate scope of use.

Limitations of IOS in Edentulous Patients

Despite the growing integration of IOS into removable prosthodontic workflows, its use in edentulous patients remains constrained by several biological and technical factors. The most significant limitation relates to reduced accuracy and trueness compared with dentate arches, primarily resulting from the absence of stable anatomical reference points and the predominance of smooth, homogeneous soft tissue surfaces (Al Hamad & Al-Kaff, 2022; Hack et al., 2020; Wang et al., 2024)

Importantly, IOS deviations are not uniformly distributed across the edentulous arch. Evidence from 3D superimposition analyses indicates that acceptable trueness is often achieved in localized regions, particularly along the alveolar ridge crest, whereas progressively greater deviations are observed toward peripheral and functionally critical areas, including the vestibular borders and posterior palate (Al Hamad & Al-Kaff, 2022; Kontis et al., 2025; Russo et al., 2020; Wang et al., 2024). These discrepancies are largely attributed to cumulative stitching errors, soft tissue mobility, and acquisition geometry rather than to the performance of a specific scanner system.

A further fundamental limitation of IOS lies in its static mode of data acquisition. In contrast to conventional impression techniques, IOS records denture-bearing tissues at rest, without functional loading (AlRumaih, 2021; D'Arienzo et al., 2020). Consequently, IOS may underestimate the functional extent of denture borders, potentially compromising peripheral seal, retention, and stability, particularly in patients with mobile or resilient mucosa. This limitation is especially evident in the PPS region. Conventional impression protocols intentionally compress this area to enhance retention and compensate for processing-related dimensional changes. By contrast, digital workflows rely on static records and a virtual PPS design, which may introduce operator-dependent variability and reduce biological fidelity compared with direct functional recording (Lee, 2021).

Additional limitations associated with IOS include scanner and workflow-dependent variability, the operator learning curve, and economic considerations. Variations in scanning strategy, operator experience, and system-specific algorithms can substantially affect reproducibility in edentulous arches (Alehaideb et al., 2025; Le Texier et al., 2024). Furthermore, the cost of intraoral scanners, software licenses, and ongoing maintenance may limit widespread adoption, particularly when conventional impression techniques already provide predictable cost-effective outcomes.

Taken together, these limitations indicate that IOS should not be considered a standalone approach for definitive impressions in edentulous patients. Rather, its clinical application should be guided by careful case selection and, when necessary, supplemented by conventional or hybrid impression approaches.

Hybrid Approaches in Digital Impressions for Complete Dentures

Hybrid impression approaches have emerged as a clinically grounded response to the recognized limitations of IOS in edentulous patients. Instead of substituting conventional impression principles, these approaches integrate established functional impression principles with digital data-acquisition methods to enhance the reliability of digital impressions while maintaining functional tissue accuracy.

In removable prosthodontics, hybrid strategies represent indication-based approaches in which digital tools are applied selectively according to clinical requirements rather than solely on technological availability. This perspective supports the appropriate use of IOS within its current biological and functional limits and prevents overextension of digital impression techniques in edentulous arches (AlRumaih, 2021; Bidra et al., 2013; D'Arienzo et al., 2020).

Digitization of Conventional Impressions and Definitive Casts

In hybrid impression protocols, functional impressions are first obtained using conventional clinical techniques. The definitive impression or master cast is subsequently digitized using a laboratory scanner to generate a digital reference model for further clinical evaluation and digital data handling (Bidra et al., 2013; D'Arienzo et al., 2020).

Indirect digitization techniques have demonstrated higher trueness and predictability compared with direct intraoral scanning of edentulous arches, particularly in cases involving large surface areas and peripheral extensions (Alehaideb et al., 2025; Hack et al., 2020; Wang et al., 2024). From an impression perspective, this approach offers a low-risk and clinically reliable method for integrating digital data into complete denture workflows.

Denture Duplication Using IOS

Digital duplication of existing dentures represents a clinically practical hybrid use of IOS within impression procedures. In this approach, IOS is used to capture the intaglio surface and external contours of an existing denture or record base, allowing maintaining established occlusal relationships and prosthesis morphology. Functional tissue adaptation is subsequently refined using conventional impression procedures or combined digital–conventional techniques.

Duplication protocols are particularly advantageous in patients who are satisfied with their existing dentures but require replacement due to wear, fracture, or material degradation. In these situations, IOS serves primarily as a data transfer and replication tool rather than as a definitive impression method (Hong et al., 2019; Lo Russo & Salamini, 2018; Oyamada et al., 2021).

Combined Digital–Conventional Impression Protocols

Hybrid impression strategies may incorporate IOS for preliminary anatomical recording, followed by definitive impressions obtained using conventional materials such as polyvinyl siloxane or zinc oxide–eugenol. Within these protocols, IOS supports initial digital evaluation, while conventional impressions remain essential for accurately capturing functional tissue behavior and peripheral border extension (AlRumaih, 2021; Cameron, Evans, Tadakamadla, & Abuzar, 2025).

Available clinical evidence suggests that combined digital-conventional protocols enhance flexibility during impression procedures and help minimize the risk of compromised peripheral adaptation, particularly in patients with complex soft tissue conditions or increased functional demands.

Digitally Designed Record Bases and Impression Trays

Recent advances in digital prosthodontics have introduced the use of digitally designed custom record bases and impression trays. In selected hybrid protocols, preliminary digital data obtained from diagnostic casts, preliminary impressions, or existing records is used to design patient-specific components. These digitally fabricated custom trays or record bases are subsequently employed during conventional impression procedures using elastomeric or zinc oxide–eugenol materials. By integrating digitally optimized custom tray design with conventional impression techniques, such approaches may enhance impression consistency, reduce chairside adjustments, and preserve the functional accuracy required for definitive complete denture impressions (Al-Kaff & Al Hamad, 2024; Bidra et al., 2013; Liao & Budsabong, 2024).

Figure 5. *Digitally designed custom tray for an edentulous maxillary arch, generated based on a virtual model to ensure uniform spacer thickness and controlled material distribution.*

Clinical Indications and Current Position

Hybrid impression strategies are particularly indicated in edentulous patients presenting with advanced ridge resorption, resilient mucosa, shallow vestibules, or increased functional demands, where reliable functional tissue recording remains critical. In such clinical scenarios, hybrid approaches offer a balanced impression strategy by preserving denture retention and stability while allowing the selective use of digital data acquisition and documentation.

Based on the current body of evidence, hybrid impression approaches are regarded as among the most predictable and clinically supported methods for incorporating digital technologies into complete denture impression procedures. Until further technological developments enable accurate and reproducible functional tissue recording through fully digital methods, selective implementation of hybrid impression strategies remains the preferred clinical position (Al-Kaff & Al Hamad, 2024; Mohamedin et al., 2025).

Conclusion

Digital impression technologies have significantly expanded the scope of removable prosthodontics by enhancing workflow efficiency, improving patient comfort, and facilitating more effective digital data management.

Despite these advancements, their application in the context of edentulous arches remains limited by the inherent anatomical and functional complexities of denture-bearing tissues. The lack of stable anatomical landmarks, coupled with the predominance of mobile soft tissues and the necessity for functional border recording, diminishes the reliability of static intraoral scans, especially in peripheral regions and the postural periodontal space (PPS) area. As a result, conventional impression techniques continue to serve as the gold standard for the registration of functional tissues during the fabrication of complete dentures. In this setting, hybrid workflows have emerged as a promising and evidence-supported approach, combining the functional accuracy offered by traditional impression methods with the efficiency and standardization achievable through digital design and manufacturing processes. Ongoing technological innovations aimed at enhancing soft tissue capture, dynamic functional recording, and the accuracy of scan registration algorithms are likely to further define and broaden the role of fully digital approaches in the rehabilitation of edentulous patients, potentially transforming clinical practices in the future.

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Chapter
3

PHOTOGRAMMETRIC RECORDING SYSTEMS

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1. Introduction

The historical development of photogrammetric recording systems is closely linked to the advent of photographic technology and the evolution of spatial and dimensional measurement principles. The term photogrammetry is derived from the Ancient Greek words *photos* (light), *gramma* (drawing), and *metron* (measurement), collectively denoting the measurement and documentation of objects using light. In its earliest stage, photogrammetry emerged as an experimental method aimed at extracting metric information from photographic images. However, from the mid-19th century onward—following the invention and widespread adoption of photography—it evolved into a systematic and scientifically established measurement technique (Schwidefsky, 1961; Wolf, 1983).

The initial phase of photogrammetric systems largely corresponds to the era of analog photogrammetry. During this period, measurements were performed using stereoscopic image pairs processed through mechanical and optical instrumentation. Analog photogrammetry was primarily applied in cartography and topographic surveying, where three-dimensional (3D) spatial information was derived by exploiting the parallax effect between images acquired from different viewpoints). Despite its pioneering significance, this approach was inherently time-consuming and exhibited limited flexibility due to its strong reliance on specialized equipment and operator expertise. (Schwidefsky, 1961

A major transformation occurred during the 1970s and 1980s with the emergence of analytical photogrammetry, characterised by the introduction of computer-assisted calculation methods and the mathematical modelling of camera geometry and image coordinates. Compared with analog systems, analytical photogrammetry provided substantially improved accuracy and achieved widespread adoption, particularly in terrestrial photogrammetry applications (Baş, 1993; Karara, 1989). Since the 1990s, the field has been further reshaped by the transition to digital photogrammetry, driven by advances in digital imaging sensors and image-processing algorithms. This transition enabled largely automated workflows in which essential processes—such as image orientation, point matching, and triangulation—are executed computationally. As a result, photogrammetry expanded beyond its traditional domains of cartography and geodesy and became widely applied in architecture, archaeology, industrial metrology, and cultural heritage documentation (Anderson, 1982; Boehler & Heinz, 1999; Ogleby, 1995).

In particular, close-range photogrammetry has gained considerable importance in the documentation of archaeological and architectural heritage. Through the initiatives of international organizations such as the International Committee for Documentation of Cultural Heritage (CIPA) and the

International Society for Photogrammetry and Remote Sensing (ISPRS), photogrammetry has become established as a standard method for the accurate, non-contact, and efficient preservation and monitoring of cultural heritage assets (Boehler & Vincent, 2003; Cooper & Robson, 1994). Today, supported by advances in digital photogrammetry and multi-image-based reconstruction techniques, photogrammetry has evolved beyond a conventional measurement tool into a multidisciplinary methodology for data acquisition and analysis, with applications extending from cartography and geodesy to industrial metrology and three-dimensional digital modelling (Wolf, 1983; Karara, 1989; Boehler & Heinz, 1999).

1.1. Fundamental Concepts and Measurement Principles of Photogrammetry

Photogrammetry is an optical measurement technique that uses multiple two-dimensional (2D) images acquired from different viewpoints to reconstruct the 3D geometry of an object or scene. The primary objective of this technique is to determine the true spatial coordinates of physical points by exploiting the geometric projection relationships inherent in the acquired images (Zhou et al., 2024; Eldefrawy et al., 2022).

The photogrammetric measurement process begins with the acquisition of overlapping photographs or video frames captured from multiple viewpoints surrounding the object or scene of interest. These multi-view images enable evaluation of positional changes in the same physical point across different images. Such positional discrepancies constitute the fundamental source of depth perception in photogrammetry and are collectively referred to as the parallax effect (Zhou et al., 2024; Eldefrawy et al., 2022).

1.2. Parallax Effect and Central Projection Geometry

The mathematical foundation of photogrammetry is rooted in central projection geometry, in which a point in 3D space is mapped onto a 2D image plane by rays passing through the camera's optical centre. The parallax difference observed between the image projections of the same physical point acquired from different camera positions enables the computation of the point's depth and precise spatial coordinates (Hartley & Zisserman, 2004; Zhou et al., 2024). This fundamental principle underscores that a single image is inherently insufficient for reliable three-dimensional reconstruction and that acquiring multiple images from different viewpoints is essential for accurate and robust spatial analysis.

1.3. Identification and Matching of Feature Points

Within the acquired image set, distinctive feature points that are robust to variations in illumination, scale, and viewpoint are automatically detected. These features function as local descriptors, characterized by edge-, corner-, or texture-based variations, and enable the reliable identification of corresponding structures across different images (Eldefrawy et al., 2022).

Subsequently, the detected feature points are matched across multiple images to determine the image coordinates associated with the same physical point in 3D space. This matching process establishes the geometric correspondences between images and constitutes the fundamental dataset required for accurate 3D reconstruction and subsequent photogrammetric analysis (Paul et al., 2025).

1.4. Structure from Motion (SfM): Simultaneous Estimation of Camera and Scene Geometry

Following the feature matching stage, both the camera parameters—including position and orientation—and the 3D spatial distribution of scene points are estimated simultaneously using the Structure from Motion (SfM) approach, which constitutes a core methodology in photogrammetry. SfM is an iterative reconstruction process in which camera motion and scene geometry are jointly estimated from a set of overlapping images. After the initial camera poses are determined, additional images are incrementally integrated into the reconstruction, and both camera parameters and 3D point coordinates are progressively refined at each iteration (Zhang, 2011; Zhou et al., 2024). The outcome of the SfM process is a sparse point cloud that represents the overall geometry of the scene. Although this sparse reconstruction captures the fundamental spatial structure, it does not yet provide a detailed representation of surface morphology (Eldefrawy et al., 2022).

1.5. Triangulation and Bundle Adjustment

The fundamental mathematical operation underlying the generation of a sparse point cloud is triangulation, which enables the computation of the 3D coordinates of a physical point by intersecting projection rays originating from multiple camera positions in space (Hartley & Zisserman, 2004). Following triangulation, the estimated camera poses and reconstructed 3D point coordinates are jointly refined to minimize the reprojection error observed in the image space. This optimization procedure, referred to as bundle adjustment, represents one of the most critical determinants of overall photogrammetric accuracy. Bundle adjustment simultaneously optimises internal and external camera parameters, along with the spatial coordinates of reconstructed points, thereby improving global consistency, numerical stability, and accuracy in photogrammetric reconstruction (Eldefrawy et al., 2022; Paul et al., 2025).

1.6. Dense Reconstruction: Multi-View Stereo (MVS)

Following the generation of a sparse point cloud, the photogrammetric workflow typically advances to Multi-View Stereo (MVS) techniques. At this stage, depth information from multiple viewpoints is integrated to generate a dense point cloud, yielding a more detailed and continuous representation of the scene's surface geometry (Zhou et al., 2024; Paul et al., 2025). These dense reconstructions constitute the foundation for subsequent surface modeling, as they more accurately capture geometric continuity and fine structural details of the object compared with sparse reconstructions. (Zhou et al., 2024; Paul et al., 2025).

1.7. Surface Modeling and Texture Mapping

In the final stage of the photogrammetric workflow, the dense point cloud is converted into a triangular mesh that represents the object's or scene's continuous surface geometry. Subsequently, radiometric (color) information extracted from the original images is projected onto the reconstructed surface via texture mapping. This procedure results in photogrammetric 3D models that are both geometrically accurate and visually realistic, thereby supporting reliable spatial analysis and high-fidelity visual representation (Paul et al., 2025).

1.8. The Historical Development of Photogrammetry in Dentistry

The application of photogrammetry in dentistry became feasible with advances in close-range photogrammetric accuracy and the successful adaptation of optical measurement systems to the clinical environment. Photogrammetry was first introduced into dental research and practice in the early 1990s and has since been applied to a wide range of purposes, including the measurement of implant positions, evaluation of the fit of implant-supported prostheses, detection of framework deformation, assessment of peri-implant mucosal changes, and three-dimensional (3D) topographic quantification of implant surfaces (Chadwick, 1992; Jemt, Book, Lie, & Börjesson, 1994; Lie & Jemt, 1994; Hussein, 2023).

A major milestone in the historical development of implant photogrammetry was achieved by Lie and Jemt, who recorded the spatial positions of implants using a calibrated camera and a high- accuracy analytical plotter and subsequently introduced a coordinate-based technique for evaluating the fit between implants and superstructures (Lie & Jemt, 1994). This pioneering work demonstrated that implant positions could be directly transferred into a digital coordinate system, thereby establishing photogrammetry as a viable alternative to conventional implant impression techniques. In the following years, Jemt and colleagues published pilot studies that further confirmed the feasibility and clinical relevance of photogrammetric methods for assessing the fit of implant-supported fixed prostheses (Jemt et al., 1999).

During the early 2000s, implant photogrammetry was investigated predominantly at an experimental and in vitro level. These studies focused on improving measurement accuracy by using custom-designed light boxes, digital single-lens reflex (DSLR) cameras, and precisely manufactured reference markers affixed to abutments (Bergin et al., 2013; Forlani & Rivara, 2014). However, the routine clinical implementation of early photogrammetric systems remained limited due to their reliance on complex optical setups, high operator dependency, and susceptibility to clinical environmental factors—such as saliva, bleeding, and patient movement—that could negatively influence measurement accuracy (Hussein, 2023).

The true integration of implant photogrammetry into routine clinical workflows gained momentum in the 2010s with the introduction of commercial stereoscopic photogrammetric systems specifically designed for intraoral application. Systems such as the PIC camera were developed to enable rapid, highly accurate recording of the three-dimensional spatial coordinates of implants by using coded reference bodies attached to the implants (Agustin-Panadero et al., 2015; Pradíes et al., 2014). Clinical investigations reported that these systems significantly reduced impression time in full-arch implant cases, simplified both clinical and laboratory procedures, and yielded favorable outcomes in terms of passive fit of implant-supported prostheses (Peñarrocha-Diago et al., 2017).

The studies by Revilla-León and colleagues constitute key contributions that define the modern era of implant photogrammetry. In a landmark in vitro study published in 2020, photogrammetry was compared with conventional impression techniques and intraoral scanning, with accuracy evaluated using a coordinate measuring machine (CMM). The results demonstrated that photogrammetry is a reliable method for transferring implant positions—particularly in full-arch implant impressions—while also indicating that accuracy outcomes may vary with the specific system and protocol employed (Revilla-León, Att, Özcan, & Rubenstein, 2020). Subsequent investigations further compared intraoral and extraoral photogrammetry systems, highlighting that device configuration and data acquisition protocols play a decisive role in determining trueness and precision (Revilla-León et al., 2023; Revilla-León et al., 2025).

One of the primary reasons photogrammetry has gained clinical preference is that stereoscopic camera systems can record implant coordinates with high accuracy and are relatively less affected by factors that commonly compromise intraoral scanning, such as restricted intraoral access and cumulative stitching errors (Pradíes et al., 2014; Peñarrocha-Diago et al., 2017). Nevertheless, photogrammetric systems have an important limitation: although they provide highly accurate spatial information on implant positions, they cannot directly capture peri-implant soft-tissue morphology. Consequently, in contemporary digital workflows, photogrammetry is primarily employed for implant coordinate transfer, whereas soft-tissue and occlusal data are obtained using intraoral scanners or other three-dimensional imaging modalities (Hussein, 2023).

In summary, the historical development of photogrammetry in dentistry can be regarded as a progressive evolutionary process, extending from experimental applications introduced in the 1990s for implant position measurement to its current role as an integral component of digital clinical workflows. Today, photogrammetry is recognized as a reliable and well-established method for implant coordinate transfer, particularly in cases involving multiple implants and full-arch rehabilitations (Lie & Jemt, 1994; Jemt et al., 1999).

2. PHOTOGRAMMETRIC MEASUREMENT SYSTEMS AND APPLICATION PRINCIPLES IN DENTISTRY

Photogrammetric measurement systems are advanced, digital, non-contact impression technologies used to determine the 3D spatial positions of implants in implant dentistry with high accuracy. These systems are based on the optical acquisition of geometrically defined reference markers placed on implants, abutments, or specially designed reference elements. Images captured from multiple viewpoints are analyzed through the mathematical relationships between corresponding image points. By establishing camera geometry from multi-view images, identifying distinctive geometric features, and applying fundamental photogrammetric operations—such as triangulation—the spatial position and orientation of implants can be calculated with high accuracy (Jemt & Lie, 1995; Jemt, 1996; Jemt, Back, & Petersson, 1999).

Dental photogrammetry has evolved by adapting the general photogrammetric workflow to the specific requirements of implant dentistry, with the primary objective of determining implant positions directly within a coordinate-based framework, independent of surface-based scanning. The clinical applicability of this method is largely enabled using geometrically standardized reference elements that can be reliably identified by the system and evaluated under the assumption of rigid scan bodies. Under this assumption, the relative linear distances and angular relationships between reference markers can be computed with high accuracy, largely independent of deformation-related effects (Jemt & Lie, 1995; Jemt, 1996).

In the context of full-arch implant-supported fixed prostheses, accurate transfer of implant positions is regarded as a critical clinical prerequisite for achieving passive fit. The elimination of distortion risks associated with conventional impression materials, together with improved measurement accuracy in cases involving multiple implants, has accelerated the integration of photogrammetric systems into routine clinical workflows (Hussein, 2023; Revilla-León et al., 2020; Brånemark et al., 2018). Accordingly, photogrammetry has emerged as a reliable alternative measurement method for assessing and verifying passive fit in full-arch implant-supported prosthetic rehabilitations.

Based on their data acquisition approach, photogrammetric systems used in implant dentistry are generally classified into two main categories: extraoral and intraoral photogrammetry systems. (Revilla-León et al., 2025)

2.1. Extraoral Photogrammetry Systems

Extraoral photogrammetry systems are measurement technologies in which implant positions are recorded using camera systems positioned outside the oral cavity. In these systems, the 3D spatial coordinates of implants are calculated by detecting specially coded scan bodies attached to the implants. Because extraoral photogrammetry systems are unable to directly capture soft tissue morphology and occlusal relationships, they are most commonly implemented in combination with intraoral scanners within contemporary digital workflows (Hussein, 2023; Revilla-León & Kois, 2025).

2.1.1. Precise Implant Capture Systems

The PIC system (PIC Dental, Spain) is among the first commercially available extraoral photogrammetry systems introduced into clinical implant dentistry. The system incorporates an infrared flash and a dual-sensor charge-coupled device (CCD) stereoscopic camera capable of detecting specially designed PIC reference abutments on implants (Figure 1). By capturing multiple image frames of these reference elements within a very short acquisition time, the system computes the three-dimensional spatial coordinates of the implants with a high degree of accuracy (Hussein, 2023).

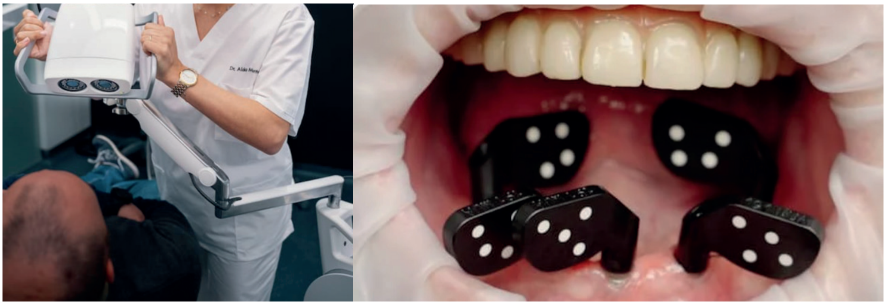

Figure 1: *Extraoral photogrammetry workflow of the PIC system illustrating stereoscopic acquisition of coded scan bodies for three-dimensional determination of implant positions.*

The clinical workflow of the PIC system involves placing coded scan bodies on the implants, followed by extraoral image acquisition directed at the implant region(Figure 1). The resulting implant coordinate data are subsequently transferred to computer-aided design (CAD) software for prosthetic planning. However, because the system is limited to recording implant positions alone, an additional intraoral scan is required to obtain information related to soft tissue morphology and maxillomandibular relationships (Peñarrocha-Diago et al., 2017).

In the existing literature, the accuracy of the PIC system has been evaluated predominantly based on clinical outcomes. Multiple studies have reported satisfactory passive fit in full-arch implant-supported prostheses fabricated using the PIC system, as verified by clinical assessment methods such as screw resistance tests and the Sheffield test (Pradíes et al., 2014; Peñarrocha-Diago et al., 2017). Nevertheless, investigations assessing the system's absolute accuracy using independent metrological reference instruments remain limited. As a result, despite its well-documented clinical success, the lack of standardized, instrument-based accuracy validation continues to be a subject of discussion in the literature (Hussein, 2023).

2.1.2. iCam4D System (iMetric)

The iCam4D system (iMetric 4D Imaging, Switzerland) is a hybrid extraoral impression system that integrates photogrammetric principles with structured light technology. In this system, geometrically calibrated optical reference markers, referred to as iCamBody, are positioned on the implants and detected using a multi-camera configuration combined with a structured light projection unit, enabling accurate three-dimensional localization of implant positions (Hussein, 2023) (Figure 2). In the iCam4D workflow, data acquisition is performed extraorally, and the spatial positions of implants are calculated within a proprietary coordinate framework known as iCamPosition. Similar to other extraoral photogrammetry systems, iCam4D is limited to recording implant positions and therefore requires integration with intraoral scanning to obtain information related to soft tissue morphology and occlusal relationships.

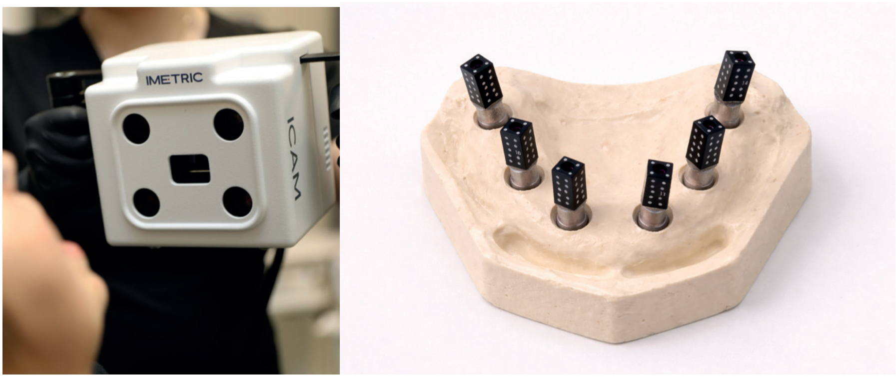

Figure 2: *Extraoral implant position recording using the iCam4D system based on multi-camera detection of calibrated optical reference markers.*

In an *in vitro* study conducted by Revilla-León et al., the accuracy of the iCam4D system was evaluated using a coordinate measuring machine (CMM) as the reference standard. The authors reported higher deviations for the photogrammetry group along certain spatial axes (Revilla-León et al., 2020). However, other investigations have demonstrated accuracy values within clinically acceptable limits under different experimental conditions. Collectively, these findings indicate that the accuracy performance of the iCam4D system is highly dependent on the evaluation metrics, reference standards, and methodological design employed in individual studies (Hussein, 2023).

2.1.3. Grammee and Micron Mapper Systems

The Grammee and Micron Mapper systems represent next-generation extraoral photogrammetry technologies developed to enhance the accuracy of implant position transfer using high-resolution imaging sensors and advanced data-processing algorithms. Among these systems, Micron Mapper has been specifically designed to improve clinical usability by incorporating an ergonomic system architecture and optimized software workflows, thereby facilitating efficient, reliable, and reproducible data acquisition (Prott et al., 2025) (Figure 3). Recent investigations have compared these photogrammetry systems with conventional intraoral scanners and grammetry-based measurement techniques. The findings indicate that photogrammetry groups generally demonstrate lower root mean square (RMS) deviation values in terms of both trueness and precision, underscoring the potential advantages of photogrammetric measurement—particularly in full-arch implant-supported rehabilitations (Prott et al., 2025). Despite these promising results, the availability of long-term clinical outcome data for the Grammee and Micron Mapper systems remains limited. Furthermore, additional well-controlled experimental and clinical studies are required to establish standardized evaluation protocols and to validate the reproducibility and clinical reliability of these systems across different clinical scenarios. (Revilla-León et al., 2025)

Figure 3: *Extraoral photogrammetry systems (Grammee and Micron Mapper) illustrating implant position recording through image-based acquisition and computational data processing*

2.1.4. OxoFit System

The OxoFit system is an implant position-transfer technology based on principles of extraoral photogrammetry, in which implant coordinates are calculated from the optical detection of coded scan bodies attached to the implants (Figure 4). Although the number of studies specifically evaluating the OxoFit system remains limited, the general advantages attributed to photogrammetric measurement—such as high accuracy in implant position transfer and reduced susceptibility to deformation-related errors—are considered applicable to this system as well (Hussein, 2023). Similar to other extraoral photogrammetry systems, OxoFit is restricted to the recording of implant positions and does not provide information regarding soft tissue morphology or occlusal relationships. Therefore, its clinical application typically requires integration with intraoral scanning within a combined digital workflow. (Revilla-León et al., 2025)

Figure 4: *Extraoral photogrammetric implant position capture using the OxoFit system based on optical detection of coded scan bodies.*

2.2. Intraoral Photogrammetry Systems

Intraoral photogrammetry systems are next-generation digital measurement technologies that integrate photogrammetric principles directly into intraoral scanner devices. These systems enable simultaneous acquisition of implant position data, soft-tissue morphology, and occlusal relationships within a single device and a unified digital workflow. As a result, the need for additional data merging and alignment steps—commonly required in extraoral photogrammetry workflows—is eliminated or substantially reduced, thereby enhancing both workflow efficiency and clinical reliability (Pozzi et al., 2025).

· *Aoralscan Elite (Shining 3D)*

Aoralscan Elite (Shining 3D) is among the first systems to integrate intraoral scanning and photogrammetry within a single portable device. The system employs two independent camera modules, one for surface scanning and the other for photogrammetric data acquisition, allowing the simultaneous recording of implant positions, soft tissue morphology, and maxillomandibular relationships in a single scanning procedure (Pozzi et al., 2025) (Figure 5). In an in vitro study by Pozzi et al., the mean three-dimensional Euclidean deviation (ΔEUC) for full-arch implant measurements obtained with Aoralscan Elite was reported to be approximately 57 μm, with a corresponding angular deviation of 0.26°. Both values were well below the thresholds commonly accepted for passive fit in implant-supported prostheses (150 μm and 1°, respectively), indicating a high level of measurement accuracy (Pozzi et al., 2025). By enabling the integration of implant position, soft-tissue, and occlusal data within a single STL file, intraoral photogrammetry simplifies the digital workflow and improves clinical efficiency. In this context, Aoralscan Elite represents a paradigmatic example of the ongoing transition toward single-device, single-workflow photogrammetric systems in full-arch implant rehabilitation. (Pozzi et al., 2025).

Figure 5: *The intraoral photogrammetry system Aoralscan Elite is illustrated.*

3. Literature-Based Comparative Evaluation of Photogrammetric Measurement Systems

In recent years, the number of studies comparing the accuracy of extraoral and intraoral photogrammetry systems has increased substantially. In the context of full-arch implant-supported fixed prostheses, the accuracy of implant position transfer is primarily evaluated using quantitative metrics such as linear deviation (ΔEUC), angular deviation, and root mean square (RMS) values. These parameters are widely used to assess both trueness and precision, and their relationship with the achievement of clinical passive fit is a central focus of contemporary investigations. (Revilla-León et al., 2025)

3.1. Comparison of Extraoral Photogrammetry Systems

In an in vitro study by Revilla-León et al. (2025), four extraoral photogrammetry systems (PIC, iCam4D, Grammee, and OxoFit) were compared with an intraoral photogrammetry system (Aoralscan Elite) following the ISO 20896-1:2019 standard. Measurements were performed using Geomagic Control X software, with a laboratory scanner serving as the reference. PIC and iCam4D demonstrated the lowest linear trueness values (approximately 17–18 µm). The PIC system showed the highest linear and angular precision, whereas Grammee exhibited the lowest angular trueness (≈0.17°). OxoFit demonstrated linear and angular accuracy comparable to Grammee but exhibited greater deviations than PIC and iCam4D. These results indicate that no single extraoral photogrammetry system can be considered universally superior; rather, system performance varies with the evaluated axis and accuracy metric (Revilla-León et al., 2025). Similarly, Abuduwaili et al. (2025) reported significantly lower RMS and angular deviation values for the PIC and iCam4D systems compared with conventional impressions and intraoral scanning. Although no statistically significant difference was observed between the two systems, both remained well below the widely accepted 150 µm passive-fit threshold.

3.2. Comparison of Extraoral and Intraoral Photogrammetry Systems

A major limitation of extraoral photogrammetry systems is their inability to directly capture soft tissue morphology, occlusal relationships, and antagonist arch information. Consequently, these systems require integration with intraoral scanners, which introduces additional data alignment steps and increases the risk of cumulative registration errors. In contrast, Revilla-León et al. (2025) reported that the Aoralscan Elite intraoral photogrammetry system achieved accuracy values statistically comparable to those of extraoral systems such as Grammee and OxoFit. The mean linear and angular deviations for intraoral photogrammetry were approximately 27 µm and 0.27°, respectively—both well below the clinically accepted thresholds of 150 µm and 1°, supporting its clinical reliability. Similarly, Fu et al. (2025) compared intraoral photogrammetry (IPG), extraoral photogrammetry (EPG), conventional intraoral scanning (IOS), and IOS augmented with auxiliary structures (IOSA). IPG demonstrated the lowest RMS trueness (≈26 µm), while EPG showed the highest RMS precision. No significant difference was observed between IPG and EPG in terms of angular deviation. Overall, these findings indicate that intraoral photogrammetry is not only a viable alternative to extraoral systems but may also offer advantages in specific accuracy metrics, depending on the evaluation criteria.

3.3. Evaluation in Terms of Clinical Significance and Passive Fit

The passive fit threshold originally defined by Jemt and consistently referenced in the literature is generally accepted to be approximately 150 µm. The mean deviation values reported in studies by Revilla-León et al. (2025), Abuduwaili et al. (2025), and Fu et al. (2025) for all evaluated photogrammetry systems were well below this threshold. These findings indicate that both extraoral and intraoral photogrammetry systems, when applied within properly designed clinical and digital workflows, can achieve the required accuracy to ensure passive fit in full-arch implant-supported fixed prosthetic rehabilitations.

3.4. Comparison of Photogrammetric Measurement Systems and Intraoral Scanners

Accurate and repeatable transfer of implant positions in full-arch implant-supported fixed prostheses is essential for achieving passive fit and minimizing long-term biomechanical complications. In contemporary digital workflows, implant position recording is primarily performed using conventional intraoral scanners (IOS) or photogrammetric measurement systems (Revilla-León et al., 2021; Hussein, 2023). Although IOS systems demonstrate clinically acceptable accuracy in single-tooth and short-span restorations, their performance decreases in full-arch implant cases. This reduction in accuracy has been attributed to the lack of stable anatomical reference points in extended edentulous regions, cumulative stitching errors inherent to surface-based scanning algorithms, and the destabilizing effect of mobile soft tissues—particularly in mandibular arches (Revilla-León et al., 2021; Negreiros et al., 2025). In contrast, photogrammetric systems rely on the simultaneous detection of optically coded reference elements using multi-camera configurations, thereby eliminating the need for sequential image stitching. As a result, photogrammetry consistently demonstrates lower linear, angular, and RMS deviations than IOS in full-arch implant measurements (Hussein, 2023; Altalla et al., 2025). Systematic reviews and meta-analyses further confirm the statistical superiority of photogrammetry over IOS in terms of both trueness and precision in complex implant rehabilitations (Altalla et al., 2025). Comparative studies by Revilla-León et al. reported linear deviations of approximately 10–30 µm and angular deviations of 0.17–0.34° for extraoral photogrammetry systems, whereas IOS groups exhibited higher deviations, particularly along the Y-axis and YZ angular plane (Revilla-León et al., 2021; Revilla-León et al., 2025). These findings highlight the greater predictability of photogrammetry in full-arch implant position transfer.

A key limitation of extraoral photogrammetry systems is their inability to capture soft tissue morphology, occlusal relationships, and antagonist arch information, necessitating additional intraoral scanning or conventional impression steps and introducing potential data registration errors. To overcome these limitations, intraoral photogrammetry (IPG) systems have been developed that integrate implant position recording and surface scanning within a single device and a unified digital workflow. (Hussein, 2023; Revilla-León et al., 2025). Recent in vitro and in vivo studies indicate that IPG systems achieve accuracy comparable to extraoral photogrammetry while significantly outperforming conventional IOS approaches (Brakoč et al., 2025; Revilla-León et al., 2025). Notably, IPG systems have demonstrated lower deviation values across multiple accuracy metrics and superior repeatability, particularly in mandibular full-arch cases (Negreiros et al., 2025; Pozzi et al., 2025).

In summary, while conventional IOS systems show limited reliability in full-arch implant measurements, extraoral photogrammetry provides high accuracy at the cost of additional workflow complexity. Intraoral photogrammetry systems represent a balanced and evolving solution, combining high measurement accuracy with streamlined clinical workflows, and are therefore increasingly favored in full-arch implant-supported rehabilitations (Hussein, 2023; Revilla-León et al., 2025; Altalla et al., 2025).

4. The Future of Photogrammetry in Implant Dentistry and Emerging Directions

Photogrammetric measurement technologies have undergone significant evolution in recent years, largely driven by the increasing demand for high-accuracy transfer of implant positions in implant dentistry. Early photogrammetric applications were limited by complex optical setups and restricted clinical accessibility; however, contemporary systems have progressed toward compact, user-friendly, and clinically adaptable designs that can be efficiently integrated into digital workflows (Hussein, 2023; Revilla-León et al., 2025).

Current literature indicates that photogrammetry has moved beyond its role as an alternative to conventional intraoral scanners and is increasingly being recognized as a reference digital measurement approach in full-arch implant rehabilitation. This paradigm shift is primarily attributed to superior measurement accuracy, streamlined clinical and laboratory workflows, and the development of patient-centered digital solutions that enable more predictable and efficient implant-supported prosthetic outcomes (Altalla et al., 2025).

5. Transition from Extraoral Photogrammetry to Intraoral and Mobile Systems

One of the most significant trends shaping the future of photogrammetry is the technological shift from extraoral to intraoral measurement systems. Although extraoral photogrammetry systems—such as PIC, iCam4D, Grammee, and OxoFit—demonstrate high trueness and precision, their inability to directly capture soft tissue morphology and occlusal relationships necessitates additional data acquisition and alignment steps within the clinical workflow (Revilla-León et al., 2025).

These limitations have accelerated the integration of photogrammetric principles into intraoral scanner platforms, leading to the development of intraoral photogrammetry (IPG). Current evidence indicates that IPG systems achieve accuracy comparable to extraoral photogrammetry while providing significantly higher trueness and precision than conventional intraoral scanners (Brakoč et al., 2025; Negreiros et al., 2025). Collectively, these findings suggest that photogrammetry is evolving toward single-device, single-workflow digital measurement solutions, representing a paradigm shift in digital implant impression technologies.

6. Smartphone-Based Photogrammetry Systems

Another emerging direction in the evolution of photogrammetry is the development of smartphone-based photogrammetric systems. Recent in vivo and in vitro studies have demonstrated that implant positions can be recorded with clinically acceptable accuracy using high-resolution smartphone cameras combined with advanced photogrammetric algorithms (Santamaría-Laorden et al., 2025). By reducing dependence on dedicated and costly hardware, this approach has the potential to broaden the clinical accessibility of photogrammetry. Reported linear deviations of approximately 20–25 µm and angular deviations around 0.20° suggest that smartphone-based photogrammetry extends beyond an experimental concept and may represent a clinically viable alternative for implant position transfer. These findings indicate that future photogrammetric systems may become increasingly portable, economical, and widely applicable in digital implant dentistry (Santamaría-Laorden et al., 2025).

7. Current Limitations and Areas for Improvement

Despite significant technological advances in photogrammetry, the current literature still identifies several fundamental limitations. These include the scarcity of long-term clinical outcome data, the lack of standardized evaluation and validation protocols across different photogrammetry systems, and the continued dependence on indirect methods for soft tissue data acquisition (Altalla et al., 2025; Hussein, 2023). Moreover, well-designed prospective clinical studies are needed to clarify how the high accuracy reported for photogrammetric systems translates into clinically relevant outcomes, such as screw loosening, framework fracture, and biological complications associated with implant-supported prostheses.

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Chapter
4

DIGITAL OCCLUSAL ANALYSIS

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1. THE CONCEPT OF OCCLUSAL ANALYSIS

According to the *Glossary of Prosthodontic Terms* published in 2017, occlusion is defined as the static relationship between the masticatory surfaces of the maxillary and mandibular teeth (Sutter & Rettie, 2019). When the teeth come into occlusion, occlusal forces should be distributed in a balanced manner. Proper establishment of occlusal contacts is essential for the healthy performance of masticatory function (Sutter & Rettie, 2019).

Occlusion is not a concept limited solely to the reciprocal contact between teeth; it also encompasses the harmonious and coordinated functioning of all components of the masticatory system. These components include the teeth, periodontal tissues, the neuromuscular system, masticatory muscles, the temporomandibular joint, and the craniofacial skeletal structures.

The proper distribution of occlusal forces is a critical factor across many dental disciplines. A balanced and functional occlusion constitutes the foundation of all fields of dentistry, and for the maintenance of healthy function, occlusal contacts must be compatible with the stomatognathic system. In the presence of unbalanced occlusal contacts, the temporomandibular joint, teeth, periodontal tissues, and neuromuscular system may be adversely affected. Furthermore, excessive loading may lead to complications and fractures in existing implants and restorations.

All dental disciplines require clinicians to evaluate the articulation of teeth and/or prostheses in terms of simultaneous contacts, bite force, and contact timing. The assessment of dental occlusal forces in clinical practice is largely based on non-digital occlusal indicators (such as articulating paper and shimstock) and subjective patient feedback. However, while these methods can identify the presence of contact, they do not provide quantitative or objective data regarding the magnitude, distribution, or timing of occlusal forces. Consequently, the findings require clinical interpretation, making the evaluation process more complex and potentially less objective.

2. OCCLUSAL ANALYSIS WİTH CONVENTİONAL TECHNIQUES

Interocclusal records are obtained using various materials, each expected to meet specific requirements. The material used should precisely record intercuspation without displacing the teeth, exhibit no dimensional changes after setting, and provide sufficient rigidity. It should not hinder normal mandibular movements during closure, should offer minimal resistance, be biocompatible, and not cause tissue damage. However, no recording material currently available fulfils all of these ideal properties simultaneously. Conventional tools for evaluating occlusal relationships include articulating paper, silicone-based bite registration materials, metallic foils, silk strips, and occlusal sprays (Kerstein & Radke, 2014).

In contacts recorded with articulating paper, there is no scientifically established correlation between color intensity and the depth of the mark, surface area, magnitude of applied force, or sequence of contact timing. Furthermore, articulating papers can be easily affected by saliva, may tear or wrinkle under biting force, are generally thick, and often have relatively inelastic backing materials. These factors are thought to contribute to a high incidence of pseudo-contact markings. Similarly, shimstock foils (12 µm thick), occlusal waxes, and silicone pastes are unable to accurately reproduce occlusal contacts. The sensitivity and reliability of these techniques are highly susceptible to errors related to the thickness, durability, and elasticity of the materials in the oral environment, which may lead to distortion of the recorded marks (Buser et al., 2018). Most importantly, the accuracy of occlusal analyses performed with these systems largely depends on subjective interpretation and may vary among clinicians. In addition, these methods are limited to identifying the location and number of contacts; they do not have the capacity to quantitatively measure occlusal load. Nevertheless, conventional occlusal analysis methods—particularly articulating paper—remain widely used today due to their ease of application, practicality, and low cost.

3. DIGITAL OCCLUSAL ANALYSIS

In recent years, digitalization in dentistry has led to a significant transformation in occlusal analysis and recording methods. Digital systems enable repeatable measurements, time efficiency, accurate assessment of force distribution, and close monitoring of the restoration design process in the evaluation of occlusal relationships. This allows occlusal adjustments to be tailored to the individual needs of each patient. By accurately displaying contacts occurring during the three-dimensional movements of the mandible, these systems enhance measurement precision. Technological devices improve both diagnostic and treatment accuracy, reduce the time required for many clinical procedures, and facilitate the more precise application of definitive restorations.

Virtual articulators, CAD-CAM technologies, pressure-sensitive sensors, computer-assisted occlusal analysis system and jaw-tracking devices represent the principal digital tools currently used to evaluate and define occlusal relationships (Sutter & Rettie, 2019).

3.1. Virtual Articulators

Mechanical articulators can simulate tooth and joint movements only within fixed mechanical constraints; therefore, they cannot fully replicate biological factors such as muscle activity, soft-tissue resistance, and tooth mobility. In addition, the materials and techniques used during model mounting may influence measurement accuracy due to factors such as dental stone expansion or shrinkage, deformation of bite registration materials, and the stability of the articulator. For these reasons, the precise simulation of protrusive and lateral contacts is limited in mechanical articulators (Szentpétery, 1999).

The concept of virtual reality has been adapted to dentistry through computer technology and digital applications. Virtual articulators enable comprehensive analysis of static and dynamic occlusion, intermaxillary relationships, and joint conditions through three-dimensional dynamic visualization of the mandible and maxilla. Furthermore, users can select specific cross-sectional planes to perform a detailed examination of areas of interest. When integrated with CAD/CAM technology, virtual models can be used for both diagnosis and treatment planning, allowing various prosthetic treatments—from a single crown to full-mouth rehabilitation—to be carried out more accurately and systematically. Virtual articulators offer significant advantages not only in prosthodontics but also in orthodontics and dental implant surgery (Sabalic & Schoener, 2017).

3.1.1. Evaluation and Classification of Virtual Articulators

There are two main types of virtual articulators: mathematically simulated and fully adjustable articulators.

3.1.1.1. Mathematically Simulated Articulators

This type of articulator was first developed by Szentpetery and is based on the simulation of mandibular movements using mathematical models. In this system, movement parameters such as condylar inclination, the Bennett angle, and retrusive, laterotrusive, and protrusive movements are defined using computational algorithms. This allows the digital acquisition of motion components that cannot be directly measured in some mechanical articulators. Based on the calculated data, the device can automatically replicate mandibular movements in a manner similar to that of a mechanical articulator (Mitchell & Wilkie, 1978). This approach makes mathematically simulated articulators more flexible and versatile compared to mechanical systems.

However, since this modelling method generally relies on average anatomical values, it has limitations in accurately reflecting patient-specific individual mandibular movements, similar to mechanical articulators. Examples of mathematically simulated articulators include the Stratos 200 (Ivoclar Vivadent; Amherst, NY) and the virtual articulator systems developed by Szentpetery (Gugwad, Kore, & Basavakumar, 2011).

3.1.1.2. Completely Adjustable Articulators

These articulators were first designed by Gaertner and Kordass and are capable of recording and reproducing precise mandibular movements using an electronic jaw-recording system known as a jaw movement analyser. The system tracks mandibular motion to detect retrusion, protrusion, and laterotrusion. These recorded movements are then converted into numerical data, which can be programmed into fully adjustable articulators such as the KaVo Protarevo 7 (KaVo Dental GmbH), SAM 2 (SAM Prazisionstechnik GmbH), Artex CR (Amann Girrbach AG), or Stratos 300 (Ivoclar Vivadent; Amherst, NY). In addition, in some of these systems, the recorded mandibular movements can be integrated into computer-aided design (CAD) software via .xml files. Using the CAD system, the software can visualise both dynamic and static occlusal contacts and identify necessary adjustments during occlusal redesign. A color scale consisting of yellow, red, and blue is used to represent contact points. Furthermore, the program allows the selection of a distance corresponding to the thickness of occlusion paper used in mechanical articulators for occlusal detection. Occlusal contact points can then be calculated based on this defined distance. This virtual articulator enhances communication between clinical practice and the dental laboratory and facilitates the production of optimally fitting occlusal restorations (Koralakunte & Aljanakh, 2014).

3.1.2. Operation of Virtual Articulators

The core system of a virtual articulator generates an animated simulation of mandibular movements based on input data and calculates occlusal contact points, which are displayed on the screen using a specific coding system.

Ideally, a virtual articulator should be equipped with a device that records a patient's mandibular movements (e.g., JMA) and integrates them into the animation. If a device for recording mandibular movements is not available, the movements must be defined using parameters in a manner similar to methods employed in mechanical articulators.

Some of the parameters that can be considered in this case include:

·**Protrusion:** condylar guide radius, maximum protrusive distance

·**Retrusion:** condylar guide radius, maximum retrusive distance

·**Laterotrusion:** maximum protrusion, Bennett angle, right and left condylar guide radius, right and left horizontal condylar inclination, phase angle, lateral displacement

·**Opening/closing inclination:** maximum opening angle

Once the movement parameters are defined, collision detection should be performed to determine movement limitations. In this context, leaving a distance equal to the thickness of the occlusal paper used in mechanical articulators can be useful for calculating occlusal contact points relative to that distance (Kalpana et al., 2018).

The first functional software for a virtual articulator, **DentCAM** (KaVo Dental, Hamburg, Germany), was introduced at the University of Greifswald. DentCAM provides three main windows for visualizing tooth movements from different perspectives:

a) Rendering Window: Early contacts and occlusal interferences during mandibular movements can be analyzed in this window. It allows observation from unconventional viewpoints—for example, viewing the occlusal surface of the opposing teeth during mastication. This window also provides the option to create animations and export them.

b) Occlusion Window: This window displays the contact points that occur over time on the occlusal surfaces of the maxillary and mandibular teeth. The speed of movement can be controlled with sliders, while contact force can be differentiated using color coding. A smaller inset shows the movements of the temporomandibular joint (TMJ) in sagittal and transverse views, allowing analysis and diagnosis of the interdependence between tooth contacts and TMJ motion.

c) Section Window: Provides different frontal cross-sections along the dental arch. This tool can be used to analyze the degree of intercuspation, cusp heights, and functional angles, making occlusal analysis more practical and precise.

2.1.3. Workflow of Virtual Articulation

The fundamental components of all current virtual articulators include data acquisition, data transfer to a digital environment, and the subsequent articulation of virtual models. In this context, the key steps to understanding the process are: digitally representing the dental arches, recording mandibular movements and static occlusal conditions, transferring the maxilla's position relative to the skull, and placing the virtual models into the virtual articulator. The exact procedures may vary depending on the equipment and techniques used, and clinicians may choose different methods to optimize the workflow according to each patient's diagnostic and treatment goals.

1. Creation of a Virtual 3D Model: Maxillary and mandibular arch data can be obtained using an intraoral scanner (IOS) or a desktop laboratory scanner (DLS). When using an IOS, this method is considered "direct," whereas scanning conventional plaster models is referred to as "indirect."

2. Occlusal Record Acquisition: Scanning is performed in the maximum intercuspation position to allow the mandibular model to be accurately positioned relative to the maxilla.

3. Integration of the Virtual Facebow: The facebow used during virtual articulator mounting ensures alignment of the maxilla relative to the patient's skull. A jaw-tracking system uses reference points fixed to the patient's mandible to establish a reference plane based on the hinge axis and the infraorbital plane. The spatial positions of these points are measured using ultrasonography, and patient-specific masticatory movements are simulated within the virtual articulator. If a jaw tracking system is unavailable, different mandibular movements can be defined using parameters similar to those used in mechanical articulators.

4. Integration of Digital Models into the Virtual Articulator: The scanned maxillary and mandibular arches are exported as STL files and imported into dental CAD software. Using the patient's natural head position as a reference, a horizontal plane is recorded, and the virtual patient model is aligned in 3D. Once the digital models are transferred into the virtual articulator, the maxilla is positioned using the facebow, and the mandible is aligned using an electronic bite record. This enables three-dimensional visualization of occlusion and prepares the system for kinematic analysis (Solaberrieta, Minguez, Etxaniz, & Barrenetxea, 2013).

The use of virtual articulators in dentistry offers significant advantages in both clinical and laboratory applications, though some limitations exist. Virtual articulators enhance communication between the dentist, dental technician, and patient, making the treatment process more comprehensible and predictable. When integrated with CAD/CAM systems, they enable the digital design of occlusal surfaces, the evaluation of static and dynamic occlusion, and the analysis of jaw- and joint-related disorders. Three-dimensional visualization of occlusal contacts and masticatory function also contributes to reducing production errors. Streamlined workflows save time for both clinicians and technicians and serve as an effective tool for patient education and rehabilitation.

However, virtual articulators have certain drawbacks. In many systems, models must first be mounted on a mechanical articulator using a physical facebow and plaster, which is then scanned. This requirement for additional equipment makes the process time-consuming and labor-intensive. Moreover, virtual articulators rely on supplementary technologies, such as digital sensors, scanners, software, and various virtual articulator models, which can replicate mechanical articulators to meet patient needs, resulting in high acquisition and operational costs. (10) Furthermore, effective use of virtual articulators requires advanced technical knowledge and experience in data input, evaluation of scanner-acquired records, definition of mandibular movement parameters, mechanical articulators, CAD/CAM technology, and associated software. Analyzing data from sensors and scanners, implementing minor design adjustments, and correctly integrating movement parameters also demand additional user skills. Consequently, while virtual articulators offer high accuracy and clinical advantages, their widespread adoption depends on cost, technical infrastructure, and user expertise.

In conclusion, the virtual articulator is a precise tool that enables comprehensive analysis of occlusion in a real patient and assists the clinician in diagnosis and in establishing the most appropriate treatment plan.

3.2. Intraoral Scanners

With the increasing adoption of fully digital workflows in dentistry, intraoral scanners (IOS) have become essential tools for accurately capturing dental arches and interocclusal relationships. The precise and reliable transfer of interarch relationships to computer-aided design and manufacturing (CAD-CAM) software is critical for fabricating restorations with clinically appropriate and accurate occlusal morphology. By ensuring proper occlusal form in the digital design stage, the need for clinical occlusal adjustments can be minimized, improving both treatment efficiency and patient comfort.

IOS technologies have gained widespread use, particularly in prosthodontics and orthodontics, due to their ability to shorten procedure times, reduce the number of clinical sessions, and enhance comfort for both patients and clinicians. Currently, the accuracy of digitally obtained dental arches has reached a level comparable to conventional impression and measurement techniques, establishing a solid foundation for contemporary digital dentistry workflows. However, successful prosthetic rehabilitation depends not only on acquiring accurate dental arch data but also on accurately capturing the arches' static and dynamic three-dimensional relationships.

The digital dentistry workflow primarily consists of digitization systems, CAD software, and computer-aided manufacturing (CAM) units, with the initial stage involving the direct acquisition of patient-specific three-dimensional virtual models in the clinical setting using intraoral scanners (IOS) (Chinam et al., 2023).

The dental literature has analysed both operator- and patient-related factors that may influence the scanning accuracy of IOS, as well as variables that can affect the accuracy of the maxillo-mandibular relationship in virtual models generated by IOS.

Operator skills and decision-making processes play a significant role in IOS accuracy. These include the selection of the IOS technology and system, the size of the scanning tip, calibration procedures, scanning distance and angulation, exposure of the IOS to ambient temperature variations, environmental humidity and lighting conditions, operator experience, scanning pattern, scanning coverage, as well as procedures such as cutting off, rescanning, and overlapping.

Patient-related factors refer to intraoral conditions that can affect scanning accuracy. These include tooth type, the presence of interdental spaces, arch width, palatal characteristics, intraoral moisture, existing restorations, the properties of the digitized surfaces, edentulous areas, inter-implant distances, the position, angulation, and depth of existing implants, and the design of implant scan bodies.

The accurate and reliable transfer of interocclusal relationships to CAD-CAM software is essential for producing restorations with proper occlusal morphology and for minimizing occlusal adjustments during clinical application. Consequently, occlusal relationships must be accurately recorded and evaluated in the digital environment. Using digital workflows, the upper and lower arches and the interocclusal relationship can be fully digitised on an iOS device, thereby completing virtual articulation. This allows for precise documentation of the patient's interarch relationship and enables efficient communication with the dental technician.

Numerous techniques for establishing virtual articulation within digital models have been documented in the scholarly literature. The initial method involves manual alignment, wherein three reference points are selected on the maxillary digital model and their corresponding points on the mandibular model. An appropriate algorithm is subsequently employed to match these points, thereby aligning the virtual counterparts. This process is iteratively repeated until the optimal occlusal fit is attained. Although effective, the manual approach presents notable limitations, including the potential for unpredictable results and the necessity of marking teeth and defining contact points for interocclusal registration, which increases the time required relative to traditional techniques. A more prevalent alternative involves utilizing a scanned interocclusal record. In this methodology, the scanned interocclusal record is aligned with the maxillary digital model, which is positioned over the mandibular model. Alternatively, an independently scanned interocclusal record can be simultaneously aligned with both the maxillary and mandibular models to achieve precise virtual articulation (Rola Shadid & Nasrin Sadaqah, 2022).

Another widely used approach is the buccal occlusal scan method. Here, the maxillary and mandibular arches are first scanned separately. Then, while the patient is in the maximum intercuspation position (MIP), the buccal surfaces of the upper and lower teeth are digitally recorded. Subsequently, specialised software automatically aligns the virtual arches. This procedure can also be performed intraorally, providing an efficient, patient-friendly method for obtaining an accurate virtual occlusal record (Chinam et al., 2023).

Computer-aided occlusal analysis is performed using a digitally generated occlusal contact map. This map provides a visual representation of the interocclusal distances calculated by the intraoral scanner software after recording the jaw relationship. Differences in the distances between the functional surfaces of opposing teeth are indicated using various colors, resulting in a digital, color-coded occlusion map that illustrates the distribution of occlusal contacts (Schütze, 2023).

Occlusal analysis performed with intraoral scanners provides clinicians with valuable information. However, it cannot measure bite force, bite timing, pressure on individual teeth, pressure distribution, dynamic contacts, or changes in pressure during movement. Therefore, integrating it with pressure-sensitive systems, such as Occlusense, can provide more accurate and comprehensive data.

3.3. Pressure-Sensitive Films

The Dental Prescale System (Fujifilm Co., Tokyo, Japan), introduced in 1990, consists of a 150 µm-thick pressure-sensitive film (Dental Prescale; Fujifilm Co., Tokyo, Japan) and a computer device for film analysis (Occluzer FPD-703; Fujifilm Co., Tokyo, Japan). The horseshoe-shaped, moisture-resistant film contains color capsules sandwiched between two polyethylene terephthalate layers along with a developer solution (Wang, Chang, Yang, & Lin, 2022). Typically, two separate films are used for the maxilla and mandible, and the patient's bite is recorded in maximum intercuspation. When bite force is applied, the color capsules rupture, and their contents react with the developer solution to produce a red color. As the pressure increases, the intensity of the red color also increases. For analysis, the film is placed in the Occluzer device, which provides information on the number, location, magnitude, and distribution of occlusal contacts (Shiga et al., 2020).

The system is simple and cost-effective, visually displays contact points and overall force distribution, and can be used in both academic and clinical practice. However, it has several limitations: it only shows static forces and contact areas without providing information on dynamic occlusal forces; it cannot measure contact timing; it has low sensitivity in anterior teeth and small contacts; the film thickness may interfere with proprioceptive signals during maximum intercuspation; and the films are single-use (Lee, Cha, Chun, & Kim, 2018).

3.4. Computer-Assisted Occlusal Analysis Methods

3.4.1. T-Scan

The concept of digital occlusion emerged in 1984 with the development of the T-Scan I system, which enabled objective measurement of occlusal contact timing and force. This innovation paved the way for replacing decades-old subjective methods with numerical, reproducible measurements. In 1987, Maness and colleagues reported the development of a prototype computer-assisted occlusal analysis device, establishing the scientific foundations of the system. The first-generation T-Scan I utilized Mylar-coated sensor technology, capable of collecting 4-bit resolution data and distinguishing 16 different force levels (Kerstein, 2020).

Over time, the system has undergone significant technological advancements. In the mid-1990s, T-Scan II was introduced with higher resolution and greater force-measurement capacity. Subsequently, T-Scan III with turbo recording, the T-Scan Novus sensor handle, and the latest software version, T-Scan v10, became available. In the current versions, 8-bit resolution allows measurement of 256 relative force levels, and the sequence of occlusal contacts can be recorded in millisecond intervals. The high-resolution (HD) Novus Mylar-coated electronic printed circuit sensors used in T-Scan 10 offer significant improvements over earlier epoxy-based sensors in terms of composition, thickness, flexibility, and accuracy. These pressure-sensitive sensors, approximately 100 µm thick, are shaped to match the dental arch and contain a conductive ink layer. They are saliva-resistant, can be cleaned with alcohol, and reused on the same patient (Somkuwar, 2015).

The T-Scan system consists of a sensor handle, sensor holder, thin pressure-sensitive sensor, and computer software. When the patient bites the sensor, changes in the conductive structure are converted into digital data, recording the occlusal forces. The collected data can be visualized in real time on a computer screen, and the process from initial contact to maximum intercuspation can be analyzed as a time sequence. The order of occlusal contact formation and the distribution of forces across teeth are displayed on two- and three-dimensional graphs using a color scale (from blue to red).

The two-dimensional dental arch graph includes a "center of force" indicator, which helps evaluate the distribution of occlusal forces. This indicator dynamically shows the movement of force from lower-intensity areas to higher-intensity regions as a red trace. Clinicians can monitor force balance across the arch in real time and make adjustments if necessary. T-Scan can identify premature contacts, the sequence of achieving maximum intercuspation, areas of excessive force, and the percentage of force borne by each tooth. It can also track force transitions across the dental arch during eccentric movements, providing warnings for potential overload on implant restorations. Some versions can synchronise with EMG software, enabling real-time analysis of the relationship between muscle activity and occlusal contacts (Sutter, 2019).

A key benefit of T-Scan is its capacity to display occlusion as a dynamic process rather than a static one. It allows for instant analysis of force distribution in various mandibular positions, and post-treatment occlusal conditions can be digitally recorded and compared. This feature improves objectivity in treatment planning and outcome evaluation while decreasing the clinician's dependence on subjective interpretation. For educational purposes, the system visually shows changes in occlusal contacts and force distribution over time, helping students' understanding. However, repeated and prolonged use of the sensors may lead to decreased sensitivity. T-Scan can be used in various dental disciplines, including implant-supported prosthetics, temporomandibular joint (TMJ) disorders, occlusal adjustments, orthodontics, and periodontal evaluations. The system generally comprises pressure-sensitive foil/sensors, bite forks of various sizes (small/large), a holder, and analysis software.

Current versions feature the Digital Impression Overlay (DIO) function, which allows the occlusal force data to be overlaid on the patient's digital impression in ".stl" format. This integration enables the evaluation of force distribution directly on a three-dimensional digital model (Anselmi & Kerstein, 2020). While intraoral scanners can indicate occlusal contact points during restoration design, they cannot provide detailed, time-dependent information about the sequence of contact formation or the magnitude of applied forces. Integrating T-Scan data with digital models enables a comprehensive analysis that captures not only contact locations but also force intensity and timing.

3.4.2. OccluSense

The OccluSense is a computer-assisted system developed by Bausch for the digital analysis of occlusal contact location and force distribution. Introduced in 2017 and later released commercially, OccluSense is positioned as a more cost-effective alternative to T-Scan. The system uses a thin, flexible pressure sensor to evaluate both static and dynamic occlusion (Sutter, 2019).

The OccluSense sensor is approximately 60 µm thick, flexible, and features a red coating that functions similarly to articulation paper, visually marking contact points on teeth. This allows simultaneous digital force analysis and clinical observation.

Data collected during recording is gathered via a handheld sensor handle and transmitted wirelessly to an iPad application. The clinician can view occlusal data in both two-dimensional (2D) and three-dimensional (3D) formats. Force distribution is displayed as percentages, clearly indicating which teeth or quadrants bear greater load.

The system represents the entire dental arch with different colors. In the 3D view, contact points appear as columns, with column height corresponding to relative masticatory pressure. The color scale reflects pressure differences (Δp) between contacts. Small, localized contacts generally appear in orange-red tones, while broader contact areas are shown in yellow-green tones. Individual red points may indicate premature contacts, contacts not in maximum intercuspation, or initial contacts during dynamic movements. Green columns represent more balanced and broader contact areas. Column height indicates relative force magnitude, while color indicates pressure variation (Aung & Nyan, 2022).

The OccluSense can record contacts not only during static closure but also during mandibular movements such as protrusion and laterotrusion. Occlusal movements can be reviewed like a video, allowing the recording to be paused, rewound, fast-forwarded, or filtered for specific segments. This feature enables detailed analysis of dynamic occlusion (Jauregi et al., 2023).

3.5. JAW TRACKING SYSTEMS

In full-mouth rehabilitation, digital integration enables the development of a comprehensive and standardized workflow by allowing detailed diagnostics, rapid and efficient data acquisition, and direct processing of data in a virtual environment. Various systems are available for recording mandibular movement, including ultrasonic devices, magnetic sensors, cinematography-based video analysis, optoelectronic imaging, radiographic video X-ray fluoroscopy, and computed tomography (CT) (Tian, Dai, Li, Li, Sun, & Cheng, 2020).

Jaw tracking systems can be categorized into two main groups based on their functional capabilities: systems intended solely for diagnostic purposes (data acquisition and analysis) and systems that provide both diagnostic and design integration capabilities.

Diagnostic systems allow recording a patient's mandibular movements and analysing them within the system's software; however, the resulting data cannot be exported. Examples of such systems without CAD integration include the JT-3D Jaw Tracking System (BioRESEARCH Assoc., Inc., Milwaukee) and the K7x Jaw Tracking System (Myotronics-Noromed, Inc., Kent, WA, USA). Today, CAD compatibility can be achieved via systems such as SICAT (.jmtxd to Cerec, inLab), Zebris, and MODJAW (.xml, e.g., for Exocad). In contrast, systems that combine diagnostic and design capabilities and support CAD integration enable the export of recorded mandibular movements for use within CAD software.

Ultrasonic jaw tracking systems operate using an ultrasonic emitter (transmitter) attached to the mandibular teeth and sensors or microphones placed on the patient's head. The operator typically defines a plane based on two condylar reference points and one infraorbital reference point. The system tracks the motion of at least three points relative to this reference plane to determine all degrees of freedom of the mandible, including its rotation and precise spatial position. Ultrasonic signal travel times from the emitters to the receivers are measured in real time, and these time differences are used to calculate the mandible's relative movement with respect to the head. Based on the collected data, three-dimensional mandibular motion is reconstructed over a triangular plane formed between the condylar points and the system's reference position; this plane is used to identify the mandible's target position (Enciso et al., 2003). Examples of ultrasonic systems include the Jaw Motion Analyzer (JMA; Zebris, Germany) and Arcus Digma (KaVo, Germany). In Arcus Digma, for instance, a four-microphone frame fixed to the skull works in conjunction with a three-pin support system attached to the mandible. During jaw movement, the microphones detect signals at different frequencies, calculating the distance between the mandible and the head with high accuracy. Recordings from these systems can be used for mandibular movement analysis, comparison of occlusal positions, assessment of temporomandibular joint (TMJ) disorders, and evaluation of muscle activity. However, ultrasonic-based devices can be affected by environmental noise and temperature fluctuations, and positional accuracy may deviate by up to approximately 0.1 mm even after calibration (Tian, Dai, Li, Li, Sun, & Cheng, 2020).

Optoelectronic jaw tracking systems operate based on tracking infrared markers placed on specific anatomical regions of the face using high-speed digital cameras and specialized software. The cameras capture hundreds to thousands of frames per second, recording marker position changes, and the data are transmitted to a display in real time. An example of this technology is the Bionic Jaw Motion (BJM) system, which works with specialized software that allows mandibular movements to be reproduced on a robotic simulator (Bedrossian et al., 2022).

Similarly, Freecorder BlueFox is an optical-based recording system capable of capturing all mandibular movements as well as individual mandibular positions. In this method, a reference frame is first attached to the skull for orientation using the ears and nasal bridge. A lighter second frame is placed on the mandible, and movements are tracked through this module. Special cameras capture approximately 100 images per second, enabling high-resolution recordings.

In 2016, Planmeca introduced the 4D Jaw Motion Module, an optoelectronic tracking system compatible with the ProMax 3D Mid and ProMax 3D Max CBCT devices. This system uses two digital cameras to track reflective spheres temporarily attached to the skull and mandible. The software can visualize and measure TMJ movements in real time. By analyzing mouth opening movements, it determines the rotational center of the condylar head, providing data useful for advanced treatment planning, particularly for total TMJ replacement (Van der Helm et al., 2023).

Other optoelectronic systems include Modjaw (Villeurbanne, France) and SDiMatriX (Zurich, Switzerland). Modjaw, an AI-supported digital jaw-tracking system, records mandibular movements around the hinge axis and provides detailed analyses of occlusal and chewing patterns. The recorded data can be transferred to virtual articulators, serving as an alternative to conventional facebows, axiography, and mechanical articulators. Without requiring CBCT data, Modjaw can capture mandibular movements optically and create a kinematic model based solely on movement data (Manziuc et al., 2024)

Modjaw processes dynamic recordings in 3D and 4D formats, automatically calculating occlusal parameters such as Spee curve, Bennett angles, and condylar inclinations, and generates dynamic occlusal maps. It integrates 3D models, 4D motion records, CBCT data, and facial scans to create a comprehensive digital model of the patient. The system records jaw movements via an intraoral bite fork and head-mounted components. The camera captures movements as point-based animations, while the software reproduces these movements in real time on 3D models. All movements are recorded live, allowing clinicians to analyze, replay, or re-record if necessary.

This time-based movement recording approach is referred to as 4D CAD-CAM technology. Patients are not exposed to continuous radiation, and the system hardware is lightweight and comfortable. Both static and dynamic occlusal interferences, occlusal guidance issues, and TMJ pathologies can be detected in real time.

4. CONCLUSION

Digital occlusion analysis and recording technologies—including intraoral scanners, jaw tracking systems, virtual articulators, and computer-aided occlusal analysis devices—play a significant role in diagnosis and treatment planning in prosthetic dentistry. These systems enable more detailed assessment of static and dynamic occlusion, the digital capture of individual mandibular movements, and the patient-specific design of restorations. Additionally, digital workflows offer advantages such as time savings, data reproducibility, and enhanced patient comfort, thereby optimizing clinical procedures.

However, a review of the current literature reveals no definitive consensus on the accuracy of these technologies. In particular, the recording of the maxillomandibular relationship can be influenced by numerous variables, including the scanning technique used, the characteristics of virtual records, the presence of edentulous areas, and the underlying software infrastructure. Similarly, the clinical accuracy and long-term efficacy of ultrasonic, optoelectronic, and artificial intelligence–assisted jaw-tracking systems require more comprehensive, comparative studies.

Computer-aided occlusal analysis systems provide objective and quantifiable data, particularly regarding contact areas and force distribution at maximum bite force. Nevertheless, some studies indicate that conventional occlusal recording methods remain highly reliable and valid. This suggests that, despite the clinical potential of digital systems, their accuracy and standardisation require further research to be adequately supported.

In conclusion, digital occlusion analysis and jaw movement recording systems are increasingly integrated into modern dentistry and have the potential to become part of standard clinical practice in the future. However, to be adopted with confidence for routine clinical use, these technologies require additional high-level scientific evidence on their accuracy, clinical impact, cost-effectiveness, and user experience.

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