



Review Article

Digital Precision in Orthodontics: A Review of Three-Dimensional Implant Splints as Surgical Guides

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Skeletal anchorage has transformed contemporary orthodontics by providing stationary anchorage that is independent of patient compliance and capable of supporting complex tooth movements with high biomechanical precision. Temporary anchorage devices (TADs), particularly orthodontic miniscrews, are now routinely used for intrusion, distalization, en-masse retraction, asymmetry correction, and vertical control. However, the clinical success of TADs depends heavily on accurate placement because errors in angulation, depth, or insertion site may compromise stability and increase the risk of root contact, cortical perforation, or injury to adjacent anatomical structures. The development of three-dimensional implant splints has addressed many of these limitations by enabling digitally planned, patient-specific, and highly controlled insertion of miniscrews. This manuscript reviews the evolution of orthodontic skeletal anchorage and the transition from freehand placement to guided insertion using 3D implant splints. It outlines the digital workflow, including cone-beam computed tomography (CBCT), intraoral scanning, virtual planning, computer-aided design, and additive manufacturing. The principles of guide design, site selection, and biomechanical planning are discussed together with major clinical applications such as anterior intrusion, open-bite and deep-bite correction, space closure, molar distalization, and management of midline discrepancies. Evidence from recent clinical and systematic investigations indicates that guided miniscrew placement improves positional accuracy, reduces operator dependency, lowers the incidence of root damage, and may enhance survival rates, especially in anatomically challenging areas. Despite limitations related to cost, radiation exposure, software dependency, and technique sensitivity, 3D implant splints represent a major advance in digital orthodontics and are likely to become an increasingly important component of safe, precise, and individualized anchorage management.

Introduction

Skeletal anchorage has fundamentally changed the way orthodontic biomechanics are planned and executed. Before the introduction of temporary anchorage devices, clinicians depended heavily on conventional anchorage systems such as headgear, intermaxillary elastics, transpalatal arches, and anchorage preparation from posterior teeth [1]. Although these methods remain useful in selected circumstances, they are limited by patient compliance, reciprocal tooth movement, and reduced biomechanical efficiency [2]. In contrast, skeletal anchorage provides a stable source of resistance directly from bone, allowing the orthodontist to apply force systems with greater precision and fewer unwanted side effects [3]. Among the available skeletal anchorage systems, TADs have emerged as the most widely used because they are minimally invasive, relatively inexpensive, easy to place and remove, and capable of imme-

diate or early loading [4].

The clinical usefulness of TADs lies in their versatility. Orthodontic miniscrews can be placed in interdental regions, the palate, the infrazygomatic crest, or the mandibular buccal shelf, depending on the biomechanical objective [5]. Their introduction has expanded the scope of non-surgical orthodontic treatment by facilitating movements that were once difficult or unpredictable, including molar intrusion, anterior intrusion, maximum anchorage during extraction space closure, distalization of posterior segments, correction of asymmetric dental relationships, and management of vertical discrepancies [6]. Nevertheless, the success of a miniscrew does not depend solely on the implant itself. Proper site selection, insertion angulation, cortical engagement, soft tissue management, and force application are all essential determinants of stability and safety [7].

Freehand placement of TADs, while common in routine practice,

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is associated with important limitations. Even experienced clinicians must often rely on two-dimensional radiographs, clinical palpation, and visual estimation when placing a miniscrew between roots or near anatomical boundaries [8]. Such reliance increases operator dependency and may lead to deviations in angulation, depth, or mesiodistal position. These errors can have meaningful clinical consequences, including root contact, inadequate cortical engagement, soft tissue irritation, sinus perforation, poor biomechanics, and early implant failure [9].

The emergence of CBCT and digital dentistry has created new possibilities for overcoming these limitations. CBCT allows three-dimensional visualization of root morphology, cortical thickness, available bone, sinus boundaries, the nasal floor, and other relevant structures [10]. When this information is merged with surface data from intraoral scans, the clinician can create a comprehensive virtual model of the patient's dental-alveolar anatomy. This digital environment makes it possible to select the optimal insertion path before treatment, rather than during surgery [11].

Three-dimensional implant splints represent the clinical translation of this digital planning process. These custom-designed, 3D-printed surgical guides are fabricated to seat accurately on dental or palatal surfaces and direct the insertion of a miniscrew along a predetermined trajectory [12]. By transferring the virtual plan into the clinical setting, they improve precision, reduce variability, and increase confidence in demanding cases [13].

Evolution of Skeletal Anchorage and Surgical Guidance in Orthodontics

The modern concept of skeletal anchorage developed in response to one of orthodontics' oldest challenges: maintaining anchorage while moving selected teeth efficiently [14]. Conventional methods could not always prevent unwanted reciprocal movements, especially in extraction therapy, vertical correction, and correction of asymmetries. The introduction of miniscrews changed this paradigm by creating a source of anchorage independent of the dentition and largely independent of patient cooperation [15].

Early use of miniscrews demonstrated promising clinical benefits, but placement techniques were relatively crude. Clinicians commonly inserted devices freehand using two-dimensional radiographs and anatomical estimation [16]. Although this approach was often sufficient in sites with generous bone and favorable access, it was less reliable in narrow interradicular spaces or regions close to the sinus or roots [17].

The evolution of surgical guides in orthodontics followed advances in imaging and digital fabrication. The earliest guides were simple vacuum-formed stents with radiopaque markers [18]. As CBCT became more widely adopted, clinicians gained the ability to visualize root divergence, cortical bone thickness, and site-specific anatomy with greater accuracy [19].

The next major advance was the integration of CAD/CAM technology. By merging DICOM data from CBCT with STL files from digital models or intraoral scans, orthodontists could construct a virtual environment for precise pre-surgical planning [20]. Once the plan was finalized, a custom guide could be designed and manufactured using 3D printing [21].

Fundamentals of 3D Implant Splints

A 3D implant splint is a customized surgical guide designed to direct orthodontic mini-implant placement according to a preplanned three-dimensional trajectory. Its primary purpose is to reproduce the exact insertion position, angulation, and depth established during virtual planning. In practical terms, the splint serves as an interface between digital diagnosis and clinical execution.

The value of a 3D implant splint lies in four core principles: precision, stability, transferability, and biomechanical fidelity. Precision refers to the ability to guide insertion within a very small tolerance from the planned path. Stability refers to the secure seating of the guide on the supporting oral structures during the procedure. Transferability means that the digital plan can be reproduced accurately in the mouth. Biome-

chanical fidelity ensures that the final miniscrew position supports the intended orthodontic force system.

Guide support is a key design variable. The mechanical performance of the guiding channel is particularly important during miniscrew insertion. Orthodontic miniscrews are frequently self-drilling and may generate substantial insertion torque, especially in regions with dense cortical bone. Under these conditions, excessive stresses may be concentrated around the guide sleeve, creating a risk of micro-crack formation, localized deformation, or fracture of the resin structure. Such defects can reduce insertion accuracy and compromise the ability of the guide to maintain the planned trajectory throughout the procedure.

To improve durability and wear resistance, many contemporary guide systems incorporate metallic sleeves fabricated from stainless steel or titanium. These inserts provide a hard, dimensionally stable interface between the insertion driver and the printed guide. Metallic sleeves reduce frictional wear, prevent enlargement of the guiding channel during use, and minimize the possibility of resin abrasion. This is clinically relevant because repeated contact between rotating drills or drivers and the resin surface may generate microscopic polymer particles that could potentially be introduced into the surgical field. By providing a wear-resistant surface, metallic sleeves enhance procedural accuracy, improve guide longevity, and reduce the risk of particulate contamination during miniscrew placement.

The design of the guiding component is equally important. Sleeves or channels must be dimensioned to fit the chosen driver or drill system closely enough to control angulation, but not so tightly that insertion becomes difficult. Offset and clearance must accommodate soft tissue thickness and operator access. Guide thickness must be sufficient to resist deformation, while remaining comfortable and practical intraorally. In anatomically delicate sites, depth-control features can help prevent over-insertion and reduce the risk of cortical perforation or sinus encroachment.

From a biomaterials perspective, the accuracy and clinical safety of 3D implant splints are influenced not only by guide design but also by the properties of the printing material. Most orthodontic surgical guides are fabricated using medical-grade photopolymer resins specifically developed for stereolithography (SLA) or digital light processing (DLP) technologies. These materials are predominantly acrylic- or methacrylate-based photopolymers that undergo light-induced polymerization to form dimensionally stable structures. Depending on their intended clinical application and regulatory approval, they are commonly classified as Class I or Class II biocompatible materials according to relevant medical device standards. Class I biocompatible resins are generally intended for short-term mucosal contact, whereas Class II materials undergo more extensive biological evaluation and are frequently used in surgical guides and other intraoral devices requiring enhanced safety and mechanical reliability.

The selection of resin directly affects guide performance. Surgical guide resins are designed to exhibit high dimensional accuracy, adequate flexural strength, low polymerization shrinkage, and resistance to deformation during sterilization. In addition, biocompatibility is essential because the guide remains in direct contact with oral tissues during miniscrew placement. Modern dental photopolymers are therefore formulated to minimize residual monomer content and cytotoxicity while maintaining sufficient rigidity to ensure precise transfer of the planned implant trajectory to the clinical environment.

Digital workflow for guided miniscrew placement

The effectiveness of a 3D implant splint depends on the quality of the digital workflow used to create it. This workflow generally consists of imaging, data integration, virtual planning, guide design, additive manufacturing, and clinical execution [22].

Imaging and data acquisition

The process begins with CBCT imaging and an intraoral scan or digitized model. CBCT provides volumetric information on root positions, cortical thickness, interradicular spaces, sinus and nasal boundaries, and other critical anatomical structures [23].

Data merging and virtual modeling

The DICOM dataset from CBCT is then merged with the STL dataset from the intraoral scan. Accurate registration is essential because even small mismatches can alter the planned relationship between roots and insertion path [24].

Virtual planning

In the planning phase, the insertion site is selected according to anatomy and treatment biomechanics. The clinician evaluates available bone, root divergence, cortical thickness, soft tissue thickness, accessibility, and the intended direction of force application [25]. The implant axis is then determined virtually. This step is crucial because the chosen path affects not only safety but also the quality of anchorage and the line of action of orthodontic force.

Guide design

Using CAD software, a guide base is constructed to adapt to the selected support surfaces. A sleeve or guiding channel is positioned according to the planned implant trajectory [25]. Additional features may be added, such as windows for seating verification, reinforcement bars for rigidity, or built-in depth control. The design must balance accuracy with clinical practicality, ensuring that the guide is stable, easy to insert, and compatible with the chosen driver system.

Manufacturing and post-processing

The finalized guide is manufactured additive manufacturing technologies, most commonly stereolithography (SLA) and digital light processing (DLP). Both techniques utilize photosensitive acrylic or methacrylate-based resins that polymerize upon exposure to a controlled light source. SLA employs a laser to selectively cure successive resin layers, whereas DLP uses a projected light pattern to polymerize an entire layer simultaneously. These technologies are favored in orthodontics because they provide excellent surface quality, high dimensional fidelity, and the ability to reproduce complex anatomical details accurately.

Dental surgical guides are typically fabricated using certified Class I or Class II biocompatible photopolymer resins specifically developed for intraoral applications. The mechanical properties of these materials, including flexural strength, elastic modulus, fracture resistance, and dimensional stability, are critical for maintaining guide accuracy during insertion. Following printing, the guide undergoes post-processing procedures that include washing in isopropyl alcohol to remove uncured resin, post-curing under ultraviolet light to maximize polymer conversion, and final finishing or polishing. Appropriate post-curing is particularly important because it improves mechanical strength, reduces residual monomer content, enhances biocompatibility, and contributes to the long-term dimensional stability of the surgical guide.

An important but often overlooked consideration is the effect of sterilization on the dimensional accuracy and mechanical integrity of printed surgical guides. Because guided miniscrew placement depends on precise transfer of the virtual treatment plan to the clinical setting, even minor dimensional alterations may compromise insertion accuracy. The impact of sterilization varies according to the printing technology and resin composition. Conventional steam autoclaving exposes the guide to elevated temperatures and pressure, which may induce thermal expansion, distortion, warpage, or changes in mechanical properties, particularly in photopolymer resins that have not achieved complete polymer conversion. Although many contemporary surgical guide resins are marketed as autoclavable, studies have demonstrated that repeated sterilization cycles may result in measurable dimensional deviations and reductions in flexural strength.

Alternative sterilization techniques such as gamma irradiation, ethylene oxide gas, or low-temperature hydrogen peroxide plasma systems may reduce thermal stress on the material. However, gamma radiation can alter polymer cross-linking density and potentially affect mechanical behavior depending on the resin formulation. Consequently, clinicians should adhere strictly to manufacturer-recommended sterilization protocols and verify guide fit before use. Maintaining dimensional stability throughout post-processing and sterilization is essential because even small deviations in the guiding channel may affect implant angulation, depth control, and ultimately the clinical precision of guided miniscrew placement [27].

Accuracy and Error Propagation in the Digital Workflow

The accuracy of guided miniscrew placement depends on the cumulative precision of each stage of the digital workflow. Although three-dimensional implant splints significantly improve clinical accuracy compared with freehand insertion, every component of the workflow introduces a measurable degree of error. These include image acquisition, surface scanning, dataset registration, virtual planning, guide fabrication, post-processing, and clinical seating. Consequently, the final deviation observed during miniscrew placement represents the combined effect of multiple small inaccuracies rather than the performance of any single step.

Intraoral scanning systems generally demonstrate linear deviations ranging from approximately 20–80 μm (0.02–0.08 mm) for localized dental surfaces, although larger full-arch scans may exhibit greater cumulative distortion. CBCT imaging introduces additional uncertainty related to voxel size, patient movement, image artifacts, and segmentation procedures. Depending on acquisition parameters, dimensional errors of approximately 0.1–0.3 mm have been reported. The subsequent registration of DICOM and STL datasets represents another critical

Table 1: Typical Sources of Error in the Digital Workflow for Guided Miniscrew Placement

Workflow Stage	Typical Linear Deviation	Typical Angular Deviation	Primary Cause
Intraoral scanning	0.02–0.08 mm	<0.5°	Scanner accuracy, stitching errors
CBCT acquisition and segmentation	0.10–0.30 mm	0.5–1°	Voxel size, motion artifacts, segmentation
CBCT-STL registration	0.10–0.40 mm	0.5–2°	Dataset alignment inaccuracies
Virtual planning	Minimal	Minimal	User-dependent landmark selection
SLA/DLP printing	0.05–0.30 mm	0.5–1°	Layer thickness, polymerization shrinkage
Post-curing and sterilization	0.05–0.20 mm	<1°	Thermal distortion, resin contraction
Clinical guide seating	0.10–0.50 mm	1–3°	Seating errors, soft-tissue interference
Final guided placement	0.30–1.00 mm	1–5°	Cumulative workflow error

source of error, with reported linear discrepancies typically ranging between 0.1 and 0.4 mm. Even small registration mismatches can alter the perceived relationship between root surfaces and the planned implant trajectory.

The manufacturing stage introduces further deviations. SLA and DLP printers are generally capable of layer thicknesses between 25 and 100 μm ; however, factors such as resin shrinkage, build orientation, support removal, and post-curing can contribute to dimensional inaccuracies ranging from 0.05 to 0.3 mm. Additional changes may occur during sterilization if inappropriate protocols are used. Finally, incomplete guide seating, soft-tissue interference, or operator-related factors may further affect the transfer of the virtual plan to the clinical environment.

When these sources of error are considered collectively, reported deviations between planned and actual implant positions in guided orthodontic procedures are typically within approximately 0.3–1.0 mm linearly and 1° – 5° angularly. While these values remain substantially lower than those associated with freehand placement, they emphasize the importance of quality control throughout the entire digital workflow. Understanding and minimizing cumulative error is essential for preserving the accuracy and biomechanical predictability expected from digitally guided miniscrew placement. Table 1 summarizes the typical sources of error in the digital workflow.

Site Selection and Biomechanical Considerations

Proper site selection remains central to the success of guided miniscrew placement. The best insertion site is not simply the area with the most bone, but the location that combines anatomical safety, cortical support, soft tissue compatibility, and biomechanical usefulness.

Interradicular sites

Interradicular placement remains common because it offers direct access for many mechanics, especially retraction and intrusion. However, these sites are also among the most anatomically sensitive. Safe insertion requires adequate root divergence and careful angulation. Commonly favorable zones include the maxillary second premolar–first molar region and selected mandibular premolar–molar areas. Guided splints are particularly valuable here because they reduce reliance on visual estimation and help preserve safe root clearance.

Palatal sites

The paramedian palate is considered one of the most reliable TAD sites due to its dense cortical bone, broad anatomical safety zone, minimal risk of root damage, and relative comfort for patients. It is especially useful for molar distalization, maxillary expansion, intrusion mechanics, and bilateral anchorage systems. Palatal guides often demonstrate excellent stability because they can seat on palatal rugae and other reproducible anatomical contours.

Buccal shelf and infrazygomatic crest

Extra-alveolar sites such as the mandibular buccal shelf and maxillary infrazygomatic crest are valuable when heavy forces or large distalization movements are required. These regions allow use of longer and more robust screws and avoid interradericular constraints. Nevertheless, they demand careful angulation and awareness of nearby anatomical boundaries. Guided placement may improve safety and enhance the predictability of insertion in these less accessible regions.

Biomechanics

From a biomechanical perspective, the effectiveness of a temporary anchorage device depends not only on implant stability but also on its spatial relationship to the center of resistance (Cres) of the targeted tooth or dental segment. The center of resistance is defined as the point through which a force must pass to produce pure translatory movement without rotation. When an orthodontic force is applied at a distance from the Cres, a rotational tendency is generated according to the fundamental engineering relationship:

$$M = F \times d$$

where M is the moment ($\text{N}\cdot\text{mm}$), F is the applied force (N), and d is the perpendicular distance between the line of action of the force and the center of resistance. As the distance increases, the resulting moment increases proportionally, producing greater tipping or rotational effects. Conversely, reducing this distance minimizes the generated moment and promotes bodily tooth movement.

In conventional freehand miniscrew placement, variations in implant position may unintentionally alter the force vector and increase the distance between the line of action and the Cres, resulting in unplanned rotational moments. These biomechanical discrepancies may necessitate additional wire bends, compensatory auxiliaries, or force adjustments during treatment.

Three-dimensional virtual planning enables the clinician to evaluate the anticipated force system before miniscrew insertion. By integrating CBCT-derived anatomical data with digital dental models, the planned TAD position can be optimized so that the line of force passes as close as possible to the center of resistance of the intended tooth segment. This approach systematically minimizes the value of d in the equation above and thereby reduces unwanted rotational moments.

In situations where translatory movement cannot be achieved because of anatomical constraints or treatment objectives, digital planning permits intentional design of controlled moment-to-force (M/F) ratios. The clinician may modify implant position, force application height, or auxiliary mechanics to generate calculated counter-moments that offset undesirable rotational tendencies. Consequently, guided TAD placement serves not only as a surgical aid but also as a biomechanical planning tool that facilitates precise control of force vectors, moment generation, and three-dimensional tooth movement.

For intrusion mechanics, positioning the miniscrew so that the resultant force vector passes near the Cres of the anterior segment minimizes labiolingual tipping. During molar distalization, optimization of the force vector reduces rotational tendencies and transverse collapse. Similarly, in asymmetric mechanics, virtual planning allows calculation and balancing of force systems before treatment, thereby improving predictability and reducing unwanted side effects.

Clinical Applications of Guided TAD Placement

Anterior intrusion

Anterior intrusion is among the most technique-sensitive movements in orthodontics. Guided placement improves anterior intrusion by ensuring that TADs are inserted in root-safe zones and at a height that permits efficient vertical force application [28].

Open bite and deep bite correction

In open bite cases, posterior intrusion supported by TADs can lead to counterclockwise mandibular rotation and clinically meaningful bite closure [29]. Guided placement is especially advantageous when miniscrews are inserted near the infrazygomatic crest, buccal shelf, or palate [30].

Space closure

Maximum anchorage during extraction space closure is one of the most established indications for TAD use. Guided placement enables miniscrews to be positioned so that the retraction force passes near the center of resistance of the anterior segment, promoting bodily movement and reducing posterior anchorage loss [31].

Molar distalization

Distalization often requires prolonged force application and robust anchorage. Guided placement is advantageous in both palatal and extra-alveolar distalization systems because it improves implant orientation and allows insertion into dense cortical bone [32].

Complications and Risk Management

Although guided insertion substantially reduces complications, it does not eliminate them [33]. Root contact remains the most frequently discussed complication in orthodontic miniscrew placement [34]. Guided

placement lowers this risk by enabling assessment of root divergence and interradicular bone in three dimensions [35].

Soft tissue inflammation, cortical perforation, and implant instability may still occur if planning or insertion protocols are compromised [36]. Technical errors in CBCT-STL registration, poor print quality, or improper guide seating may reduce overall accuracy [37].

Material-related complications should also be considered when using 3D-printed implant splints. Dimensional changes resulting from inadequate post-curing, improper sterilization, resin aging, or mechanical wear may reduce the accuracy of guide seating and implant trajectory transfer. Similarly, micro-fractures or deformation of the guiding channel during insertion can compromise precision, particularly in high-torque clinical situations. Routine inspection of the guide before use, adherence to validated manufacturing protocols, and the use of reinforced metallic sleeves where appropriate can help minimize these risks and preserve the accuracy expected from digitally guided orthodontic procedures.

Limitations of 3D Implant Splints

Despite their advantages, 3D implant splints have limitations. They require access to CBCT, intraoral scanning, planning software, and 3D printing facilities [38]. Radiation exposure from CBCT must also be justified according to the diagnostic needs of the case [39]. Additionally, guided systems increase planning time and involve greater financial cost compared with conventional freehand placement [40].

Future Directions

Future developments in guided skeletal anchorage are likely to involve artificial intelligence-assisted planning, improved printable biomaterials, augmented reality navigation, and enhanced automation of digital workflows. Research should focus on long-term clinical outcomes, patient-reported experiences, and standardized assessment of guide accuracy and complications.

Conclusion

Three-dimensional implant splints represent a major advance in the placement of temporary anchorage devices in orthodontics. By combining CBCT imaging, intraoral scanning, virtual planning, CAD design, and 3D printing, these guides enable highly accurate and patient-specific transfer of the planned miniscrew trajectory into clinical practice. Their use improves positional accuracy, reduces operator dependency, enhances anatomical safety, and supports more predictable biomechanics. As digital orthodontics continues to evolve, guided miniscrew placement is expected to become an increasingly important component of individualized orthodontic treatment.

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