Progress in Medical Devices
ISSN: 2957-5478

Zentime

Review Article

https://doi.org/10.61189/489352mmqzpk

Research progress on fixation methods for mandibular defect reconstruction

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Declaration of conflict of interest: None.

Received November 13, 2024; Accepted March 06, 2025; Published June 30, 2025

Highlights

- Autologous bone grafting remains the primary method for mandibular reconstruction.
- The integration of computer-aided design and 3D printing enhances surgical precision and safety.
- Distraction osteogenesis is a promising alternative, reducing donor site morbidity.
- The mortise-and-tenon structure is a novel fixation method.

Abstract

The mandible plays a crucial role in facial structure and function. Mandibular defects, often caused by tumor resection, trauma, or congenital conditions, severely impact patients' physiological functions and quality of life. Reconstruction methods for mandibular defects primarily include autologous bone grafting, computer-aided reconstruction, and distraction osteogenesis. Among these, autologous bone grafting remains the most widely used technique. As medical technologies advance, the integration of computer-aided design and 3D printing has provided new technical support for personalized mandibular reconstruction, improving both surgical precision and safety. Moreover, distraction osteogenesis has emerged as a promising alternative in recent years. This paper reviews research on fixation methods for V mandibular defect reconstruction to offer clinical guidance for effective mandibular repair.

Keywords: Mandibular defect, reconstruction, autologous bone grafting, 3D printing, distraction osteogenesis

Introduction

The mandible is in the lower third of the face and plays a crucial role in maintaining facial structure and key physiological activities such as chewing and speech. Due to its unique anatomical structure, it is central to oral and maxillofacial surgery. Mandibular defects may arise from tumor resection, trauma, or congenital deformities, leading to varying degrees of impairment in both facial aesthetics and function. The location and size of the defect are key factors in determining its impact on the patient, making the classification of mandibular defects crucial for selecting appropriate treatment strategies and evaluating postoperative functional recovery [1].

A widely used classification system is the HLC classification, proposed by Jewer et al., which categorizes mandibular defects based on location and extent. In this system, "H" refers to unilateral mandibular defects that do not extend beyond the midline, often leading to joint dysfunction and impaired mandibular movement [2]. "C" denotes defects in the anterior mandibular region, between the canines, primarily affecting aesthetics and occlusal function. "L" represents defects in the lateral mandible (excluding the condyle), potentially impairing masticatory muscle function and mandibular mobility. Boyd et al. later refined this classification by adding subdivisions for soft tissue defects, enhancing its clinical relevance in mandibular reconstruction [3].

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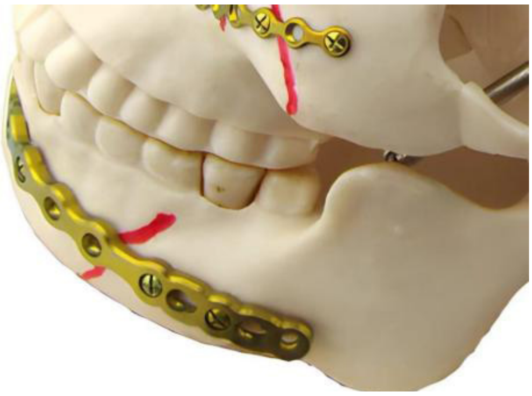

Figure 1. Titanium Plate Fixation.

Mandibular reconstruction is essential for restoring both appearance and functionality. The ideal reconstruction should achieve three primary goals: (i) restoring facial appearance as close to normal as possible, (ii) achieving normal dental alignment and occlusion, and (iii) preserving or approximating normal chewing and speech functions. Mandibular reconstruction has long been a focal point of medical research, with oral and maxillofacial surgeons constantly exploring more effective methods to restore both the form and function of the mandible [4].

Methods for mandibular defect reconstruction

Modern mandibular reconstruction surgery began to emerge in the early 20th century. Over the past century, significant advancement in research have driven rapid progress in the techniques and materials used for mandibular defect repair. Currently, various reconstruction methods are available, with the specific choice depending on the defect's location, cause, and severity [5]. While multiple methods have been applied to mandibular defect reconstruction, autologous bone grafting remains the cornerstone of the reconstruction process. Recent advances in computer technology have significantly enhanced mandibular repair techniques. The integration of computer-assisted technology and personalized reconstruction offers substantial technical support for functional mandibular restoration. For instance, Yoonjoo introduced a case of prosthetic reconstruction of maxillary defects in an elderly patient caused by a traumatic fall, demonstrating the application value of prosthetic technology in jaw reconstruction [6]. Regarding autologous bone grafting, a 2020 study by Samy et al. proposed a comprehensive digital and prosthetic-guided protocol for inserting dental implants into autogenous free bone grafts following segmental mandibular defect reconstruction [7]. Furthermore, Nobis et al. developed a template tool to assist fibular osteotomy in mandibular defect reconstruction through digital analysis of the human mandible [8]. These studies highlight the potential of digital technology to enhance the precision and outcomes of mandibular reconstruction surgery. Additionally, the application of distraction osteogenesis has opened new pathways for mandibular reconstruction, further expanding the available options for reconstruction [9].

Traditional titanium plate internal fixation

In mandibular reconstruction using autologous bone grafts, achieving stable fixation is crucial. The quality of fixation directly influences the success of fibular grafts, as inadequate fixation often leads to graft infection or necrosis. Due to the wide range of mandibular movements and the complex load-bearing environment, as shown in **Figure 1**, rigid internal fixation using titanium plates remains the most common fixation method. This technique stabilizes the graft by securing titanium or titanium alloy plates and screws at both ends of the fracture line, promoting bone healing. A 2024 prospective comparative study by Sugumar et al. evaluated the functional and radiographic outcomes of open reduction internal fixation and minimally invasive plate fixation for humeral shaft fractures, highlighting that traditional titanium plate fixation is perpendicular to the occlusal and muscular force trajectories of the mandible, which is inconsistent with the mandibular biomechanical load transfer mechanism [10]. Additionally, titanium implants may interfere with radiotherapy, potentially increasing the risk of complications like osteoradionecrosis.

Despite its widespread use, rigid internal fixation with titanium plates has notable limitations. The perpendicular alignment of the fixation method to the occlusal and muscular force trajectories contrasts with the mandible's natural biomechanical load transfer pathway. Furthermore, titanium implants may interfere with radiotherapy, heightening the risk of complications such as osteoradionecrosis.

With advancements in medical technology, the concept of semi-rigid fixation has recently gained attention. Semi-rigid fixation implants, such as sliding plates, allow for controlled micro-movements, which reduce the forces applied to the bone-metal interface during strain and promote localized bone healing. This approach offers advantages in stress distribution and biomechanics, but further research and validation are required to establish its applica-

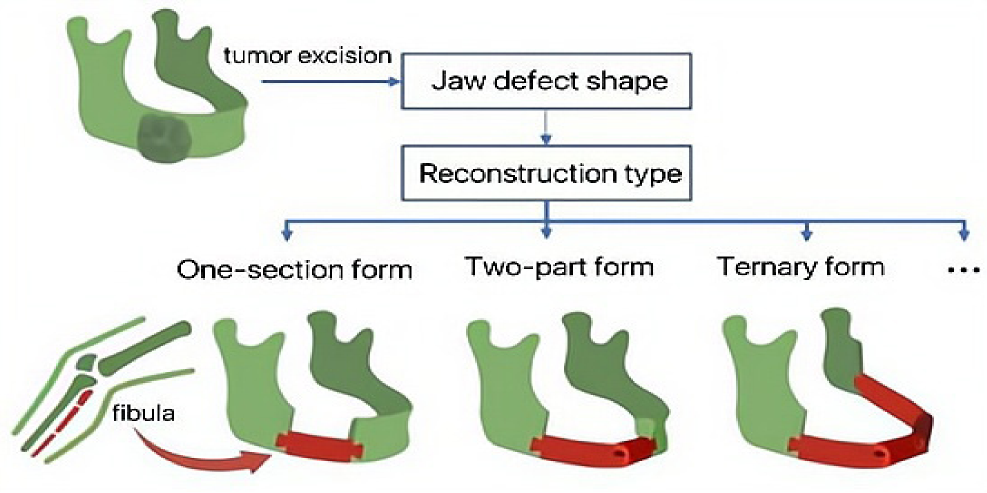

Figure 2. Mandibular Reconstruction Theory Based on Mortise and Tenon Architectural Technique (Selection of Mortise and Tenon Structure).

tion. In a 2024 study, Wang et al. introduced a specially contoured pelvic rim reconstruction titanium plate combined with cross-plate support screws (quadrangular screws) for treating acetabular fractures involving the quadrilateral plate through an anterior ilioinguinal approach [11]. The semi-rigid fixation concept demonstrated in this study offers new insights into its potential application in mandibular reconstruction. Additionally, Cui et al. introduced a novel base-fixation system and evaluated it using three-dimensional reconstruction and finite element analysis [12]. The results showed that compared to conventional buccal fixation, the base-fixation system exhibited superior fixation ability with a safety factor of 3.8, making it suitable for clinical applications. This method also reduced the volume of fixation titanium plates, shortened surgery duration, and minimized the risk of wound infection, presenting a promising alternative for mandibular defect reconstruction. Furthermore, Chen et al. conducted a finite element analysis comparing the biomechanical performance of polyetheretherketone (PEEK) and titanium alloys in mandibular defect reconstruction [13]. The study found that glass fiber-reinforced PEEK (GFR-PEEK) generated excessive stress beyond the yield strength of the mandible when loaded in the anterior region, making it unsuitable for defect repair. However, carbon fiber-reinforced PEEK (CFR-PEEK) exhibited more favorable stress distribution, positioning it as a more stable candidate for fixation systems.

Mortise and tenon structure-based fixation method

Inspired by the traditional Chinese "mortise and tenon" architectural technique, the authors propose a novel fibula-mandible semi-rigid fixation theory based on this structure, combined with tension screws, as shown in **Figure 2**. The mortise and tenon structure, with a long history in China, is renowned for its precise structural design and mechanical stability. Particularly, the dovetail mortise structure, consisting of a head tenon and tail tenon, offers enhanced structural strength and tensile resistance through precise proportion control. Finite element analysis shows that this fixation, combined with tension screws, offers superior biomechanical distribution in the mandible compared to traditional rigid internal fixation.

Inspired by this concept, researchers may explore its application in mandibular reconstruction by simulating a mortise and tenon structure between the fibula and mandible, achieving a fixation effect that is more consistent with the mandible's biomechanical properties. Xin et al. conducted a preclinical trial assessing the biomechanical performance and osteogenic capability of 3D-printed polymeric scaffold implants for repairing critical-sized mandibular defects [14]. The study incorporated in silico finite element modeling, in vivo implantation in sheep, and in vitro mechanical testing. Results showed that the selective laser sintering-printed PEEK scaffolds exhibited excellent bone-scaffold integration and new bone formation at the scaffold-bone interface, further validating the potential of 3D-printed polymeric biomaterials for mandibular defect reconstruction.

In a 2023 study, Yu et al. explored terahertz reconfigurable multifunctional metamaterials based on 3D-printed mortise and tenon structures [15]. Their in-depth analysis and applica-

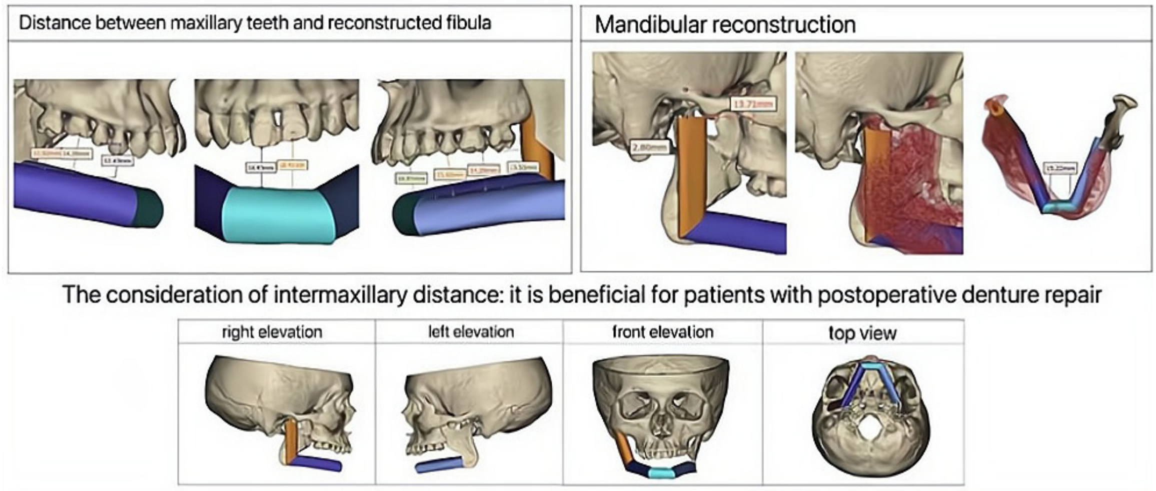

Figure 3. 3D Simulation of Mandibular Reconstruction.

tion of the mortise and tenon structure provide new inspiration for mandibular reconstruction. Finite element analysis indicates that the dovetail mortise and tenon structure, combined with tension screws, yields superior biomechanical distribution in the mandible compared to traditional rigid internal fixation. Zhang et al. investigated the use of customized bioceramic scaffolds and metal meshes for large-size mandibular defect regeneration and repair [16]. The study demonstrated that magnesium-doped calcium silicate and α-tricalcium phosphate scaffolds significantly promoted osteogenesis compared to β- tricalcium phosphate. Moreover, magnesium-doped calcium silicate exhibited superior mechanical properties during the early stage of bone regeneration, suggesting that combining high-strength bioactive scaffolds with titanium meshes could be a promising strategy for repairing large, load-bearing mandibular defects.

The core advantage of the mortise and tenon structure lies in its natural stress-dispersion capability. While traditional titanium plate fixation provides sufficient rigidity, its excessive rigidity often causes stress concentration, particularly under the complex mechanical forces generated during chewing and speaking. In contrast, the mortise and tenon structure, with its unique interlocking design, allows for micro-movements that naturally disperse external forces under load. This effectively reduces mechanical friction between the grafted segment and surrounding tissues, lowering the incidence of complications and decreasing the risk of postoperative bone resorption. Furthermore, the mortise and tenon structure offers improved shear and tensile resistance, ensuring the stability of the grafted bone segment.

Although the biomechanical advantages of the mortise and tenon structure have been preliminarily validated, its clinical application remains in an exploratory phase. Current research mainly relies on finite element simulation models, and the precise design of the mortise and tenon structure based on the type and size of mandibular defects in clinical practice remains an area requiring in-depth investigation. For instance, design parameters such as the angle, size, and fit of the mortise and tenon structure directly affects its mechanical performance. Future research should leverage personalized three-dimensional imaging and simulation technology to further optimize the design of the mortise and tenon structure, thereby enhancing its clinical applicability.

Computer-aided mandibular reconstruction

In recent years, with the continuous development of medical imaging technology and computer science, digital surgical techniques have gained widespread recognition and application in maxillofacial surgery. To achieve personalized restoration of mandibular appearance and function with optimal reconstruction accuracy, scholars worldwide have applied digital surgical technologies to repair segmental mandibular defects. In 1983, Hemmy et al. first utilized 3D CT technology for the diagnosis and treatment of cranio-maxillofacial diseases, a groundbreaking advancement that opened new directions for maxillofacial surgery [17].

With ongoing advancements in computer technology, computer-aided design (CAD)/manufacturing technology based on 3D reconstruction and computer-assisted navigation systems have been widely applied in the maxillofacial field, as shown in **Figure 3**. This technology acquires 3D data of lesions using imaging techniques such as CT or MRI, generates 3D models through computer systems, and conducts simulation analyses to formulate scientifically sound treatment plans. It aids surgeons in preoperative planning, including defining resection boundaries, determining the shape and position of reconstruction materials, and designing the optimal surgical approach. This approach ensures intraoperative precision, predicts postoperative outcomes, and enables the production of customized prostheses, thereby supporting personalized medicine in clinical practice.

In a 2024 study, Bagheri et al. used finite element analysis to explore the application of a new intramedullary internal distractor in distraction osteogenesis [18]. Based on a patient's 3D model, 3D printing technology can be used to produce surgical guides, such as osteotomy guides and shaping guides, which assist surgeons in precise cutting and fixation of bone tissue during surgery. Additionally, 3D printing enables the creation of customized titanium plates, prostheses, or implants to ensure a perfect fit between the grafted bone and the mandibular defect area [19]. Xue et al. conducted a study involving 3D digital reconstruction for 26 patients who underwent mandibular resection from 2014 to 2018, examining the application value of 3D printing technology in preoperative planning and intraoperative guidance for mandibular reconstruction surgery [20]. The results indicated that combining digital reconstruction with 3D printing significantly enhanced the precision of mandibular repair surgery.

Yu et al. from the First Affiliated Hospital of Zhejiang University School of Medicine investigated the application of a novel surgical guide in achieving positional accuracy for mandibular reconstruction and implants, finding that the guide improved the accuracy of mandibular repair, increased both the fit of the prosthesis, and enhanced patient satisfaction [21]. Liang et al. developed a digital surgical guide technique, combined with the Combined Osteotomy and Reconstruction Pre-bent Plate Positioning technique, which reduced errors between the pre-bent titanium plate and reconstructed mandible, yielding satisfactory clinical results [22]. Studies have shown that 3D printing technology achieves submillimeter accuracy, as demonstrated in mandibular reconstruction procedures where bone displacement errors are maintained below 1.27 mm, ensuring patient-specific anatomical solutions. Furthermore, it significantly enhances clinical quality and efficiency by reducing the production time of facial prostheses from weeks to 2–3 days, while achieving 100% aesthetic approval rates in prosthetic rehabilitation. This advancement markedly improves patient satisfaction and reduces postoperative complications [23, 24].

Yan et al. studied the application of computer-assisted surgical systems combined with 3D printing technology in free fibula flap reconstruction for mandibular defects, outlining three main advantages of the technology [25].

Firstly, it allows for personalized customization. By obtaining precise anatomical information of the patient's mandible through CT scanning, this approach provides a foundation for tailored reconstruction. Using CAD technology, surgeons can precisely design and simulate a reconstruction plan based on the patient's mandibular defect, osteotomy range, and repair requirements, ensuring that the reconstruction closely matches the patient's unique anatomical structure. Subsequently, 3D printing technology converts the virtual design into a physical prosthesis, completing the entire personalized reconstruction process, which significantly enhances surgical outcomes and the potential for functional recovery.

Secondly, this technology improves surgical precision. By transforming virtual images into 3D models, computer-assisted systems and 3D printing enable a more accurate understanding of the patient's physiological structure, thereby increasing diagnostic precision. During surgery, the computer-assisted system provides precise navigation and visualization, aiding the surgeon in performing more accurate procedures and improving surgical success rates. Particularly for free fibula flap transfers, computer systems secure and pre-bend titanium plates, enhancing stability at the mandibular endpoint, which is critical for accurate temporomandibular joint reconstruction. Furthermore, designing the surgical plan with computer software and creating a guide ensures that osteotomy shaping perfectly aligns with the defect site, further enhancing the precision of mandibular reconstruction.

Lastly, technology enhances surgical safety. Surgeons utilize 3D reconstruction tools and surgical simulation systems to gain a comprehensive understanding of the patient's anatomy, accurately define the surgical resection boundaries, and ensure predictability and precision in surgery. This predictability enables surgeons to anticipate and manage potential intraoperative issues, reducing damage to blood vessels and surrounding normal tissues, thus significantly increasing surgical safety. Additionally, the technology broadens the surgical field of vision, enhancing operational flexibility and autonomy, allowing for minimized incisions while reducing functional damage to the reconstructed tissue structure to the lowest possible level [25]. Clinical studies indicate that this technology effectively reduces surgical time, decreases blood loss, accelerates postoperative recovery, and improves patient satisfaction with appearance, chewing, and phonation functions while reducing postoperative complications. Kang et al. developed a novel functional repair method combining a 3D-printed PEEK implant with a free vascularized fibula graft, assessing its performance under masticatory motion [26]. Finite element analysis indicated that the safety factor exceeded 2.3, and the deformation of the reconstructed model was lower than that of a normal mandible during most clenching tasks, ensuring primary stability. Additionally, this method demonstrated superior clinical outcomes compared to conventional fibular grafting, offering enhanced safety, stability, and aesthetic restoration.

Distraction osteogenesis

Distraction osteogenesis (DO) has become increasingly common in mandibular reconstruction, especially for treating mandibular defects and deformities, where it demonstrates significant advantages. Compared to traditional bone grafting methods, DO minimizes donor site damage and reduces the risk of immune rejection. By utilizing the principle of tension-stress bone regeneration, it facilitates simultaneous growth of bone and soft tissue, achieving a more natural repair outcome [27]. The core concept of DO involves using a distraction device to gradually widen the space between bone segments or osteotomized bones, at a specified rate and frequency, stimulating new bone formation and enabling bone lengthening or widening. This technique is particularly suitable for complex mandibular reconstructions, including segmental defects, condylar loss, and congenital or acquired craniofacial deformities [28].

In the 1990s, DO began to be used in oral and maxillofacial surgery, primarily for correcting maxillofacial deformities and repairing bone defects. In 1992, McCarthy et al. first attempted to use DO to treat hemifacial microsomia, which marked the beginning of the technique's widespread application. Su et al. performed tumor resection surgeries on six patients with ameloblastoma or odontogenic keratocyst and used DO to repair the mandibular defects, further validating the feasibility and clinical value of this technique for broader application [29].

Huang et al. investigated the clinical application of pedicled mandibular osteomuscular flaps in the reconstruction of acquired segmental mandibular defects, assessing postoperative speech, swallowing function, and aesthetic outcomes [30]. The study found that all flaps remained viable, with an average speech function score of 7.6 ± 0.6 and satisfactory masticatory efficiency. The Visual Analog Scale score for appearance was 7.8 ± 0.8. These results demonstrate that this method is an effective option for secondary repair, offering functional and aesthetic benefits.

Conclusion

The mandible is a central component of the maxillofacial region, and repairing its defects and deformities is crucial for patients. In recent years, fixation techniques for mandibular defect reconstruction have made significant advancements. Among the various methods, autologous bone grafting, particularly vascularized grafts, remains the preferred technique for defect repair. Notably, the application of digital technologies, such as CAD and 3D printing, has enabled personalized mandibular reconstruction, significantly enhancing surgical success rates, precision, and patient satisfaction postoperatively. Additionally, distraction osteogenesis is emerging as an effective alternative, offering advantages such as reduced donor site damage, avoidance of immune rejection, and the ability to simultaneously repair of soft tissue and bone structures.

Future research should focus on further optimizing these techniques and exploring their applications for different types of mandibular defect. The success of mandibular defect reconstruction depends not only on advanced technologies and materials but also on appropriate fixation methods to ensure graft stability and effective postoperative recovery. This review systematically examines existing mandibular fixation techniques, analyzes the strengths and weaknesses of various methods, and introduces a novel mortise-and-tenon-based fixation approach. While this approach shows clear biomechanical advantages, it is still in the research and development phase, necessitating further clinical trials and validation studies for widespread clinical adoption.

Author contributions: Xiaohan Yu: Conceptualization, Methodology, Investigation, Data Curation, Writing-Original Draft. Haipo Cui: Conceptualization, Methodology, Validation, Su-

pervision, Writing-Review & Editing. Hui Zhong: Supervision, Writing-Review & Editing.

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