Registration and data-merging strategies between photogrammetry and intraoral scanners in completely edentulous implant arches: a technical and clinical review

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ABSTRACT

Background: Digital capture methods like intraoral scanners (IOS) and photogrammetry/stereophotogrammetry (PG/SPG) are being used more frequently in complete-arch, implant-supported prosthetic workflows for arches that don't have any teeth. For passive fit and long-term success of a prosthesis, it is very important to accurately register and merge data from IOS soft-tissue scans with implant position data from PG or IOS.

Objective: To assess current registration and merging methodologies between photogrammetry and intraoral scanners for completely edentulous implant arches, summarise the technical and practical challenges, evaluate the existing evidence regarding accuracy and clinical relevance, and propose recommended clinical protocols and research priorities.

Methods: A narrative, evidence-based review of peer-reviewed literature (clinical studies, in vitro comparisons, systematic reviews, technical reports) regarding photogrammetry, intraoral scanning, implant scan bodies, and registration methods for full-arch/edentulous implant cases (searches conducted across PubMed/PMC, Scopus, Wiley, MDPI, JPD, and other dental sources; 2013–2025). It included important references and descriptions of technical devices.

Results: In many full-arch situations, photogrammetry and stereophotogrammetry systems are better at capturing implant positions than IOS. They also have better angular and linear fidelity in multi-implant, completely edentulous arches. IOS offers comprehensive soft-tissue and mucosal surface morphology that PG/SPG generally fails to record. To work, digital full-arch workflows need to accurately combine (register) implant coordinate data (from PG/SPG or IOS scan bodies) with IOS soft-tissue scans or extraoral laboratory scans. Scan body design/material and surface properties, implant angulation and distance, scanning strategy, operator technique, and the registration algorithm used are all important factors that affect accuracy.

Conclusions / Clinical recommendations: For completely edentulous full-arch implant prostheses, the recommended approach is to utilize photogrammetry/SPG for implant coordinate capture when available, integrating PG implant coordinate export with an IOS soft-tissue/stump scan through fiducial/scan body-based registration or common-geometry alignment, and meticulously validating the merged STL through fit-verification procedures. Using standard scan body shapes, two-step verification (intraoral trial fit + lab checking), and clear records of registration steps will improve passivity and cut down on clinical remakes. Future research ought to standardise accuracy metrics and delineate clinically significant thresholds.

Keywords: Photogrammetry, stereophotogrammetry, intraoral scanner, edentulous, registration, scan body, full-arch, implant prosthesis

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Introduction

The digitisation of implant prosthodontics has undergone a noticeable evolution, progressing from the straightforward scanning of single-tooth preparations to the complex challenge of capturing completely edentulous arches for full-arch, implant-supported rehabilitations. This change is not just a change in scale; it also marks a major change in the technological and clinical requirements for success. The ultimate goal is to make a prosthetic framework that fits passively and stays stable over time. This depends on accurately capturing two different but related datasets in three dimensions: the exact positions and angles of the dental implants and the shape of the soft tissues around them. Inaccurate implant data causes strain, which can lead to bone loss or mechanical failure. like screws coming loose or breaking. An error in capturing the soft tissue affects how the prosthesis looks, feels, and functions such as the aesthetics, phonetics, ease of cleaning, and emergence profile of the final prosthesis.

Intraoral scanners (IOS) have changed restorative dentistry by taking optical pictures of surfaces and putting them together to make a continuous digital mesh. They work great for small, empty spaces and single implants, but in the long, flat, and often featureless landscape of a completely empty arch, cumulative stitching errors make them less effective [6–9,14,18]. These mistakes, along with the possibility of the patient moving and the absence of stable anatomical reference points, can cause a gradual distortion or "drift" across the arch, which makes the distances and angles between implants less accurate. On the other hand, photogrammetry (PG) and its more advanced version, stereophotogrammetry (SPG), are two different ways to capture digital images. These systems don't map large areas; instead, they use triangulation to find the exact three-dimensional coordinates of specific coded targets or scan bodies that are attached to implants. PG/SPG systems can figure out where implants are with high accuracy by taking several calibrated pictures from different angles. This mostly avoids the stitching-related errors that IOS has over long spans [1–4,10–13]. But this strength is also their biggest clinical problem: they usually don't give much or any useful information about the contours of the surrounding mucosa, the structure of the gingiva, or how they relate to opposing teeth [3,12,30]

The idea of the hybrid digital workflow came about because the two technologies have strengths and weaknesses that work well together. The idea is very simple: use photogrammetry to get the "skeleton" (the exact implant coordinates) and intraoral scanning to get the "flesh" (the detailed soft tissue morphology, emergence profiles, and occlusal relationships). This approach promises to combine the accuracy of both traditional impressions and digital efficiency. But the most important part of this workflow is the process of registration and data merging. The main technical challenge is to successfully align and combine the highly accurate but sparse point-cloud data from PG with the dense but possibly less accurate surface mesh from IOS into a single, coherent, and accurate virtual model. If this registration step doesn't work, it can make either dataset less accurate and cause a prosthetic to not fit properly. Consequently, this review seeks to consolidate the existing evidence, clarify the technical principles, and assess the clinical protocols for registration and integration strategies between photogrammetry and intraoral scanners, particularly in the challenging scenario of the fully edentulous implant arch [1–6].

Materials and Techniques

To achieve the specified objectives, an extensive narrative review was conducted with a focused intent on aggregating and rigorously evaluating the existing evidence. The goal was not to do a statistical meta-analysis, but to give a thorough, evidence-based summary of methods, results, and useful tips. A systematic search strategy was utilised across major scientific databases to guarantee comprehensive coverage of the pertinent literature. The main sources were PubMed/PMC, Scopus, and the Web of Science core collection. These were augmented by searches in leading dental publishing platforms, including Wiley Online Library, MDPI journals, and essential speciality journals such as the Journal of Prosthetic Dentistry, Clinical Oral

Implants Research, and the International Journal of Prosthodontics.

The search period was set from January 2013 to the present (2025), which was when both high-accuracy IOS and dedicated dental photogrammetry systems were being developed and sold quickly. We used a mix of Medical Subject Headings (MeSH) terms and keywords, such as "photogrammetry," "stereophotogrammetry," "intraoral scanner," "digital impression," "edentulous," "complete arch," "full arch," "implant," "scanbody," "scan abutment," "registration," "data merging," "alignment," and "digital workflow." We used Boolean operators (AND, OR) to combine these terms in a way that worked.

We set up inclusion criteria to choose studies that were directly related to the review's focus. These encompassed: (1) in-vitro comparative studies assessing the accuracy (trueness and precision) of PG/SPG versus IOS or conventional impressions for multi-implant models, particularly those simulating edentulous arches; (2) clinical studies, case series, and technical reports elucidating the application of hybrid PG-IOS workflows for complete-arch implant prostheses; (3) systematic reviews and meta-analyses regarding the accuracy of digital impressions in implant dentistry; and (4) technical papers examining factors affecting registration accuracy, such as scanbody design or software algorithms. The exclusion criteria included studies that only looked at single implants or short spans, articles that weren't in English, and opinion pieces or editorials that didn't have any primary data or a clear methodological basis.

The first searches of the database found a lot of citations. We looked through the titles and abstracts to see if they were relevant, and then we got full-text articles of studies that might work. We also searched the reference lists of important papers by hand to find more relevant literature. Data from the included studies were thematically extracted, concentrating on study design, compared technologies, reported accuracy metrics (linear distortion, angular deviation, root mean square error), descriptions of registration methods, and reported clinical outcomes or challenges. The following sections put all of this information together into a single story that goes from the basic ideas behind the technologies to the main technical strategies for combining data, to a critical look at the evidence, and finally to practical clinical advice [1,3,5,7–9].

The fundamentals of Capture Technologies

Photogrammetry and Stereophotogrammetry:

In dentistry, photogrammetry is a method that uses two-dimensional images to get very accurate three-dimensional geometric information. The basic idea is triangulation. When a coded target or a geometrically known scan body attached to an implant is photographed from two or more different known positions (defined by a calibrated camera system), the distinct points on the target can be located in 3D space by calculating the intersection of lines of sight from the different camera perspectives. Stereophotogrammetry improves this process by using a special device with several built-in cameras that take a burst of synchronised pictures from slightly different angles almost instantly. This not only speeds up data collection, but it also makes it more accurate and redundant by giving the triangulation calculation many more data points to work with.

Dedicated dental PG/SPG systems, like the PIC camera (PiC Dental) or the 3D Pro (3D Pro), are not scanners that can be used for anything. They are tools for measuring things. They need special scan bodies with machine-readable codes. The device is set at a certain distance and angle from the arch during capture, and a series of pictures are taken. Then the software finds the unique codes, figures out the centroid and axis of each implant interface, and makes a dataset. This output is not a surface mesh of the soft tissues; instead, it is a precise set of coordinates and vectors that show where each implant is in relation to the others and how it is angled. The primary reported advantage of this method is its consistency and doesn't let errors spread. There is no sequential "stitching" process because each implant position is calculated separately from a common set of images. So, the mistake in measuring the distance between two implants, even if they are at opposite ends of a long arch, does not add up; it is a direct calculation. Several in vitro studies have validated this, demonstrating that PG/SPG systems frequently display enhanced accuracy (proximity to the true value) for linear and angular measurements between implants, particularly in scenarios involving non-parallel implants or extended spans, when compared to both IOS and traditional polyvinyl siloxane impressions [1–4,10–13]. The clinical implication is significant: for the essential variable of implant spatial relationship—the foundation of a passive framework—PG/SPG seems to provide a consistently precise digital substitute. But the limit is also very clear. The output is a sparse dataset of geometric shapes. It has almost no information about the vestibule, the gingival contours, the palate, or the occlusal plane. A prosthesis constructed solely from PG data would be devoid of all contextual soft-tissue morphology [3,12,30].

Intraoral Scanners in the Edentulous Arch

Intraoral scanners work on different optical principles, like structured light, confocal microscopy, or active wavefront sampling. They

shine light patterns on tissues and use sensors to record how these patterns change. This creates a point cloud that is turned into a triangulated surface mesh in real time. When it comes to capturing preparation margins, soft tissue contours, and the surface detail of teeth, they are the best in terms of ease of use and detail resolution. IOS has been shown to be clinically acceptable and effective in implant dentistry for single units or short spans.

The problem comes up in the completely toothless arch. The process of scanning is always done in order. The scanner takes a picture of a small area and then has to find overlapping features in the next area it captures in order to "stitch" them together and build the arch piece by piece. The mucosal surface of an edentulous arch is often smooth and uniform, and it doesn't have the distinct, high-contrast features (like tooth grooves and embrasures) that make stitching easy. This can make the scanner software depend on less clear features, which raises the risk of "drift," which is when small alignment errors build up over time and cause the overall arch length or curvature to be wrong. Some things that make this problem worse are patient movement (even small movements of the tongue or jaw), moisture, and the fact that some scanners don't have a wide enough field of view. Additionally, accurately capturing multiple scan bodies within a single, undistorted arch mesh adds another level of difficulty. Modern scanners and better methods (like starting with a stable scanbody) have made these problems less common, but systematic reviews show that IOS accuracy for full-arch implant impressions is still less reliable than for shorter spans and can be worse than PG/SPG when comparing implant coordinate capture directly [6–9,14,18]. Still, the IOS is still very important because it can capture the soft tissue landscape, the transitional zone around scanbodies, the opposing dentition, and the dynamic occlusal records all in one file. These are all necessary for making a prosthesis that works and looks good.

Hybrid Workflow

The hybrid or fusion workflow is the logical combination of these technological profiles. The reason for this is to use each technology in the best way for the job, with the goal of getting the best overall result. By using photogrammetry to accurately capture the implant "foundation," one can theoretically secure the most important factor for passive fit. After that, an intraoral scanner can be used to take a full surface scan that includes the same scanbodies (or markers), the mucosa, and the occlusion. This gives all the morphological and functional information needed to design a prosthesis. The IOS scan doesn't have to be completely accurate about where the implants are; it just needs to be a consistent and detailed picture of the mouth. After that, the registration software takes over the workflow's intelligence. It must correctly line up the "gold standard" implant coordinates from the PG dataset with the "morphological map" from the IOS scan. When done right, this fusion creates a virtual master model that combines precise coordinates with surface detail, making it the best digital base for computer-aided design (CAD). This method also has practical benefits, such as cutting down on chairside time compared to traditional impressions and making the digital laboratory workflow smoother, from virtual design to computer-aided manufacturing (CAM) of the framework and prosthetic parts [3,9,16,23].

Core Technical Strategies

The hybrid workflow will only work if the data merging process is accurate and dependable. This part talks about the recommended clinical sequence, the technical ideas behind different registration methods, and the most important things that affect the accuracy of the final merged dataset.

Data Acquisition

The first line of defence against registration errors is a standardised acquisition protocol. Technical reports and clinical studies all agree on a certain order: first, photogrammetric capture, and then intraoral scanning. The reason is that the PG capture is quick, the scanbodies need to be clean and dry, and it creates the final implant dataset. The clinician then does the full-arch IOS scan, leaving the same coded scanbodies in place as long as they can also be scanned by the IOS (i.e., they aren't too reflective or geometrically difficult for optical capture). This scan should include not only the scanbodies but also the whole edentulous ridge, vestibules, palate, and opposing arch. Some protocols suggest getting a separate "scanbody-only" IOS file with the mucosa digitally removed or hidden by retraction cords to get a cleaner geometry of the scanbodies for registration. However, this adds a step and may not be necessary with strong registration algorithms.

You can't skip important steps in preparation. To get rid of any micromovement at the implant interface, which could cause a lot of errors, the implant scanbodies must be torqued to the manufacturer's specifications [3]. To keep the mucosa from moving too much, it should be handled carefully. Air drying and using retractors to hold the lips and cheeks in place are both important. Controlling saliva is very important because pooling fluids can hide landmarks and make scanning artefacts. The goal is to make the tissue position during the PG capture (which lasts a few seconds) as close as possible to its position during the longer IOS scan. This will make the two datasets less different when it comes to soft tissue [7].

Methods for technical registration

The PG coordinate file (which is usually an STL file with only the scanbody geometries or a direct text file of coordinates) and the IOS surface mesh (which is an STL file) must be aligned after they are imported into CAD software. This is not just an overlay; it is a precise rigid-body registration in which one dataset is moved and rotated in three-dimensional space to get the best fit with the other dataset based on shared features. There are three main methodological approaches, and each one has its own rules and ways of working.

The first and most common method is to match the geometry of the scan body. This method works because both datasets show the same physical scanbodies. The software algorithm finds the scanbody shapes in the IOS mesh, which is often noisy, and compares them to the clean, known shapes of the scanbodies from the PG export or from a CAD library provided by the manufacturer. An "iterative closest point" algorithm is a feature of advanced software that repeatedly changes the alignment to make the distance between matching points on the two scanbody sets as small as possible. Library-based substitution is a more advanced and possibly more accurate version of this. In this case, the scanned geometry of the scanbodies in the IOS mesh is identified, divided into parts, and then replaced with the exact, nominal CAD geometry from the manufacturer's library. Then, the registration is done between the PG scanbodies and these "perfect" library models. This gets rid of any mistakes that were made when the scanbody surfaces were scanned optically. This method works very well, but it only works if the CAD software has a digital scanbody library that is both available and accurate [1,14,16].

The second method is registration based on markers or fiducials. This is similar in concept to techniques used in surgery guided by images. It entails the placement of three or more small, distinct markers (fiducials) on stable structures within the scan field. These markers may be positioned on the scan bodies themselves (if they possess non-coded but unique features), on adjacent teeth in a partially edentulous case, or even on a stable custom baseplate in a fully edentulous case. The most important thing is that both the PG images and the IOS scan clearly show and accurately record these markers. Then, the software finds the centroids of these identical markers in each dataset and does a point-based registration, which means that it lines up the two point clouds by making the distance between the centers of the markers as small as possible. This method can be very strong, especially when the soft tissue doesn't have any features. This is because it doesn't use the tissue at all and only uses engineered markers. But it needs to be done carefully, and it adds an extra step to the clinical procedure [12,18].

The third method, which is often used as a secondary improvement, is to align the best-fit surface based on common areas. After an initial rough alignment using one of the above methods, the software can be told to do a final "best-fit" alignment using parts of the scan that are thought to be stable and captured reliably in both datasets. This could be parts of the scanbody shafts (excluding the coded portions) or, more riskily, selected areas of the gingiva. The latter is generally less reliable due to tissue deformation and should be used with caution and only after a primary, more rigid registration has been established [3,16].

Important Factors That Affect Registration Accuracy

The choice of registration method does not solely determine the final accuracy of the merged dataset. It is the result of a chain of variables, and each link in that chain needs to be improved. The design of the scanbody is probably the most important hardware factor. An ideal scanbody for a hybrid workflow should be tall enough to give good geometry for both PG coding and IOS surface capture. It should also be stiff enough to keep from bending and have a matte, non-reflective surface to make optical scanning easier. The IOS should be able to capture it clearly because of its simple shape, but it should be unique enough for software to recognise it. Research conducted by Mohajerani et al. (2025) and Gómez-Polo et al. (2023) has shown that the geometry of the scanbody directly affects precision, with taller and more rigid bodies producing more reliable outcomes [14,15].

The way the implants are spread out in space matters. Widely spaced implants give the registration algorithm a longer "baseline," which usually makes angular stability better. If the scanbody geometry is partially hidden from some camera or scanner angles, it can be hard to work with implants that are very angled. The way the operator does things is another human factor. A steady hand when taking PG images, a systematic and overlapping scanning path during IOS, and careful attention to controlling moisture and retraction all help the software get cleaner, more reliable data to work with. Last but not least, the software algorithm is a variable. Different CAD packages might use slightly different math methods to do the iterative closest point calculation or to deal with noise and outliers in the IOS mesh. The clinician and technician need to know how to use the registration tools in the software they choose and follow the rules that come with it.

Combining Evidence and Clinical Results

Findings on Accuracy from Comparative Studies

A growing amount of in-vitro evidence backs up the theoretical benefits of photogrammetry and hybrid workflows. A groundbreaking in-vitro study conducted by Tohme et al. (2021) examined IOS and PG impressions on a complete-arch model featuring both parallel and angled implants. The photogrammetry system exhibited markedly superior accuracy for both linear and angular measurements in comparison to two distinct IOS systems [3]. For PG, the linear distortion was usually less than 20 µm, but for IOS, it could be more than 50–100 µm across the arch, especially for the implants that were farthest away from the center. This is a clear sign of stitching drift. Revilla-León et al. (2021) and subsequently Abuduwaili et al. (2025) obtained analogous findings, demonstrating that PG consistently ranks as the most precise method for capturing implant coordinates in full-arch scenarios, occasionally rivalling or exceeding the accuracy of traditional implant-level impressions [9,10].

The pivotal inquiry regarding the hybrid workflow is whether the registration process itself generates errors that undermine PG's intrinsic accuracy. There are fewer studies that focus on this, but they are starting to come out. Revilla-León et al. (2025) examined the registration precision of integrating IOS soft-tissue scans with PG implant data. Their results showed that by following a strict protocol that included library-based scanbody substitution and best-fit alignment, the registration error could stay very low (usually under 30 µm RMS error). This meant that the final merged dataset had implant positional accuracy that was closer to that of the original PG data than to that of the standalone IOS data [24]. This is a significant finding because it confirms the main idea behind the hybrid approach: it is possible to successfully transfer the high fidelity of PG into a complete soft-tissue model.

Clinical reports, despite the absence of the controlled metrics found in in-vitro studies, offer practical validation. Case series, including those by Jung et al. (2022) and Auduc et al. (2025), record the effective clinical implementation of PG-IOS hybrid workflows for the immediate loading of complete-arch prostheses and for conclusive rehabilitation [4,16]. These reports consistently stress the importance of the verification step, which is to use a 3D-printed or milled trial framework to clinically test the passive fit of the virtual design before moving on to final fabrication. The reported clinical outcomes, which include successful seating of prostheses and positive short-term follow-up, indicate that the workflow is clinically feasible when performed with accuracy [3,9,10,21,22,24,25].

Common errors

To use clinical tools reliably, you need to know about common failure modes. A common mistake is not getting a full or good scanbody capture in the IOS scan. If saliva, tissue, or the scanner's housing partially blocks the scanbody, or if the scanbody's surface is very reflective and causes "blow-out" in the scan, the mesh will be wrong. The registration algorithm will have to make compromises in order to match this imperfect geometry to the perfect PG geometry, which will cause misalignment. The answer is careful planning: dry the field, use anti-reflective spray if the scanbody maker allows it, and make sure that the scan is clear from all angles [14].

Another big problem is that proprietary systems can lock you in and don't work well with other systems. A PG system from one company usually needs its own special coded scanbodies. If the dental laboratory's CAD software doesn't have the right digital library for those scanbodies, they can't use the library-based substitution method. Instead, they have to use less accurate best-fit methods on scanned geometries. This shows how important it is for the clinician (who chooses the PG system and scanbodies) and the dental lab (who does CAD and registration) to talk to each other openly [3,4].

Soft-tissue compression and movement between captures is a biological variable that software cannot completely resolve. The mucosa can be moved. If the lip retractor or the patient's tongue position puts different amounts of pressure on the ridge during the PG capture (which lasts a few seconds) and the longer IOS procedure, the shape and position of the ridge will look different in the two datasets. The registration focuses on the rigid scanbodies, but a big difference in the tissue can make it hard to visually check the alignment and could change how the prosthesis emerges. It is very important to standardise how patients are positioned and retracted between the two capture phases [7].

Finally, it is a big mistake to rely too much on software automation without checking it with a doctor. The digital workflow helps with accuracy, but it doesn't guarantee it. The only real test is physical and clinical, no matter how good the registration metrics look on screen (like a low RMS error). A full-arch framework has a lot of stress on it, and it doesn't allow for mistakes. So, before the final fabrication uses expensive materials and lab time, the digital design must always be checked in person.

Recommended Clinical Protocol

The following step-by-step plan is suggested for putting a PG-IOS hybrid workflow into action for a full-arch implant case with no teeth. This is based on the combined evidence and technical principles.

The first step is to get the patient ready. If necessary, local anaesthesia is given, and then effective retractors are put in place to show the arch and keep the cheeks and lips stable. To keep the field dry, high-volume suction is used. Any extra soft tissue that might get in the way of seeing the scanbody necks is carefully pulled back. To reduce movement, the patient is placed in a comfortable position, with the arch to be scanned roughly parallel to the floor [7].

First, the photogrammetric capture is done. According to the recommended torque value, the manufacturer's proprietary coded scanbodies are tightly attached to each implant. The PG device is placed the right distance away, usually 20 to 30 cm from the arch, so that all of the coded scanbodies are in the field of view. The device's software tells it to take a series of pictures from different angles. The whole thing usually takes less than a minute. The software then processes the pictures, checks that all the codes were captured, and makes an output file. This file, which is usually an STL file with simplified geometric representations of the scanbodies at their exact coordinates, is saved and sent out. The scanbodies stay where they are [1,3].

The intraoral scanning procedure is done right after that. The clinician starts a new scan with the chosen IOS. One good way to do this is to start by scanning the occlusal surfaces of the scanbodies to create a stable reference. Then, systematically scan the buccal and lingual sides of the ridge, connecting the scanbodies into a continuous arch mesh. To define the soft tissue contours, the vestibules and palate are recorded. Last, the opposing arch and a buccal bite registration or other occlusal record are scanned to find the relationship between the jaws. The entire IOS dataset, which includes the arch with scanbodies, the opposing arch, and the bite, is saved and exported [7,8].

The CAD software is where the digital data merge happens. We import both the PG export file and the IOS STL file. The process of signing up begins. If possible, the best way to do this is to use the manufacturer's scanbody library to replace the scanned geometries of the scanbodies in the IOS file with their nominal CAD equivalents. After that, the software does a rigid alignment, matching the library scanbodies to the PG file's geometries. The PG data shows where the implants should go, and the IOS data shows where the soft tissue, opposing teeth, and occlusion should go. The software should give a quantitative registration report, like an RMS error value, that should be kept for quality control. A visual check of the alignment, especially in the neck areas of the scanbody, is also required [16].

No process is finished without checking things out in person. A verification device is made based on the combined and checked digital model. Most of the time, this is a rigid, non-flexible trial framework or verification jig that is made of rigid resin and printed in 3D. If the right trial abutments are used, this jig should fit perfectly on the implant scanbodies or directly on the implant interfaces. This jig is tested in the mouth at the patient's next appointment. The surgeon or prosthodontist checks the fit by feeling it with their hands (the Sheffield or one-screw test) and looking for any rocking or gaps. A periapical or cone-beam computed tomography (CBCT) radiograph with the jig held in place by one screw is an essential tool for confirming a precise fit at the implant-abutment interface. It can show any microscopic misfits that can't be seen in a clinical setting. The laboratory should only move forward with the design and construction of the final titanium or zirconia framework after this jig has shown that it fits passively [23,24].

Discussion

The evidence presented in this review leads to a clear and actionable conclusion: for the digital fabrication of complete-arch, implant-supported prostheses, a strategic hybrid workflow that combines photogrammetry for implant coordinate capture with intraoral scanning for soft-tissue morphology presents a robust and potentially superior approach. The main conclusion from in vitro studies is that PG/SPG systems always have a mechanical advantage when it comes to accurately capturing the relative positions of multiple implants. This effectively reduces the linear and angular distortions that can happen during the sequential stitching process that is part of IOS in long, featureless arches. This means that PG/SPG is not only an alternative, but in many cases the best way to protect the basic geometric dataset that a passive framework needs.

But dentistry is more than just mechanical engineering; it is also a biological and aesthetic field. The IOS is still the best way to capture the changing, contoured landscape of the mouth, including the ridge's subtle curve, the vestibule's depth, the desired emergence profile from each implant site, and the occlusal relationship with the opposing dentition. So, the hybrid model isn't a contest between technologies; it's a combination of them. The clinical success of this integration depends entirely on the registration process, which acts as the "digital luting agent" that connects the exact skeleton to the detailed morphological map. The evidence reviewed indicates that through meticulous attention to detail—optimal scanbody selection, regulated clinical capture conditions, and the implementation of advanced registration techniques such as library-based substitution—this binding can be accomplished with minimal error

propagation, thereby maintaining the integrity of the PG data within the final design environment.

In the clinic, this means that the workflow needs more procedural discipline than a regular impression or a single IOS scan. The clinician needs to be skilled in two different ways to capture data and know what each one needs. The investment is worth it, though, because of the possible benefits: less need for physical impression materials and less discomfort for patients, a smoother digital handoff to the lab, and most importantly, a higher chance of getting a passively fitting framework on the first try, which means fewer expensive and time-consuming clinical remakes.

Limitations of Existing Evidence

Even though the data looks good, there are some big problems with the evidence base that need to be recognised in order to move forward. First, there is a big difference in how accuracy is reported. Different studies use different metrics, such as mean linear deviation, three-dimensional error, angular deviation, and RMS error, to measure the distance between different points (implant platform, scanbody top, abutment interface). There is no universally recognised "clinically acceptable threshold" for digital full-arch impressions. Although the range of 50-150 µm is frequently referenced, it is predominantly derived from traditional prosthodontic literature. Future research should progress beyond merely stating that one method is more accurate than another, and instead concentrate on identifying the specific threshold of in-vitro digital error that corresponds with clinical misfit, biological compromise, or mechanical failure. This necessitates meticulously structured prospective clinical trials that assess digital error during the impression phase and subsequently correlate it with objectively evaluated fit at delivery and long-term clinical outcomes [22].

Second, most of the strong evidence comes from in vitro studies. These controlled studies are important for separating technological factors, but they can't take into account all the real-life situations that happen in a clinic, like patients moving around, not being able to open their mouths very wide, tissue that moves around a lot, or blood and saliva being present. There is an urgent necessity for additional high-fidelity clinical studies that not only assess the feasibility of the hybrid workflow in case series but also directly compare it with conventional workflows in randomised controlled trials, evaluating outcomes such as total chair time, number of adjustment visits, prosthesis survival, and patient-reported outcomes [23].

Thirdly, there needs to be more research on the "hardware" of the workflow. Although the impact of scan body design is recognised, extensive studies that methodically evaluate various geometries, materials, and surface treatments across multiple PG and IOS platforms are limited. Such research may facilitate the creation of optimised "universal" or system-agnostic scan bodies that function effectively in both capture environments [14]. Lastly, the problem of interoperability is a big practical problem. Proprietary formats make it hard to reach the goal of an open digital ecosystem, where PG coordinate data and scanbody libraries can move easily between any clinical capture device and any laboratory CAD software. Advocating for and creating open standards, like DICOM in medical imaging, would make these advanced digital workflows much more reliable and widely used. This is because it would make it easier for both practitioners and technicians to use them by reducing vendor lock-in and making the technical pipeline easier to use [9].

Conclusion

The path to fully digital, implant-supported rehabilitation of the completely edentulous arch is one of the most technically challenging areas in modern prosthodontics. This review has outlined the terrain of that frontier, concentrating on the critical challenge of amalgamating two disparate digital capture technologies. Photogrammetry and stereophotogrammetry have proven to be superior methods for the precise task of determining implant positions. Intraoral scanning is still the best way to get a detailed picture of the oral environment. The hybrid workflow, which aims to combine these strengths, is not just a technical curiosity; it is a logical and evidence-based step forward in digital dentistry.

However, for it to work, we need to change the way we think about digital tools from seeing them as automatic solutions to seeing them as parts of a precise engineering process. To be successful, you need to carefully choose compatible parts (scan bodies), strictly follow controlled clinical protocols, master software-based registration techniques, and, most importantly, always be committed to physical validation through tried-and-true verification methods. The digital model is a strong guess, and the try-in framework is the test that puts it to the test.

As the evidence base grows through standardised research and systems become more interoperable, the hybrid PG-IOS workflow is likely to become the standard of care for full-arch implant therapy. It provides a way to bring together the timeless goals of prosthodontics, such as passivity, function, and aesthetics, with the efficiency, accuracy, and data-rich potential of the digital age. By accepting both the promise and the discipline that come with this method, clinicians can reliably turn the virtual

accuracy of the digital workflow into real clinical success for their patients.

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