Computational Models and Their Applications in Biomechanical Analysis of Mandibular Reconstruction Surgery

Hamidreza Aftabi

aftabi@student.ubc.ca

Department of Electrical and Computer Engineering, University of British Columbia, Vancouver, British Columbia, Canada

Atabak Eghbal

Department of Electrical and Computer Engineering, University of British Columbia, Vancouver, British Columbia, Canada

Sophie McGregor

Department of Surgery, University of British Columbia, Gordon and Leslie Diamond Health Care Centre, Vancouver, British Columbia, Canada

Katrina Zaraska

Department of Surgery, University of British Columbia, Gordon and Leslie Diamond Health Care Centre, Vancouver, British Columbia, Canada

Eitan Prisman

Department of Surgery, University of British Columbia, Gordon and Leslie Diamond Health Care Centre, Vancouver, British Columbia, Canada

Antony Hodgson

Department of Mechanical Engineering and School of Biomedical Engineering, University of British Columbia, Vancouver, British Columbia, Canada

Sideny Fels

Department of Electrical and Computer Engineering, University of British Columbia, Vancouver, British Columbia, Canada

---

Research Article

Keywords: Mandibular Reconstruction, Computational Models, Biomechanical Analysis

Posted Date: July 19th, 2023

DOI: https://doi.org/10.21203/rs.3.rs-2939858/v2

Version of Record: A version of this preprint was published at Computers in Biology and Medicine on February 1st, 2024. See the published version at https://doi.org/10.1016/j.compbiomed.2023.107887.

Computational Models and Their Applications in Biomechanical Analysis of Mandibular Reconstruction Surgery

Hamidreza Aftabi*[1], Atabak Eghbal+[1], Sophie McGregor+[2], Katrina Zaraska+[2], Eitan Prisman[2], Antony Hodgson[3], and Sidney Fels[1]

***Abstract*—Advanced head and neck cancers involving the mandible often require surgical removal of the diseased parts and replacement with donor bone or prosthesis to recreate the form and function of the premorbid mandible. The degree to which this reconstruction successfully replicates key geometric features of the original bone critically affects the cosmetic and functional outcomes of speaking, chewing, and breathing. With advancements in computational power, biomechanical modeling has emerged as a prevalent tool for predicting the functional outcomes of the masticatory system and evaluating the effectiveness of reconstruction procedures in patients undergoing mandibular reconstruction surgery. These models enable surgeons to provide cost-efficient and patient-specific treatment tailored to the needs of individuals. To underscore the significance of biomechanical modeling, we conducted a review of 66 studies that utilized computational models in the biomechanical analysis of mandibular reconstruction surgery. These studies were categorized based on the main components analyzed, including bone flaps, plates/screws, and prostheses, as well as their design and material composition.**

***Index Terms*—Mandibular Reconstruction, Computational Models, Biomechanical Analysis**

I. Introduction

Approximately 5,000 Canadians are affected by oral cancer each year, and 1,500 will die from it [1]. Advanced head and neck cancers (HNC) involving the mandible often require surgical removal of the diseased part. HNC can have a vital impact on cosmetic and functional outcomes of speaking, mastication, and breathing. Consequently, this disease profoundly impacts social acceptance. In the conventional approach, an oncologist evaluates HNC patients and arranges for staging, diagnostic testing, and radiological imaging. Those fit for surgery will attend the surgery, during which the diseased soft tissue and bone often require extirpation, leaving behind a defect. In most cases, large continuous segments of the mandible and soft tissue are cut out from the patient in order to achieve a negative cancer margin in the patient (Figure 1). This leaves the patients with a mandible defect, unable to eat, speak or breathe safely. As the prevailing technique, autologous tissue from the patient, such as the fibula, iliac crest, or scapula, is commonly transplanted to reconstruct the resulting defect in order to recreate the form and function of the premorbid defect [2]–[4]. In addition, a titanium plate is often used to hold bones in place while they heal [5]. Depending on the nature of the defect and the patient's specific requirements, there may be instances where surgeons opt to employ alloplastic prostheses for the defect reconstruction [6]. Overall, the reconstruction procedure is complex and time-consuming, demanding the surgeon to work within a limited window of ischemia.

Recently, the field has been undergoing a revolution due to the integration of advanced digital technologies in surgical design and the convergence of microvascular reconstruction techniques [9, 10]. Virtual pre-planning of the mandibular resections, transplanted donor bone and/or prosthesis has provided an opportunity to pre-calculate optimal outcomes based on which the subsequent intraoperative execution is guided using pre-fabricated cutting guides. Once the virtual resection is planned and a choice of donor bone or prosthesis is made, optimizing the reconstruction can be reduced to a solvable algorithm, based upon which a cutting guide for the mandible resection, a complimentary guide for donor bone or patient-specific prosthesis are virtually designed, fabricated, sterilized and brought to the operating room. Our research group (ISTAR Group) at The University of British Columbia, has been successfully testing this approach using the pre-op workflow which limits the variability and complexity of the time-sensitive intraoperative tailoring. Early studies using virtual pre-planning have demonstrated a decrease in ischemia and operating time [11, 12]. Additionally, guided surgeries result in better contact between segments [13], leading to a better blood supply and less need for revision surgery, which would have a significant impact on cost savings. However, current mandibular reconstruction techniques can alter mandible movements, muscle paths, and bite forces in ways that are not currently modeled or explicitly planned for, thereby resulting in ongoing deficits in function [14, 15]. Furthermore, even when using VSP techniques, the non-union and partial union rates can be relatively high (e.g., as much as 37% of cases [16]). Since complete rehabilitation after surgery might take up to two years [14], the biomechanical events associated with these changes are challenging to evaluate clinically at the time of the index surgery and are, therefore, not well reported or studied.

In recent years, there has been a significant focus on the development of computational models aimed at gaining a deeper understanding of the functional outcomes of the

* Corresponding author, Email: aftabi@student.ubc.ca
+ Co-second Authors. These authors contributed to this work equally.
1 Department of Electrical and Computer Engineering, University of British Columbia, Vancouver, British Columbia, Canada
2 Department of Surgery, University of British Columbia, Gordon and Leslie Diamond Health Care Centre, Vancouver, British Columbia, Canada
3 Department of Mechanical Engineering and School of Biomedical Engineering, University of British Columbia, Vancouver, British Columbia, Canada

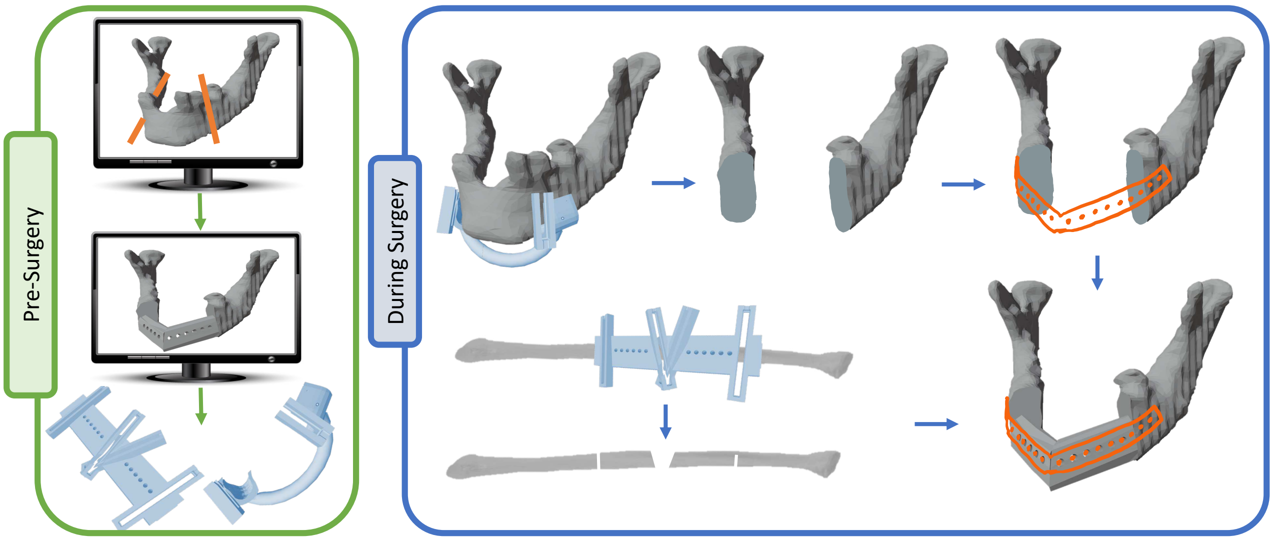


Fig. 1. Overview of the Mandible Reconstruction Surgery Using Fibula Bone with Two Different Phases: Pre-surgery (Virtual Planning) and During Surgery [7, 8].

patient masticatory system undergoing mandibular reconstruction Surgery [17]–[19]. These models seek to capture dynamic, kinematic, and biomechanical changes in the mandible resulting from the surgery [19, 20]. Computer modeling offers the unique advantage of being able to perform work in a virtual environment, where complex numerical models can be handled with relative ease. A detailed investigation of the biomechanics of surgically reconstructed mandible through computer simulation can provide preoperative benefits in planning reconstruction procedures and post-operative benefits by guiding rehabilitation. These computational approaches can provide patient-specific treatment and complement other factors such as clinician experience and intuition in order to improve surgical outcomes and patients' quality of life. The objective of this study is to investigate the computational models developed for the biomechanical assessment of mandibular reconstruction surgery. Our survey provides surgeons with state-of-the-art methods for creating biomodels, along with the most prevalent techniques used in designing plates and prostheses, whose effectiveness is then assessed through computational models.

II. Method

A. Searching Methodology

The authors conducted a search on the Medline (Pubmed), Google Scholar, and Scopus computer databases, covering all available years up to 2022, using a combination of subject headings and keywords related to mandible biomechanics and modeling. AND and OR operatives were also used when allowed by the search engine to create a combination of these terms. The subject headings used were 'Biomechanics/Biomechanical', 'Mandible/Jaw reconstruction', 'Models, computer', 'Models, computational', 'Computer simulation', and 'Finite element analysis/modeling'. The keyword search included terms such as mandible biomodels, computer models, computer simulation, finite element analysis, biomodels, biomechanics, biomechanical and mandible/jaw reconstruction. The authors restricted the search to studies published in English.

B. Searching Result

A comprehensive literature search was conducted up to December 31st, 2022, utilizing subject headings and keywords in Scopus and PubMed, resulting in a total of 147 papers and 241 papers, respectively. These papers underwent a thorough review process by a team of three researchers who carefully assessed the titles, abstracts, and content to narrow down the selection to 77 relevant papers. Of these papers, only 66 were ultimately included, based on the following inclusion criteria which encompassed: 1) utilization of human anatomy data, 2) inclusion of biomechanical simulation, 3) focus on mandible reconstruction (excluding cases such as marginal resection, mandibular atrophy, joint replacement, fracture, distraction osteogenesis, and dental implantation), 4) availability of full text, 5) publication in peer-reviewed journals or conferences (pre-print versions were excluded), and 6) being written in English. These stringent inclusion criteria were applied to ensure the quality and relevance of the selected papers in the final review.

III. Discussions

A. Wrorkflow Overview

Figure 2 provides the overview of the workflow of the simulation-based analysis of mandibular reconstruction surgery. The process comprises three major parts: data acquisition, modelling, and analysis. Computerized tomography (CT) and magnetic resonance imaging (MRI) images are the most common source of data input used to segment

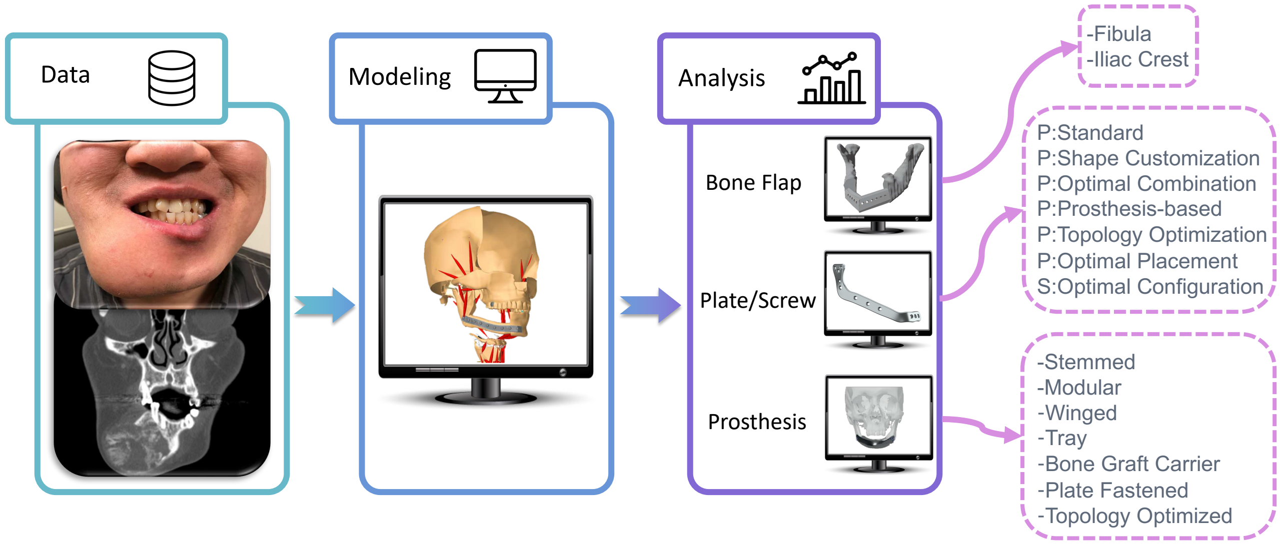


Fig. 2. Overview of the Workflow in Developing Computational Models for Biomechanical Analysis of Mandibular Reconstruction Surgery. The Process consists of Three Major Sections: Data Acquisition, Modeling, and Analysis.

and reconstruct the mandible as well as soft tissues. These elements are then combined to form the structure of the ultimate model. The model can be further investigated using other tools such as finite element modeling, which allows for the study of the model's behaviour under various loading conditions. The last step in the workflow entails analyzing the key components of the reconstructed mandible, including bone flaps, plates, and prostheses, through computer simulations. This process aids in evaluating different designs and their effectiveness in mandibular reconstruction surgery. The details of each workflow stage are explained in further depth in the sections that follow.

B. Source of the Mandibular Model

Various sources of mandibular models are used in developing the computational model (Figure 3). The vast majority of papers use CT data from a single human mandible (48/66). There was a small proportion of papers that used two or more human mandible CTs (6/66). Given that most of the papers in our review were focused on the optimization of a single mandibular component, or were comparing two specific components, a single mandible for analysis removes possible confounders in the data. However, studies that compare more than 10 different human mandibles may have a more direct clinical application, as they account more for human variation in anatomy [15, 21, 22].

Artificial mandibles (6/66), and cadaveric data (2/66), are two other sources of data used in computer modeling for mandibular reconstruction. The most commonly used artificial mandible is Synbone (Synbone, Malans, Switzerland), which has an anatomical appearance similar to that of the human mandible [23]–[27]. The geometric mesh of the mandible in such cases is generated by scanning the Synbone. Nevertheless, in some cases, the physical version of Synbone is used as well to perform repeatable biomechanical experiments, which might help in validating the simulation results [25].

Out of the reviewed paper, only two studies incorporated scans of the cadaveric mandible in their analysis. Kimura *et al.* [21] used CT scanning slices from eight dry human mandibles to construct the mandibular model and determine the optimal plate fixation for stress dispersion around screws. Lang *et al.* [22] scanned 21 pairs of fresh frozen cadaveric human mandibles and respective fibulas to investigate the effect of topology optimization on plate design. Using the cadaveric mandibles, they were able to conduct biomechanical testing including static and dynamic analysis.

C. Computational Models

The computational models used in the biomechanical analysis of mandibular reconstruction can be broadly classified into three main categories: static/quasi-static, dynamic, and kinematic.

1) Static Analysis: The static analysis evaluates the stress and deformation of the reconstructed mandible or its components (such as the reconstruction plate or prosthesis) under

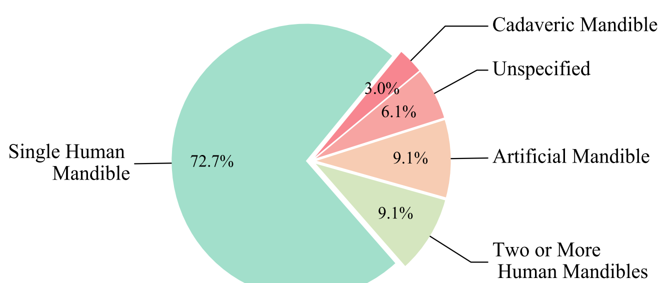


Fig. 3. Source of Mandibular Data Used in Computational Models

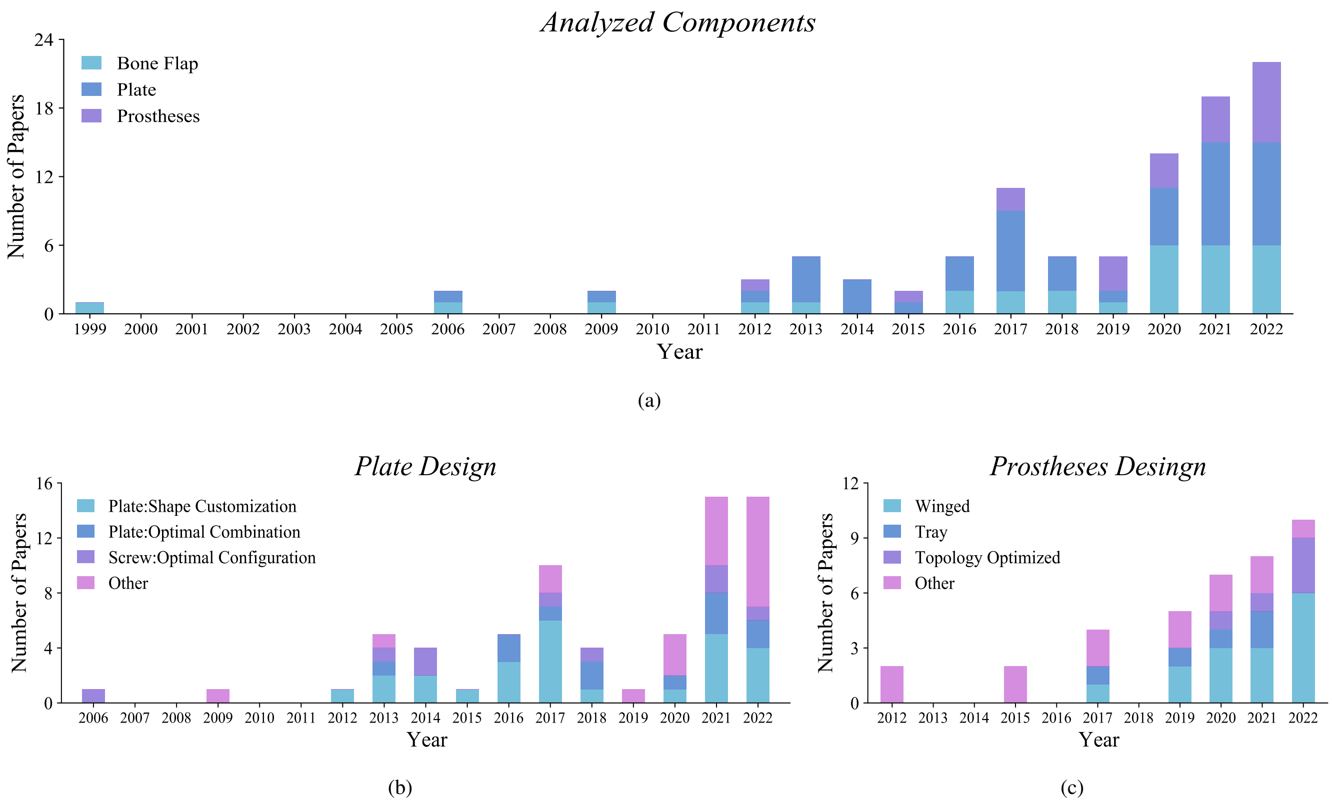


Fig. 4. Trends of (a) Main Analyzed Components (b) Plates Design, and (c) Prostheses Design in Biomechanical Analysis of Mandibular Reconstruction Surgery.

specific boundary conditions [19]. The most common techniques for developing models for biomechanical analysis are multi-body dynamics (MBD), finite element method (FEM), or a combination of both. MBD is used to determine the rigid-body displacement of a component, while FEM is used to determine the deformation of a body.

All 66 studies in this article considered static/quasi-static conditions in their analysis, with 65 of these studies using the finite element method (FEM) to determine stress or strain distribution in specific parts. Alternatively, as the only non-FEM study reviewed in this article, Curtis *et al.* [15] developed a computer model of mandible biomechanics in the reconstructed mandibulectomy patient based on the static equilibrium theory [28]. They demonstrated that various metrics predicted by the computer simulations, such as first molar or incisal occlusal force, were consistent with clinical findings.

2) Finite Element Method in Mandible Reconstruction: While stress and strain distribution may be determined analytically in biomodels, it gets increasingly challenging to solve such equations in more complex geometries. In such cases, FEM can approximate the problem by decomposing complicated forms into a large number of finite elements connected at their nodes. In the finite element analysis (FEA) of the reconstructed mandible, the external force (such as biting and muscle force), boundary condition, and mechanical characteristics of the model are known, from which the nodal displacement can be calculated. These nodal displacements are then utilized through interpolation techniques for computing the strain and stress distributions, which are the desired outputs [19, 85, 86].

Kimura *et al.* [21] introduced the use of FEM in the biomechanical analysis of mandible reconstruction in 2006. They conducted a simulation study using a three-dimensional finite element method to specify the most appropriate plate fixation for redistributing the stress around screws in mandibular reconstruction.

a) Element Types: With the progress in computational power and the availability of advanced software tools, the use of finite element analysis has become more frequent in the analysis of mandibular reconstruction in order to examine other components such as bone flaps and prostheses (Table I and Figure 4a). In FEA, the choice of element type can have a substantial effect on the accuracy and efficiency of the solution. Linear and quadratic elements are the two most common types of elements used to represent the geometric order of the mesh. A linear element is characterized by a linear basis function in which the displacements of the mesh region vary linearly with the distance between the nodes. On the other hand, quadratic elements utilize a non-linear shape function, and displacements between the nodes are interpolated using a higher-order polynomial [87]. Our survey shows that linear/four-node tetrahedral (Tet4) and quadratic/ten-node tetrahedral (Tet10) are the most common elements used in the FEA of mandibular reconstruction.

Tet10 elements are expected to provide more accurate

TABLE I
OVERVIEW OF THE REVIEWED PAPERS

Author	Year	Analyzed Components			Experimental Analysis	Clinical Evaluation
		Bone Flap	Plate/Screw	Prosthesis		
Curtis *et al.*[15]	1999	✓	-	-	-	CDC
Kimura *et al.*[21]	2006	-	✓	-	-	-
Tie *et al.*[29]	2006	✓	-	-	-	-
Schuller-Götzburg *et al.*[30]	2009	✓	✓	-	-	HA
Wu *et al.* (a)[31]	2012	✓	✓	-	-	-
Wong *et al.*[23]	2012	-	-	✓	-	-
Jedrusik-Pawłowska *et al.*[32]	2013	✓	✓	-	-	RA
Li *et al.* (a)[33]	2013	-	✓	-	-	CI & PF
Chang *et al.*[34]	2013	-	✓	-	-	-
Wu *et al.* (b)[35]	2013	-	✓	-	-	-
Li *et al.* (b)[36]	2014	-	✓	-	-	CI & PF
Bujtár *et al.*[37]	2014	-	✓	-	-	-
Narra *et al.*[38]	2014	-	✓	-	CoT	-
Pinheiro and Alves[39]	2015	-	-	✓	-	-
Al-Ahmari *et al.*[40]	2015	-	✓	-	-	-
Jahadakbar *et al.*[41]	2016	✓	✓	-	CoT	-
Mehle *et al.*[42]	2016	-	✓	-	-	-
Park *et al.* (a)[43]	2016	✓	✓	-	-	-
Dahake *et al.*[44]	2017	-	-	✓	-	-
Nasr *et al.*[45]	2017	-	✓	-	-	-
Moiduddin *et al.* (a)[46]	2017	-	✓	✓	-	-
Wu *et al.* (c)[47]	2017	✓	✓	-	FT	-
Luo *et al.*[48]	2017	-	✓	-	-	RA
Sanal *et al.*[49]	2017	-	✓	-	-	-
Seebach *et al.*[24]	2017	✓	✓	-	-	-
Gutwald *et al.*[50]	2017	-	✓	-	FT	-
Yoda *et al.*[18]	2018	✓	-	-	-	CI & PF & CDC
Moiduddin *et al.* (b)[51]	2018	-	✓	-	-	-
Park *et al.* (b)[52]	2018	✓	✓	-	-	-
Hoefert and Taier[53]	2018	-	✓	-	-	-
Gao *et al.*[17]	2019	-	-	✓	CoT	-
Moiduddin *et al.* (c)[54]	2019	-	✓	✓	-	-
Huang *et al.*[55]	2019	-	-	✓	-	-
Cheng *et al.* (a)[56]	2019	✓	-	-	-	-
Kucukguven and Akkocaoğlu[57]	2020	✓	✓	-	-	-
Li *et al.* (c)[58]	2020	✓	-	-	CoT	CI & PF & CDC
Kargarnejad *et al.* (a)[59]	2020	✓	✓	-	CoT	CI & PF
Kargarnejad *et al.* (b)[60]	2020	✓	✓	✓	TT	CI & PF
Prasadh *et al.*[61]	2020	-	-	✓	-	-
Cheng *et al.* (b)[62]	2020	✓	✓	✓	-	-
Wu *et al.* (d) [63]	2020	✓	✓			
Kargarnejad *et al.* (c)[64]	2021	✓	✓	✓	-	-
Koper *et al.*[25]	2021	-	✓	-	CoT	-
Lang *et al.*[22]	2021	✓	✓	-	CoT & FT	CA
Kang *et al.*[65]	2021	✓	✓	✓	-	CI
Shi *et al.* (a)[66]	2021	-	✓	-	CoT & MA & FA	RA
Shi *et al.* (b)[67]	2021	✓	✓	-	DE	-
Peng *et al.*[68]	2021	✓	✓	✓	-	-
Farajpour *et al.*[69]	2021	-	-	✓	-	CI & PF
Zhong *et al.* (a)[70]	2021	✓	✓	-	-	-
Muftuoglu *et al.*[71]	2021	-	✓	-	-	-
Lin *et al.*[72]	2022	-	✓	-	CoT	-
Kootwijk *et al.*[26]	2022	-	-	✓	CoT & FT & DIC	-
Zheng *et al.*[73]	2022	✓	✓	-	-	CI & PF & CDC
Liu *et al.* (a)[74]	2022	-	-	✓	-	-
Shen *et al.*[27]	2022	-	-	✓	CoT	-
Jung *et al.*[75]	2022	✓	✓	-	-	-
Zhong *et al.* (b)[76]	2022	-	✓	-	-	-
Cui *et al.*[77]	2022	✓	✓	-	-	-
Ferguson *et al.*[78]	2022	-	✓	✓	-	-
Wan *et al.*[79]	2022	✓	✓	-	-	CI & PF & CDC
Liu *et al.* (b)[80]	2022	-	-	✓	CoT	-
Ruf *et al.* [81]	2022	✓	✓	-	-	-
Li *et al.* (d) [82]	2022	-	-	✓	-	-
Zhong *et al.* (c) [83]	2022	✓	✓	-	-	CI & PF
Wu *et al.* (e) [84]	2022	-	-	✓	CoT & MA	-
Total		**30**	**48**	**21**	**17**	**17**

Experimental Analysis:
Metallurgical Analysis (MA), Fractography Analysis (FA)
Compression Testing (CoT), Fatigue Testing (FT)
Tensile Testing (TT), Deformation Evaluation (DE)
Digital Image Correlation (DIC)

Clinical Evaluation:
Clinical Data Comparison (CDC), Histomorphological Analysis (HA)
Clinical Implementation (CI), Patient Follow-up (PF)
Retrospective Analysis (RA), Cadaveric Analysis (CA)

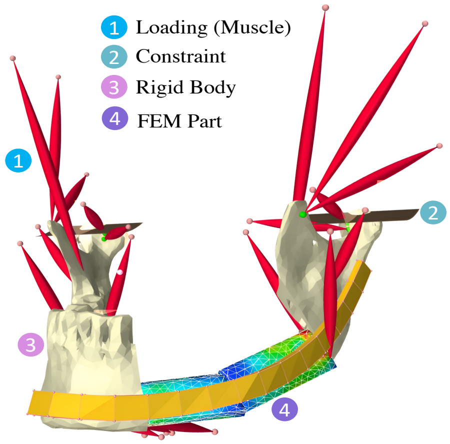


Fig. 5. An Example of a Computational Model for Biomechanical Analysis of Mandibular Reconstruction using Finite Element Method and Multi-Body Dynamics (Developed in ArtiSynth Software [88]). The Model Consists of Four Main Components: 1) Loadings (Muscles), 2) Constraints on Movement, 3) Rigid Bodies, and 4) FEM Parts (with Tet4 Mesh Elements).

results due to the inclusion of extra nodes at the midpoint of each connection in the tetrahedral. However, the increased accuracy of Tet10 elements comes at the cost of increased computational complexity, which might be a concern when dealing with large-sized samples. Moreover, human bones and patient-specific prostheses might have irregular geometries with fine structural features, which might result in producing meshes with abnormal sizes at specific locations, such as at the edge of screw holes and sharp corners of the bone and prosthesis [66, 89]. Previous studies [76, 90]–[93] that have used Tet4 elements to examine stress distribution on bone plates, and prostheses have confirmed high bone/metal material resolution within the Tet4 elements of the FEA models while maintaining reasonable simulation times. Hence, Tet4 is preferred over Tet10 in certain studies.

b) Material Properties: In addition to geometry, each element of the finite element model has specific material properties. These properties are described by a set of constitutive equations that define the relationship between the stress and strain of the object being analyzed. Young's modulus and Poisson's ratio are two fundamental mechanical properties that describe the behaviour of materials under stress and strain [94, 95]. The studies examined in this article have adopted homogeneous isotropic linear-elastic for alloplastic components such as plates and prostheses. As per the definition, homogeneous materials exhibit a consistent composition and properties throughout their entire volume, while isotropic materials have mechanical and thermal properties that are the same in all directions [94, 96]. Nevertheless, bone is a highly complex structure with different types of tissue (e.g., cortical or cancellous) and specific characteristics such as viscoelasticity and anisotropy [22, 97], and simple modeling assumptions may not fully capture the intricate complexity of bone [95]. To account for this complexity, some studies have adopted more sophisticated modeling techniques. Some of these techniques are discussed in Analyzed Components - Bone Flap section.

c) Mesh Convergence: Mesh convergence is another essential factor that needs to be assessed in FEM, as it plays a crucial role in determining the precision of the simulation results. The density of gross, medium and fine meshes is considered for mesh convergence, from which system responses, such as stress, strain and deformation, are evaluated [98]. Mesh convergence identifies the number of elements required in a model to ensure that the results of an analysis are unaffected by a change in mesh size since the system response will converge to a repeatable solution with decreasing element size. Several studies have investigated the optimal mesh size for finite element analysis of mandibular reconstruction. As cases in point, Dahake *et al.* [44] and Al-Ahmari *et al.* [40] conducted a mesh convergence study based on variations in von Mises stress and deformation to determine the best mesh size in FEA of the reconstructed mandible, while Shen *et al.* [27] only considered von Mises stress in their study.

d) Main Measurements in FEA: The results of our investigation indicate that the von Mises stress is the most commonly used measure of stress in the FEA of mandibular reconstruction. Von Mises stress is a scalar quantity derived from the stresses operating on any structure to evaluate the yielding (or failure) of components with ductile material such as plate (e.g., see [43, 53]) and prosthesis (e.g., see [17, 27]). In fact, von Mises stress is a measure of the total stress distributed across all axial planes [99] which can be expressed using the following equation:

$$\sigma_{VM} = \sqrt{\frac{1}{6}\sum_{i=1}^{3}\sum_{j=1}^{3}(\sigma_{ij} - \overline{\sigma})^2} \tag{1}$$

where σ_{ij} is the stress tensor component and $\overline{\sigma}$ is the mean stress (i.e., the average of the three diagonal components of the stress tensor). Principal stress and strain are also two other common measurements in the FEA of mandibular reconstruction. These metrics help to identify the areas of highest stress and strain in the reconstructed mandible, which can aid in optimizing the design and placement of the plate and prosthesis. By analyzing the principal stress and strain values, it is possible to determine the magnitude and direction of the stresses and strains acting on the attached components and surrounding bone tissue [52, 71, 76]. Furthermore, among all reviewed papers, there are five studies that measured strain energy density (SED) in FEA of mandibular reconstruction [18, 73, 78, 79, 84], which is defined as the energy stored in a material due to deformation [100]. In literature, the strain energy density (SED) per unit apparent density has been widely accepted as an appropriate mechanical stimulus for jawbone remodeling [101, 102]. Different stages of bone remodeling in addition to details of these studies are discussed in the Analyzed Component - Bone Flap section.

e) Boundary Conditions: Another vital aspect of FEM that needs attention is the interfaces between the system being modeled and the surrounding environment which are defined with the boundary conditions. These boundary conditions are

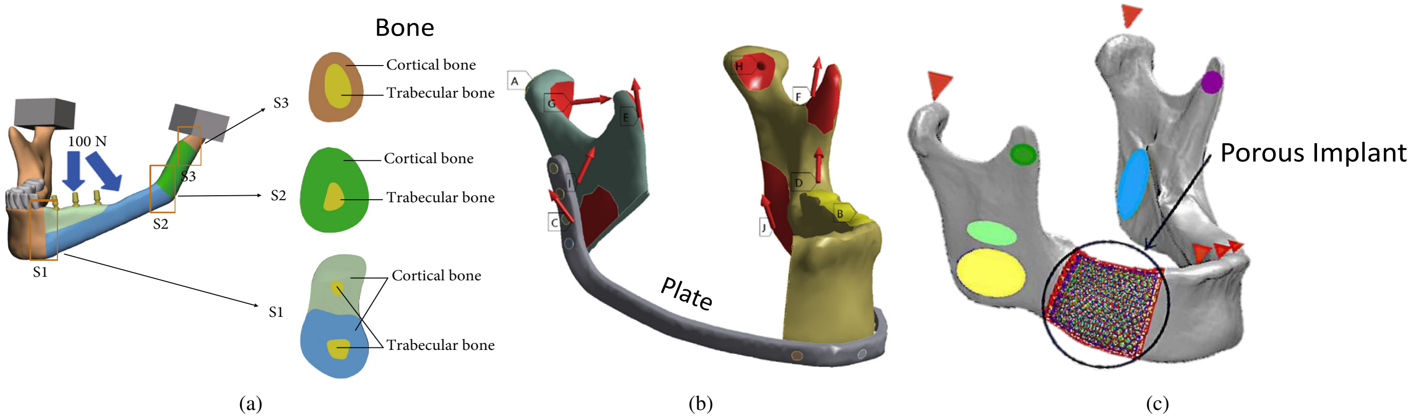
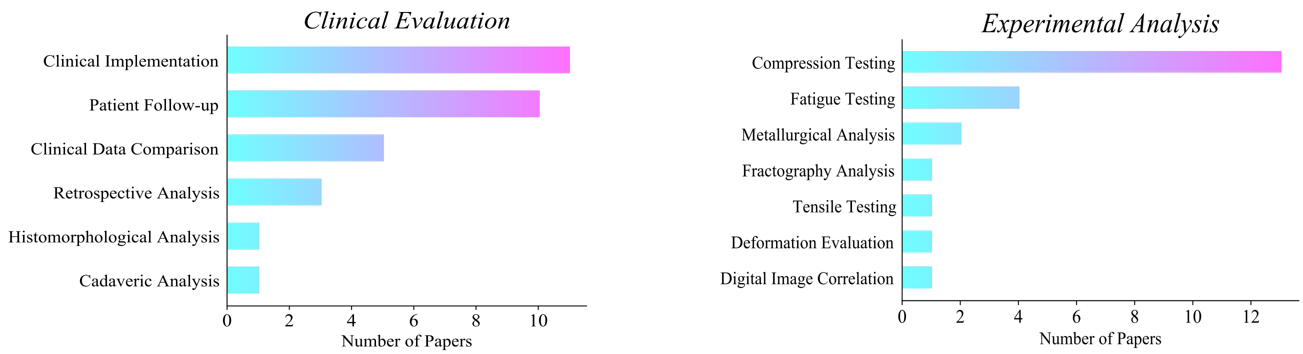


Fig. 6. Three Recent Computational Models for Biomechanical Analysis of (a) Bones [58], (b) Plates [76], and (c) Prostheses [68], Including Corresponding Modeling Assumptions and Constraints (Images Used with Permission)

mainly divided into forces and constraints. Forces simulate the effects of external loads while constraints represent the physical limits on the motion of the system [19, 94]. In FEA of mandibular reconstruction, the force typically includes muscle loading, and/or biting force applied to the mandible [24, 30, 76]. The direction and the magnitude of muscle forces in the majority of research have depended on data already available in the literature, which employ the muscle forces of the mandible in its complete and undamaged state (e.g., see [18, 27, 56]). The constraints, on the other hand, involve limiting temporomandibular joint (TMJ) [45, 62] or teeth movements, such as incisors or molars [38, 48, 78]. Our survey shows that a common approach for implementing the constraints is fixing the condyle movement in all directions, while the teeth are restrained to move vertically in order to create tooth clenching. However, there are a limited number of studies that considered more sophisticated modelling. For instance, Li [58] *et al.* utilized sliding contact to define the interfaces between the condyle process and the disc in TMJ and sliding between the interfaces was allowed during the simulation process, while in a work by Li *et al.* [82], a TMJ disc is defined and connected to the mandible with springs.

3) Dynamic and Kinematic Analysis: While there have been a significant number of articles on the static analysis of mandibular reconstruction, less focus has been given to the dynamic and kinematic investigation. Dynamic models use muscle forces and directions to study the masticatory system, taking into account the time-varying nature of the system. These models can provide valuable insights into the complex interactions between the mandible, the muscles, and the surrounding tissues during mastication. Kinematic models, on the other hand, focus on the study of mandibular movement, analyzing the position, orientation, and motion of the mandible [19]. As noteworthy works in these categories, Stavness *et al.* [20] utilized the ArtiSynth [88] software to develop dynamic computer models for surgical mandible reconstructions, building upon the mandible model previously introduced by Hannam *et al.* [103]. Through their research, Stavness *et al.* investigated the effect of altered musculoskeletal structure on the biomechanics of mastication. Their findings indicated that the loss of the lateral pterygoid and mylohyoid muscles on one side of the mandible can result in mandible deviation towards the ipsilateral side during opening. In 2010, they continued their research by comparing the simulated mandible dynamics in models of segmental mandibular resection versus resection with alloplastic reconstruction [104], followed by research on muscle patterns prediction of hemimandibulectomy models using inverse technique [105]. Although these studies provide useful insights for better understanding the dynamic and kinematic consequences of mandibular reconstruction surgery, they were not included in our review as they did not meet the criteria specified in the Methodology section.

4) Limitations: Computational models have proven to be a valuable tool for analyzing mandibular reconstruction, providing insight into predicting the outcome of surgery such as the chance of bone union, as well as assessing the performance of new designs for plates or prostheses. Some of these simulations have been validated through experimental or clinical analysis, as outlined in Table I and Figure 7. Nevertheless, these models are still subject to major restrictions. While all reviewed studies consider static or quasistatic conditions in their analysis, some processes, such as bone regeneration and ingrowth, differ significantly under dynamic conditions. [17]. Therefore, it is necessary to account for more realistic dynamic loading conditions to accurately predict the local mechanical environment of bone tissue growth. Another limitation is the lack of attention given to modeling patient-specific muscles and soft tissues. As previously stated, most studies have relied on previously published data in the literature which utilize muscle forces of the intact mandible. Only a few papers have incorporated patient-specific parameters, such as muscle physiological cross-sectional area (PCSA), or optimized muscle force based on the reconstruction in their modeling [14, 48, 73]. Although some studies have shown that muscle strength returns to pre-surgery levels during the healing period following resection [71, 106], others suggest that reduced muscle force may occur



(a) (b)

Fig. 7. Number of Publications in Each Category of (a) Clinically Evaluated, and (b) Experimentally Analyzed Papers.

due to decreased chewing power after reconstruction surgery [22, 26, 41]. We believe, this topic needs more investigation since there is still a lack of information about post-operative muscle forces in patients especially, those with extensive mandibular defects [48, 74]. Upon further review, we also found that a considerable number of studies implemented a simplified model of the TMJ, primarily using fixed or hinge joint configurations as discussed before. Nevertheless, it is established that the TMJ is a complex and critical component of the masticatory system [107, 108], and this simplification may lead to inaccuracies in results, particularly in dynamic simulations. We hold the belief that future studies should incorporate a more detailed and accurate representation of the TMJ in a model of the reconstructed mandible. This may involve incorporating critical elements such as the articular disc and ligaments [108, 109], which play vital roles in joint function.

D. Analyzed Components

1) Definition of Key Terms: The papers included in this set have been written at a variety of institutions from around the world and use varying conventions in terminology. Some key terms for this section have been defined below to standardize the extraction of data from the set.

a) Bony Implant/Graft/Flap: The term bony implant, graft or flap is defined as the method of mandibular reconstruction that replaced resected bone with donor bone by the free flap method. This is a traditional method for mandibular reconstructions and is performed at many of the centers as described in the papers we analyzed. This can include a variety of donor bones including fibula and iliac crest.

b) Prosthesis: A prosthesis or implant is any medium that is designed to replace the resected bone during a mandibular reconstruction. A prosthesis is not made from the patient's own bone but may be supplemented with bone powder or soft tissue. This terminology refers to only the hardware within the resection space and does not include hardware fastened only to the outer faces of the mandibular shell (e.g., a traditional fixation plate.)

c) Plate: A plate in this context is a hardware used to fasten/support/connect bone/implant/prosthesis to other bone/implant/prosthesis without attempting to fill in the resection space.

2) Overview and Trend: Our systematic analysis involved recording the primary components investigated in papers that utilized computer modeling for biomechanical analysis of mandibular reconstruction surgery. We categorized the studies based on whether they used computer modeling to analyze the biomechanical characteristics of bony implants, prostheses, and plates/screws (Table I). Figure 4a provides an overview of the trend in component analysis, starting with a study on the bone flap in 1999, and followed by studies on plate and prosthesis design in 2006 and 2012, respectively. Over time, the number of publications has increased, with only one paper published in 1999 and 15 papers in 2022. Our analysis revealed that the majority of papers focused on the plate/screw component of mandibular reconstruction (48/66) or bone flaps (30/66), while a smaller proportion investigated the biomechanics of prostheses (21/66). In addition, 17 papers (25%) employed experimental analysis, and an equal number of papers (25%) aimed to perform clinical evaluations alongside computer modeling (Table I). The following sections provide a detailed analysis of the three primary components (bone flaps, prostheses, and plates/screws) in mandibular reconstruction using computer modeling.

3) Bone Flap: The most common approach in mandibular reconstruction is the use of bony implants, especially using autologous bone grafts. Therefore, significant attention has been directed towards using computer simulations to assess the efficacy of bony implants in mandibular reconstruction. Of the 66 studies reviewed, 30 papers used bony implants, 26 studied models with fibula free flaps (2 double-barreled) and 7 used iliac crest (please see Table II, and Figure 8). Many of the bone models are simplified as homogenous and isotropic in the modeling [52, 65]. As brought up before, the structure of bone is highly complex, consisting of various types of tissue, and simple modeling assumptions may not be sufficient to fully capture the intricate complexity of bone [95]. Therefore, some studies incorporated more complex model-

TABLE II
TYPES OF BONE FLAP ANATOMY AND MODELING

Author	Year	Bone Flap Anatomy			Bone Flap Modeling			
		Fibula	Iliac Crest	Unspecified	Cortical	Cancellous	Cortico-Cancellous	Unspecified
Curtis *et al.*[15]	1999	✓	✓	-	-	-	-	✓(×2)
Tie *et al.*[29]	2006	✓	✓	-	✓	✓	-	-
Schuller-Götzburg *et al.*[30]	2009	-	✓	-	-	-	✓	-
Wu *et al.* (a)[31]	2012	✓	-	-	-	-	-	✓
Jedrusik-Pawłowska *et al.*[32]	2013	-	✓(×2)	-	-	✓	✓	-
Jahadakbar*et al.*[41]	2016	✓	-	-	-	-	✓	-
Park *et al.* (a)[43]	2016	✓	-	-	-	-	-	✓
Wu *et al.* (c)[47]	2017	✓	-	-	-	-	✓	-
Seebach *et al.*[24]	2017	✓	-	-	✓	-	-	-
Yoda *et al.*[18]	2018	✓	-	-	-	-	✓	-
Park *et al.*[52] (b)	2018	✓	-	-	-	-	✓	-
Cheng *et al.* (a)[56]	2019	✓	-	-	-	-	✓	-
Kucukguven & Akkocaoglu *et al.*[57]	2020	✓	✓	-	✓	✓	-	-
Li *et al.* (c)[58]	2020	✓	-	-	-	-	✓	-
Kargarnejad *et al.* (a)[59]	2020	✓	-	-	-	-	✓	-
Kargarnejad *et al.* (b)[60]	2020	✓	-	-	-	-	✓	-
Cheng *et al.* (b)[62]	2020	✓	-	-	-	-	✓	-
Wu *et al.* (d)[63]	2020	-	-	✓	-	-	✓	-
Kargarnejad *et al.* (c)[64]	2021	✓	-	-	-	-	✓	-
Lang *et al.*[22]	2021	✓	-	-	-	-	-	✓
Kang *et al.*[65]	2021	✓	-	-	✓	-	-	-
Shi *et al.* (b)[67]	2021	✓	-	-	✓	-	-	-
Peng *et al.*[68]	2021	✓	-	-	-	-	✓	-
Zhong *et al.* (a)[70]	2021	✓	-	-	✓	-	-	-
Zheng *et al.*[73]	2022	✓	-	-	-	-	✓	-
Jung *et al.*[75]	2022	-	✓	-	-	-	✓	-
Cui *et al.*[77]	2022	✓	-	-	✓	-	-	-
Wan *et al.*[79]	2022	✓	-	-	-	-	✓	-
Ruf *et al.*[81]	2022	✓	-	-	-	-	✓	-
Zhong *et al.* (c) [83]	2022	✓	-	-	-	-	✓	-
Total		**26**	**7**	**1**	**7**	**3**	**19**	**5**

ing approaches in their analysis. For instance, Lin *et al.* [72] and Narra *et al.* [38] modeled the bone in the reconstructed mandible as an orthotropic material, which is a subgroup of the anisotropic material, having different material properties along three principal axes [94]. Additionally, researchers have dedicated significant effort to empirically model the relationship between the mechanical and physical properties of bone [110, 111]. The literature contains several empirical models describing the relationship between Young's modulus and apparent density. Linear [112, 113] or power [111, 113, 114] relations are generally reported, however, power relation is generally preferred over linear to model heterogeneous and anisotropic bone in simulation-based analysis of mandibular reconstruction [26, 37, 56, 57, 60, 62, 69, 75]:

$$E = a + b\rho_{app}^{c} \tag{2}$$

where E is the material Young's modulus, ρ the apparent density, a, b and c the model parameters [96]. The apparent density which refers to the ratio of the mass of a material to its apparent volume is computed using a pixel-based mapping algorithm that maps the Hounsfield units (HU) of the CT image to the density distribution [18, 73, 115].

The modeling of the bony material properties also varied depending whether the study simplified the bone to just cortical/cancellous bone or retained some heterogeneity of the natural bone by modeling with both cortical and cancellous properties. 19/29 papers modeled both cortical and cancellous properties, 7/29 modeled only cortical properties, 3/29 modeled only cancellous and 5/29 did not specify (Table II).

When it comes to selecting from the available bone flap anatomies, multiple papers discuss the iliac crest performing better biomechanically over the fibula [29], stating "The widely preferred, most advantageous from the biomechanical point of view and therefore also used in our analysis, is the iliac crest [29]." The iliac crest demonstrates stress distributions more similar to that of the native mandible and in some cases, the von Mises stress in fibular reconstructions was higher than those of the iliac crest reconstructions [29]. Furthermore, the 2 studies that applied a double barrel fibula technique stated that this was "the most efficient approach for the reconstruction of the mandibular body and ramus defect [58]" and that modeling a double barrel flap would "simulate a high fidelity reconstructive surgery [41]."

Overall, there is a tendency in the current state of research to model reconstructions using fibular flaps, although some papers tend to suggest that the iliac crest is biomechanically superior [75]. This may largely be due to the shape of the iliac crest, and its similarities to the mandible [75]. As far back as World War II, researchers have emphasized the importance of

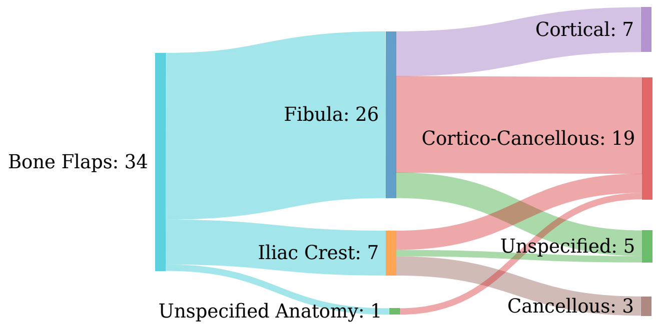


Fig. 8. Sankey Chart of Bone Flap Anatomy and Modeling Used in Biomechanical Analysis of Mandibular Reconstruction Surgery.

cancellous bone in mandibular reconstructions [4]. The iliac crest is mainly cancellous [29, 32, 57] bone while the fibula is mainly cortical [24, 65, 77].

Some other options for vascularized bone flaps that are not covered in this set of papers include the scapula free flap and radial forearm free flap. Due to limitations in the size, and shape, the radial forearm free flap is not sufficient for mastication [4] and this is likely one of the reasons why its use is not studied biomechanically. The scapular flap is a viable flap for mastication and osseointegration in some cases, however, it is used much less frequently due to its donor site location and variability in whether it can provide support for dental implantation [4].

Alongside examining various bone flap anatomies, five studies assessed bone remodelling following mandibular reconstruction, which allows researchers to predict the likelihood of bone union after the surgery [18, 73, 78, 79, 84]. Underloading resorption, equilibrium, apposition, and overloading resorption are the four phases of bone remodeling, according to Zheng *et al.* [73], and strain energy density (SED) per unit apparent density has gained widespread acceptance as an appropriate mechanical stimulus for jawbone remodeling [101, 102]. Recent advances in computerized tomography have made it possible to evaluate bone remodeling sequences noninvasively by measuring bone mineral density and structural changes. For instance, Yoda *et al.* [18] generated finite element-based virtual CT by incorporating the stimulated densities. They compared the result with CT data obtained from the clinical follow-up at months 4, 16 and 28 and found a high correlation between the two datasets. Such analyses can aid in developing more patient-specific solutions which can facilitate the bone healing process and ultimately increase the chance of bone union.

In conclusion, while using bony implants, especially fibular flaps, is regarded as the gold standard in larger reconstructions, there is some general dissatisfaction amongst patient populations in terms of functionality and aesthetics [62]. Therefore, alternative solutions such as prosthetic implants have been proposed [27, 74]. Furthermore, autogenous grafts impact the patient even more since there are two points of surgical intervention. Additionally, the lack of literature on the biomechanics of scapular flaps is certainly an opening for further exploration. A scapular flap may provide an alternate vascular flap for patients whose fibula may not be viable and thus should be studied in more depth.

4) Plate/Screw Design: One of the key components of mandibular reconstruction is plate design, which refers to the shape, size, material, and fixation method of a device that is used to stabilize and support the reconstructed mandible [116]. Plate design has a significant impact on the biomechanical stability, aesthetic outcome, infection rate, and quality of life of patients undergoing mandibular reconstruction [117]. As such, a substantial portion of the studies reviewed (48 out of 66 papers) has employed computational models to examine and enhance plate design by incorporating patient-specific factors and surgical techniques.

a) Trend in Plate Design: Over time, there has been a noticeable shift towards employing more personalized fixation techniques involving plates and screws in maxillofacial surgery. Additionally, diverse approaches for designing plates, taking into consideration factors such as the location, size, shape of the defect, graft type, and fixation method, have been proposed (see Figure 4b and Table III). The trend started in 2006 with the introduction of screw-optimal configuration [21] and progressed towards plate:optimal placement [30] and plate-shape customization [31] in 2009 and 2012, respectively. Overall, as it can be seen from Figure 4b the three major categories that were investigated throughout the years were plate - shape customization, plate - optimal combination, and screw - optimal configuration. More specifically, 26 of the total papers involved shape customization, 12 of them involved plates combination and 9 of them included screw configurations. These advancements in computational techniques for titanium plate and screw fixation have helped to improve the accuracy, efficiency, and outcomes of maxillofacial surgery. The subsequent sections will elaborate on the specific intricacies of each plate design, providing detailed information.

b) Plate - Standard Plate: Mandibular reconstruction surgery often involves the use of autogenous bone grafts stabilized with standard reconstruction plates made of titanium. The standard plate is a widely used traditional titanium locking reconstruction plate that provides simple reconstruction [118]. Using standard reconstruction plates has several advantages in mandibular reconstruction surgery [119], including stability for the graft and the ability to allow for early loading of the stomatognathic system. Additionally, these plates are cost-effective and widely available. However, Cheng *et al.* [56] found that 3D-printed bone with topological optimization may provide better functional and cosmetic outcomes for surgical mandibular reconstruction. Additionally, there are some potential disadvantages to using standard reconstruction plates, such as soft tissue irritation or infection and the possibility of needing to remove the plates after the healing process is complete [120]. Ultimately, the suitability of using standard reconstruction plates will depend on various factors, including the patient's anatomy, the extent of the mandibular defect, and the surgeon's expertise.

TABLE III
MAIN TYPES OF PLATE/SCREW DESIGN

Author	Year	Main Category							Plate Material
		P:S[a]	P:SC[b]	P:OC[c]	P:PC[d]	P:TO[e]	P:OP[f]	S:OC[g]	
Kimura *et al.*[21]	2006	-	-	-	-	-	-	✓	Ti
Schuller-Götzburg *et al.*[30]	2009	-	-	-	-	-	✓	-	Ti
Wu *et al.* (a) [31]	2012	-	✓	-	-	-	-	-	Ti
Jedrusik-Pawłowska *et al.*[32]	2013	✓	-	-	-	-	-	-	Ti
Li *et al.* (a) [33]	2013	-	✓	-	-	-	-	-	Ti
Chang *et al.*[34]	2013	-	-	✓	-	-	-	✓	Ti
Wu *et al.* (b) [35]	2013	-	✓	-	-	-	-	-	Ti
Li *et al.* (b) [36]	2014	-	✓	-	-	-	-	✓	Ti
Bujtár *et al.*[37]	2014	-	-	-	-	-	-	✓	Ti
Narra *et al.*[38]	2014	-	✓	-	-	-	-	-	Ti6Al4V ELI
Al-Ahmari *et al.*[40]	2015	-	✓	-	-	-	-	-	Ti6Al4V ELI
Jahadakbar *et al.*[41]	2016	-	✓	✓	-	-	-	-	Ti6Al4V & NiTi
Mehle *et al.*[42]	2016	-	✓	-	-	-	-	-	Ti & PEEK
Park *et al.* (a) [43]	2016	-	✓	✓	-	-	-	-	Ti
Nasr *et al.*[45]	2017	-	✓	-	-	-	-	-	Ti6Al4V ELI
Moiduddin *et al.* (a)[46]	2017	-	-	-	✓	-	-	-	Ti6Al4V ELI
Wu *et al.* (c) [47]	2017	-	✓	-	-	-	-	-	Ti6Al4V
Luo *et al.*[48]	2017	-	✓	-	-	-	-	-	Ti6Al4V
Sanal *et al.*[49]	2017	-	✓	-	-	-	-	✓	Ti6Al4V
Seebach *et al.*[24]	2017	-	✓	✓	-	✓	-	-	Ti
Gutwald *et al.*[50]	2017	-	✓	-	-	-	-	-	Ti
Moiduddin *et al.* (b)[51]	2018	-	✓	-	-	-	-	-	Ti6Al4V ELI
Park *et al.* (b) [52]	2018	-	-	✓	-	-	-	-	Ti
Hoefert and Taier[53]	2018	-	-	✓	-	-	-	✓	Ti & Ti6Al4V
Moiduddin *et al.* (c) [54]	2019	-	-	-	✓	-	-	-	Ti6Al4V ELI
Kucukguven and Akkocaoğlu [57]	2020	-	-	✓	-	-	-	-	Ti
Kargarnejad *et al.* (a) [59]	2020	✓	-	-	-	-	-	-	Ti6Al4V ELI
Kargarnejad *et al.* (b) [60]	2020	✓	-	-	-	-	-	-	Ti6Al4V ELI
Cheng *et al.* (b) [62]	2020	✓	-	-	-	-	-	-	Ti6Al4V
Wu *et al.* (d) [63]	2020	-	✓	-	-	✓	-	-	Ti
Kargarnejad *et al.* (c) [64]	2021	✓	-	-	-	-	-	-	Ti6Al4V
Koper *et al.* [25]	2021	-	✓	-	-	✓	-	-	Ti6Al4V
Lang *et al.* [22]	2021	-	✓	✓	-	✓	-	-	Ti & Ti6Al4V
Kang *et al.* [65]	2021	-	-	✓	✓	-	-	-	Ti
Shi *et al.* (a) [66]	2021	-	✓	-	-	-	-	-	Ti6Al4V
Shi *et al.* (b) [67]	2021	-	✓	✓	-	-	-	-	Ti6Al4V
Peng *et al.* [68]	2021	✓	-	-	-	-	-	-	Ti6Al4V
Zhong *et al.* (a) [70]	2021	-	✓	-	-	-	-	✓	Ti6Al4V ELI
Muftuoglu *et al.* [71]	2021	-	-	-	-	-	-	✓	Ti
Lin *et al.* [72]	2022	-	✓	-	-	-	-	-	Ti6Al4V
Zheng *et al.*[73]	2022	-	-	-	-	-	-	✓	Ti
Jung *et al.* [75]	2022	-	✓	✓	-	-	-	-	Ti & PLLA-HA
Zhong *et al.* (b) [76]	2022	-	✓	-	-	-	-	-	Ti6Al4V ELI
Cui *et al.* [77]	2022	-	✓	-	-	-	✓	-	Ti
Ferguson *et al.* [78]	2022	-	-	-	✓	-	✓	-	Ti6Al4V
Wan *et al.* [79]	2022	✓	-	-	-	-	-	-	Ti
Ruf *et al.* [81]	2022	-	-	✓	-	-	-	-	Ti6Al4V
Zhong *et al.* (c) [83]	2022	✓	-	-	-	-	-	-	Ti6Al4V
Total		**8**	**26**	**12**	**4**	**4**	**3**	**9**	

[a] Plate:Standard
[b] Plate:Shape Customization
[c] Plate:Optimal Combination
[d] Plate:Prosthesis-based Customization
[e] Plate:Topology Optimization
[f] Plate:Optimal Placeemt
[g] Screw:Optimal Configuration

c) Plate - Shape Customization: A shape-customized plate is a type of reconstruction plate that is designed specifically for the patient's anatomy, based on imaging data. Shape-customized plates, compromising 26 out of 48 papers, have gained popularity in mandibular reconstruction surgery due to their optimal anatomical fit, which can reduce surgical time and improve clinical outcomes [121]. Studies have shown that shape-customized plates can offer advantages over stock plates in terms of structural performance, stability, and safety [38, 40, 41].

One significant development in this field is the work of Lang *et al.*[22], which demonstrated superior fatigue properties in patient-specific osteosynthesis plates compared to standard mini plates in mandibular reconstruction using human cadaveric specimens. The patient-specific shape of the plate not only provided better biomechanical properties but also had intrinsic guiding properties to support the reconstruction process during surgery.

Customized plates can also be made of materials with mechanical properties closely matching those of bone, such as porous nickel titanium (NiTi) and polyetheretherketone (PEEK), which can reduce stress shielding and promote bone healing [41, 42]. However, customized plates can induce high stresses and strains in the plate-screw-bone assembly, which can lead to micro-damage and bone resorption near the screw-bone interface [38]. The design of the plates and screws significantly influences the structural behaviour of the plates, and attention should be paid to the expected physiological forces on the plates [38]. In addition, plastically deformed reconstruction plates have a higher risk of fracture than mini-plates, despite having superior fixing force [43].

Overall, the use of shape-customized plates in mandibular reconstruction surgery is a promising area of research. The advancements, such as those demonstrated by Lang *et al.* [22], show potential for improving clinical outcomes, but further studies are needed to fully understand the benefits and limitations of such plates.

d) Plate - Optimal Combination: Plates optimal combination refers to the use of two or more reconstruction plates with different combinations of fixed screws to stabilize a defective mandible. 12 research studies have investigated the effectiveness of different plate combinations in mandibular reconstruction surgery. Some studies have investigated the efficacy of combining custom-made, patient-specific NiTi fixation hardware and found that it results in more normal stress distribution and enhanced contact pressure at the bone graft interface compared to Ti-6Al-4V hardware [41]. Another study suggested that the second reconstruction plate could offer better mechanical efficacy with an increase in screw quantity, but that a single screw was sufficient for stabilization without an increase in screw quantity [34]. Park *et al.* [43] investigated the stability of three commonly used surgical plates for two types of mandible defect cases and found that plastically deformed plates have higher stress values and a higher risk of fracture than a mini-plate. The use of a reconstruction plate may result in more stable surgical outcomes in most cases but may increase the risk of atrophy due to lack of bone stimulation [52]. Seebach *et al.* [24] designed and validated topology-optimized, patient-specific bone mini plates for mandible reconstruction after tumour resection, resulting in sufficient stability, stiffness, and durability while minimizing the volume of implanted material and improving patient recovery after surgery. However, limitations of the study include the use of synthetic bone models and the need for further in vivo testing to fully validate the design.

Overall, the use of plate combinations in mandibular reconstruction surgery has its advantages and limitations, and proper selection and customization of the plates based on the individual patient's condition is crucial for achieving the best possible surgical outcome.

e) Plate - Topology Optimization: Topology-optimized plates (5 out of 48 papers) are designed to provide customized and effective bone reconstruction after mandibular tumour resection or trauma. These plates are created using advanced engineering techniques, such as topology optimization and finite element analysis, to provide optimal biomechanical performance while minimizing material usage [24]. In a study by Seebach *et al.* [24], these techniques led to a 44.9% reduction in the total volume of the bone plates, resulting in sufficient stability, stiffness, and durability while minimizing the volume of implanted material and improving patient recovery after surgery. The benefits of using topology-optimized plates in mandibular reconstruction also include reduced risk of screw failure due to even load distribution [24]. Moreover, patient-specific shape and design of topology-optimized plates provide intrinsic guiding properties to support the reconstruction process during surgery [22]. However, the use of synthetic bone models in validation and the need for further in vivo testing limited the generalizability of Seebach *et al.*'s results [24]. Furthermore, although promising results have been obtained from biomechanical testing and validation, more work is needed to refine the finite element analysis models and make topology-optimized plates ready for clinical use [25]. Ultimately, further research is required to validate the production process and design of these implants [22].

f) Plate - Optimal Placement: Plate optimal placement in mandibular reconstruction surgery involves optimizing the positioning of plates based on biomechanical principles to achieve enhanced stability and minimize complications. 3 research papers have investigated the use of positionally optimized plates in this context, identifying both the advantages and disadvantages of this technique.

One of the advantages of using positionally optimized plates is their ability to enhance the stability and fixation of the bone graft on the jaw stumps, as well as promote tissue ingrowth, structural strength, and stiffness of the scaffold-host bone construct [78]. A notable study conducted by Schuller-Götzburg et al. investigated mandibular reconstruction using a 3D finite element model to study the positioning of the bridging plate, emphasizing the biomechanical advantages of the caudal positioning of the bridging plate and the use of autologous bone grafts for mandibular reconstruction [30].

Additionally, the use of positionally optimized plates can reduce the risk of complications such as titanium plate fracture, screw loosening, titanium plate exposure, and postoperative infection, as well as require fewer screws and have a smaller volume compared to traditional buccal-fixation systems [77].

However, studies like Schuller-Götzburg *et al.*'s work, are limited in scope, only considering a specific type of reconstruction method, and may not fully reflect the complexities of real-life scenarios [30]. Other studies have used simple loading conditions and assumed uniform material properties for the mandible, which may not accurately represent the range of forces the mandible experiences in vivo [77]. Furthermore, while positionally optimized plates may enhance stability and fixation, they may not necessarily improve patient outcomes or quality of life, which are essential factors to consider in any surgical intervention.

g) Screw - Optimal Configuration: The optimal configuration of screws in plates is a critical aspect of mandibular reconstruction surgery, as it directly affects the stability and durability of the plate, implant, and screws. This area of research encompasses a total of 9 studies, all aimed at determining the most effective arrangements or designs for screws to superior surgical outcomes. Studies such as [34] and [49] have investigated the effects of different reconstruction plates and screw combinations on stress distribution and stabilization. According to Chang *et al.*, a single screw was sufficient for the second plate fixation to stabilize the mandible following tumour resection, without the need for additional screws [34]. Furthermore, for stress reduction on the screws, Hoefert and Taier [53] recommended the use of an extra plate. However, there is a need for careful consideration of the screw geometry, plate adaptation, and bone quality, as pointed out by Bujtar *et al.* [37], who also suggested that bicortical locking screw fixation may be necessary in some cases. Overall, the use of optimally configured screws in plates has shown promising results in enhancing the stability and durability of mandibular implants. Still, the design should be tailored to individual patient characteristics to ensure optimal results.

h) Additional Techniques: Prosthesis-based customization of plates is another technique used in the design of the plates. In this approach, the plate is not attached directly to a bone graft but rather is screwed to a prosthesis that connects to the mandible on both sides of the resection area. This technique is often utilized when a significant portion of the mandible has been removed due to tumour removal, and traditional plate fixation might not be feasible. Further information about this category can be found in the plate fastened subsection of Prosthetic Design.

i) Material Consideration: As research progresses, the flow of material used in plates is likely to be driven by the continuous pursuit of better patient outcomes and more personalized solutions. The comprehensive list of references in Table III highlights the ongoing efforts of researchers to develop and optimize the use of different materials for various applications.

Titanium (Ti) is the most commonly used material, with works by Kimura et al. [21], Schuller-Götzburg et al. [30], Wu et al. (a) [31], and Jedrusik-Pawłowska et al. [32] among others, showcasing its popularity. Titanium alloys, such as Ti6Al4V and Ti6Al4V ELI, are also frequently used, as seen in the studies by Narra et al. [38], Al-Ahmari et al. [40], and Moiduddin et al. (a) [46], to name a few.

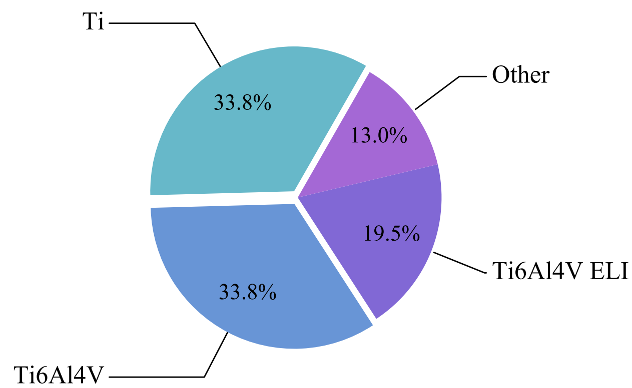


Fig. 9. Material Used in Modelling Plates and Prostheses in Biomechanical Simulations.

These titanium-based materials are known for their biocompatibility, strength, and corrosion resistance, making them suitable for a wide range of applications. Plates and screws can be standard, shape customized, combined, prosthesis-based customized, topology optimized, positionally optimized, or optimally configured, depending on the specific needs of the patients and the desired outcomes.

Furthermore, some studies investigated the use of alternative materials, such as PEEK and ooly-L-lactic acid - hydroxyapatite (PLLA-HA), which offer unique properties that could be advantageous in certain situations. Mehle et al. [42] explored the use of both Ti and PEEK, while Jung et al. [75] investigated the combination of Ti and PLLA-HA. PEEK is a lightweight, biocompatible material with a modulus of elasticity similar to that of human bone, while PLLA-HA is a biodegradable material that can gradually be replaced by native bone tissue.

5) Prosthetic Design: Amongst the set of papers, 21 studies reviewed various techniques in prostheses design through simulation and computer modeling. Starting in 2012 with Wong *et al.* [23], a titanium, stemmed endoprosthesis is introduced in the literature. As illustrated in Figure 4c, since 2012, there has been an increasing trend in the number of publications exploring prosthesis-based mandibular reconstruction modeling. In 2022 there were 7 papers modeling variations of prostheses in comparison to only one in 2012 (Table IV).

Various styles and geometric designs have been proposed for prostheses development in mandibular reconstruction. The shape and attachment style of the prosthesis makes an impact on loading distributions on an implant caused by mastication, mechanisms of healing/bone remodeling, patient facial aesthetics and design and fabrication burden. Computer modeling has proven to be an effective tool for

TABLE IV
MAIN TYPES OF PROSTHESIS DESIGN

Author	Year	Design							Material	Structure
		ST[a]	MD[b]	WN[c]	TRY[d]	BGC[e]	PF[f]	TO[g]		
Wong *et al.*[23]	2012	✓	✓	-	-	-	-	-	Ti6Al4V	Solid
Pinheiro and Alvescite[39]	2015	✓	✓	-	-	-	-	-	Ti6Al4V	Solid
Dahake *et al.*[44]	2017	-	-	✓	-	-	-	-	Ti	Solid
Moiduddin *et al.* (a)[46]	2017	-	-	-	✓	✓	✓	-	Ti6Al4V ELI	Porous
Gao *et al.*[17]	2019	-	-	✓	-	-	-	-	Ti6Al4V	Porous
Moiduddin *et al.* (c)[54]	2019	-	-	-	✓	✓	✓	-	Ti6Al4V ELI	Porous
Huang *et al.*[55]	2019	-	-	✓	-	-	-	-	Ti6Al4V	Solid
Kargarnejad *et al.* (b)[60]	2020	-	-	✓	✓	✓	-	-	Ti6Al4V ELI	Solid (Hollow)
Prasadh *et al.*[61]	2020	✓	-	✓	-	-	-	-	Ti & PCL	Solid (Hollow)
Cheng *et al.* (b)[62]	2020	-	-	✓	-	-	-	✓	PEKK	Solid
Kargarnejad *et al.* (c)[64]	2021	-	-	✓	✓	-	-	-	Ti6Al4V	Solid (Hollow)
Kang *et al.*[65]	2021	-	-	-	✓	✓	✓	-	PEEK	Solid
Peng *et al.*[68]	2021	-	-	✓	-	-	-	✓	Ti6Al4V	Porous
Farajpour *et al.*[69]	2021	-	-	✓	-	-	-	-	Ti6Al4V ELI	Porous
Kootwijk *et al.*[26]	2022	-	-	✓	-	-	-	✓	Ti6Al4V ELI	Porous
Liu *et al.* (a)[74]	2022	-	-	✓	-	-	-	✓	Ti6Al4V	Porous
Shen *et al.*[27]	2022	-	-	✓	-	-	-	-	Ti6Al4V	Solid & Porous
Ferguson *et al.*[78]	2022	-	-	-	-	-	✓	-	Sr-HT-gahnite	Porous
Liu *et al.* (b)[80]	2022	-	-	✓	-	-	-	✓	Ti6Al4V	Porous
Li *et al.* (d)[82]	2022	-	-	✓	-	-	-	-	PEEK-HA/nHA & Ti6Al4V	Porous
Wu *et al.* (e)[84]	2022	-	-	✓	-	-	-	-	AL2O3	Porous
Total		**3**	**2**	**15**	**5**	**4**	**4**	**5**		

[a] Stemmed
[b] Modular
[c] Winged
[d] Tray
[e] Bone Graft Carrier
[f] Plate Fastened
[g] Topology Optimized

analyzing and refining these designs, with several approaches being commonly studied: stemmed, winged, plate-fastened, tray, graft carrier, modular, and topology-optimized. In the following sections, we will delve into the details of each design and their respective benefits and drawbacks.

a) Stemmed vs Winged: A stemmed-type prosthesis has lengthened abutments that protrude into the medullary space of the mandible on either side instead of external fixation. A winged prosthesis, on the other hand, flanges over the mandibular bone and fastens with additional screws similar to how a traditional plate would, but the wings are continuous with the body of the prosthesis. 3 of 21 papers included stemmed-styled prosthesis designs while 15 of 21 presented winged designs. Stemmed-type prostheses can be inserted using bone cement while some designs do not require bone cement. overall they aim to remove the reliance on a screw-based fixation method into the native mandible. Limitations of winged designs are observed at the interface between the winged portion and the body of the prosthesis [27].

As one of the most recent studies with a stemmed-style prosthesis, Prasadh *et al.* concluded that the winged prosthesis performs more effectively than stemmed in their FEA model [61]. It was shown that the winged design had relatively lower stress concentrations, and fewer observed areas with high-stress concentrations [61]. Under simulated forces of mastication, the winged prosthesis outperforms the stemmed. The highest concentrations of stress were observed at the "junction of the stem and body [61]" for the stemmed prosthesis.

Pinheiro and Alves also studied a stemmed-type prosthesis in 2015. They placed additional emphasis on considerations of the bone-implant interface, in which strain considerations at this interface during common mastication tasks are observed in FEA modeling. High strain values were found around the stems, with 63% and 77% of the interfacing regions experiencing strains above the threshold for bone remodeling [39]. Although the stemmed prosthesis body performed within comparable stress ranges to the native mandible, they seem to be limited by the insertion into the medullary space.

More recent papers take the design of winged prostheses a step further by optimizing other parameters such as material, length and porosity [27, 55, 61]. Considering the higher number of papers reviewing winged prostheses in comparison to stemmed, it seems as though this method has become more standard. Researchers are now applying a winged style in more varying conditions and under varied design parameters suggesting confidence in its implementation.

b) Plate Fastened: Plate-fastened designs have standard or custom titanium plates in addition to the prosthesis body that are screwed to each other as well as into the mandibular bone. 4 of 21 papers used plate-fastened prostheses in their designs. It is important to note that in this section, the plate is not fastened to a bone graft, but instead connects a prosthesis to the mandible on either side of the resection.

As a notable recent study, Ferguson *et al.* conducted a comparative study between a free flap secured with a plate and a porous biomaterial tissue scaffold prosthesis also fixed with a plate in 2022 [78]. Although this paper focuses more on the evaluation of the tissue scaffold, it also presents insights into the benefits and limitations that come with using a plate. There are still challenges with screw-based fixation promoting strains that are above desired limits into the mandibular bone. However, from a functional perspective, incorporating standard plating fixation methods is familiar to surgical teams providing benefits over novel fixation techniques. Additionally, Ferguson and colleagues have noted that the detached plating technique offers flexibility by not being integrated into the prosthesis, allowing for preoperative optimization of plate angulation and height relative to the mandibular border [78].

c) Tray/Bone Graft Carrier: In tray-type design, the prosthesis functions as a crib in which a bone graft is not necessarily applied while the bone graft carrier incorporates a tray that holds a bone graft. 9 papers in total used this design in their analysis. Tray-type prostheses geometrically allow for more patient-specific customization in design in comparison to bone grafts in isolation. Additionally, the hollow inner 'cribs' reduce the weight of the prosthesis while allowing for the integration of bony elements or topological optimization inside. This customization helps recreate native mandibular spaces more closely to mimic healthy aesthetics. These prostheses overall appear more design intensive than some of the others discussed. As a significant study in this category, Kargarnejad *et al.* used FEM to compare multiple prosthesis methods including a tray style and a bone graft carrier with the same geometry of the tray style. They conclude that with the bone graft in the 'crib,' there is limited vascularity meaning the bone graft has a decreased chance of survival "making this mechanism less attractive [60]."

d) Modular: In modulator design, which compromises only 2 papers in the set of reviewed studies, multiple components are combined together to create a prosthesis that spans at least the gap of the resection and does not incorporate a bony component. In general, the shape and geometric differences in prosthetics yield varying results. Regardless of the attachment type, a prosthesis that fills the bulk of the reaction space should be carefully fitted. Overcutting resections and inserting implants with gaps, promotes unfavourable results in maximum stresses observed in FEM analysis [44]. The addition of modularization in some works [23, 39], affords surgeons with some leeway in improper resection cutting, however as far as 2022, there is still progress to be made in 'real-time' modularization that would allow for even more specifically tailored patient results.

e) Topology Optimized: 5 of 21 of the prosthesis designs incorporated topology optimization into their computational models. The topology-optimized models were introduced in 2020, 2021 and 2022 demonstrating a trend in the recent surge of topology optimization in mandibular modeling. The goal of this type of modeling in the context of the prosthesis is to lower the maximal stress and displacement on the implant.

Cheng *et al.* demonstrated that their topology-optimized models performed more favourably than a fibular bone graft model [62]. Peng *et al.* further confirmed that a topology-optimized implant in conjunction with a porous structure is a "promising option to improve the mechanical stability and osteogenesis" [68]. Contrastingly, Kootwijk *et al.* speculates that a strictly porous implant outperforms a topology-optimized prosthesis [26]. The 2022 biomechanical testing results from Kootwijk *et al.* propose that the lower weight, higher porosity and higher reduction of stress shielding of the porous (not topology-optimized prosthesis) lead to more favourable clinical outcomes in patient comfort and osseointegration. The results from the topology-optimized prosthesis studies suggest that more conclusive and comparable testing and modeling are required to fully and confidently integrate topology-optimized prosthesis into common clinical practice. The literature demonstrates that there is validity in topology-optimized models, however, there is limited work presented on it in comparison to traditional techniques.

f) Additional Techniques: Additional model features include countersinking the screw holes on a winged-style prosthesis to better align the screw heads [46], varying the number and locations of screw holes and modifying the length of stems. Each of these variations has been explored computationally to assess the impact on the prosthesis as a whole.

g) Material Consideration: The variability in material type has also progressed with time from mainly titanium-based prostheses between 2012 and 2019 (Table IV). The structural aspects of titanium have been modified in some studies to explore the computational modeling of varying macro and microstructures of the titanium. In more recent years (2020-2022), researchers have introduced novel materials including polycaprolactone (PCL), polyetherketoneketone (PEKK), polyetheretherketone (PEEK), bioceramic tissue scaffolds, and aluminium oxide (AL2O3) [61, 62, 78, 84].

Titanium: Titanium prostheses are the most common in the set of papers (17/21). Many researchers also describe macro- or micro-structural changes that are applied to the titanium for various mechanical benefits to the prosthesis design. A porous prosthetic can be lighter than a solid one and the stress concentrations can be redistributed to reduce regions of high stress. "Studies have proved that implants with porous structures can effectively enhance the biological fixation of the bone [46]."

Altering the microstructure of the titanium also has implications for the success of the computation model. Through introductions of scaffolding such as tetrahedral or with varying pore and strut size, the models are more customizable [74, 80]. These studies answer questions related to the success of changing the material properties of titanium to create more favourable models in relation to mastication and force distributions. Some other material variations include different orientations and shapes of scaffolding, micro meshes and macro meshes.

Alternative Materials: PCL is a resorbable scaffold material speculated to have beneficial properties in mandibular reconstruction compared to non-resorbable titanium alloys [61]. The 2020 study by Prasadh *et al.* applies 2 different designs for PCL prosthesis [61]. The use of PCL however, was not recommended by the authors and they abandoned any further analysis with a PCL prosthesis since it cannot withstand the typical loading of the mandible when used on its own [61]. There may still be potential for applications of PCL in combination with other materials to increase its strength since its resorbable qualities may prove useful in the clinical setting. More biomechanical testing of resorbable materials may be warranted due to their predicted clinical benefits in an attempt to find a version capable of withstanding the loading of mandibular activity.

Kang *et al.* also performed analysis on a PEEK prosthesis implanted along with a fibula free flap and a traditional titanium plate [65]. This was shown to be biomechanically and clinically successful. The PEEK prosthesis reduced the stresses on the metal plate implant and increased the stability of the reconstruction [65]. The authors noted however that there are still some more long-term effects that need to be studied for PEEK implants, including rehabilitation, implant lifespan and surface modification/microstructure. In another study conducted by Cheng *et al.* [62], the effectiveness of PEKK prosthesis was evaluated through computer modeling. The material was equipped with micropores to promote bone-in-growth and the design of the custom implant was modeled to specifically consider forces from the dental implant posts. PEKK is approved for use by the FDA in craniofacial implants [62].

Bioceramic tissue scaffold is another type of material presented by Ferguson *et al.* [78]. This material is porous and it is favourable because of its ability to interact with the surrounding tissue following implantation to promote growth. This type of implant is customizable through 3D modeling and this benefits the patient biomechanically since replicating the native geometry of the resection "provides better buttress support to the adjoining bone segments than a free flap [78]." This type of scaffold is attached to the bone using a traditional titanium plate. Ferguson *et al.* described a limitation of this material is the design of the prosthesis to support the loading patterns of the bone and satisfy the biological considerations simultaneously.

The final alternative material evaluated in the design of prostheses is AL2O3 introduced by Wu *et al.* [84] in 2022. In this research, it was suggested that Al2O3 ceramics do not have excessive mechanical properties in maxillofacial implants compared with metal, which could potentially prevent stress shielding effects. Simulation outcomes revealed that the use of Al2O3 prosthetics resulted in symmetrical stress distribution in the mandible, and the combination of unilateral reconstruction plate and prosthesis effectively balanced stress transfer during occlusion.

IV. Outlook

Despite significant progress in developing computational models, there are still several areas that require more attention. In terms of modeling, as discussed in the Computational Model section, greater emphasis needs to be placed on patient-specific modeling, particularly for soft tissues and muscles, to more accurately estimate the loading on the mandible and produce valid simulation results. Patient-specific modeling is crucial as it enables a precise and individualized evaluation of the patient's condition. By creating computational models tailored to a specific patient's characteristics, clinicians can better understand the individual's condition and plan a more effective treatment strategy. Moreover, further investigation is necessary into the dynamic modeling of reconstructed mandibles, as it enables surgeons to better evaluate the functional outcome of the masticatory system postoperatively. Dynamic models can assist surgeons in developing individualized rehabilitation techniques tailored to the specific needs of each patient.

Another critical aspect that requires attention is the evaluation of dental implantation and the patient's chewing efficacy after mandible reconstruction. The success of dental implantation depends not only on the implant but also on the reconstruction procedure. While aesthetics are important in mandible reconstruction, surgeons may need to prioritize improved chewing function, such as bite force, over aesthetics by utilizing specialized dental implantation techniques.

V. Summary

We have reviewed 66 papers that cover the range of computational modeling efforts for predicting the functional outcome of mandible reconstruction surgery. Our main contribution from this review is offering surgeons cutting-edge approaches for developing biomechanical models, as well as the most commonly employed approaches in plate and prosthesis design, which are subsequently evaluated using computational models.

Advancing computational modeling by providing patient-specific models has a very promising future for the surgical treatment of oral cancers to provide more cost-effective treatments and better quality of life for oral cancer patients.

Acknowledgement

We gratefully acknowledge the funding provided by the Canadian Institutes for Health Research (CIHR), Grant CPG-163974. We also would like to express our gratitude to Institute for Computing, Information and Cognitive Systems (ICICS) and the Centre for Aging SMART for supporting this work.

Competing Interests

The authors declare no competing interests.

REFERENCES

[1] M. Rondinelli. (2021) Oral cancer: Importance of early detection. [Online]. Available: https://lambtonfamilydental.com/blog/oral-cancer-importance-early-detection/

[2] B. T. Goh, S. Lee, H. Tideman, and P. J. Stoelinga, "Mandibular reconstruction in adults: a review," *International journal of oral and maxillofacial surgery*, vol. 37, no. 7, pp. 597–605, 2008.

[3] J. J. Disa and P. G. Cordeiro, "Mandible reconstruction with microvascular surgery," in *Seminars in surgical oncology*, vol. 19, no. 3. Wiley Online Library, 2000, pp. 226–234.

[4] B. P. Kumar, V. Venkatesh, K. J. Kumar, B. Y. Yadav, and S. R. Mohan, "Mandibular reconstruction: overview," *Journal of maxillofacial and oral surgery*, vol. 15, pp. 425–441, 2016.

[5] K. L. Tran, M. L. Mong, J. S. Durham, and E. Prisman, "Benefits of patient-specific reconstruction plates in mandibular reconstruction surgical simulation and resident education," *Journal of Clinical Medicine*, vol. 11, no. 18, p. 5306, 2022.

[6] A. Ow, W. Tan, and L. Pienkowski, "Mandibular reconstruction using a custom-made titanium prosthesis: a case report on the use of virtual surgical planning and computer-aided design/computer-aided manufacturing," *Craniomaxillofacial Trauma & Reconstruction*, vol. 9, no. 3, pp. 246–250, 2016.

[7] G. R. Grzybowski, "Development of an image-guided surgical workflow and tracked surgical tools for mandibular reconstruction surgery," 2021.

[8] M. M. Stewart, "An image-guided platform for on-the-fly mandibular reconstruction surgery," Ph.D. dissertation, UNIVERSITY OF BRITISH COLUMBIA (Vancouver, 2021.

[9] M. Lee, R. Y. Chin, G. D. Eslick, N. Sritharan, and S. Paramaesvaran, "Outcomes of microvascular free flap reconstruction for mandibular osteoradionecrosis: a systematic review," *Journal of Cranio-Maxillofacial Surgery*, vol. 43, no. 10, pp. 2026–2033, 2015.

[10] M. M. Hanasono and R. J. Skoracki, "Computer-assisted design and rapid prototype modeling in microvascular mandible reconstruction," *The laryngoscope*, vol. 123, no. 3, pp. 597–604, 2013.

[11] B. Jacek, P. Maciej, P. Tomasz, B. Agata, K. Wiesław, W. Radosław, and G. Filip, "3d printed models in mandibular reconstruction with bony free flaps," *Journal of Materials Science: Materials in Medicine*, vol. 29, no. 2, pp. 1–6, 2018.

[12] R. S. Gil, A. M. Roig, C. A. Obispo, A. Morla, C. M. Pagès, and J. L. Perez, "Surgical planning and microvascular reconstruction of the mandible with a fibular flap using computer-aided design, rapid prototype modelling, and precontoured titanium reconstruction plates: a prospective study," *British Journal of Oral and Maxillofacial Surgery*, vol. 53, no. 1, pp. 49–53, 2015.

[13] Y. Wang, H. Zhang, S. Fan, D. Zhang, Z. Huang, W. Chen, J. Ye, and J. Li, "Mandibular reconstruction with the vascularized fibula flap: comparison of virtual planning surgery and conventional surgery," *International journal of oral and maxillofacial surgery*, vol. 45, no. 11, pp. 1400–1405, 2016.

[14] K. Zheng, Z. Liao, N. Yoda, J. Fang, J. Chen, Z. Zhang, J. Zhong, C. Peck, K. Sasaki, M. V. Swain *et al.*, "Investigation on masticatory muscular functionality following oral reconstruction–an inverse identification approach," *Journal of biomechanics*, vol. 90, pp. 1–8, 2019.

[15] D. Curtis, O. Plesh, A. Hannam, A. Sharma, and T. Curtis, "Modeling of jaw biomechanics in the reconstructed mandibulectomy patient," *The Journal of prosthetic dentistry*, vol. 81, no. 2, pp. 167–173, 1999.

[16] B. Swendseid, A. Kumar, L. Sweeny, T. Zhan, R. A. Goldman, H. Krein, R. N. Heffelfinger, A. J. Luginbuhl, and J. M. Curry, "Natural history and consequences of nonunion in mandibular and maxillary free flaps," *Otolaryngology–Head and Neck Surgery*, vol. 163, no. 5, pp. 956–962, 2020.

[17] H. Gao, X. Li, C. Wang, P. Ji, and C. Wang, "Mechanobiologically optimization of a 3d titanium-mesh implant for mandibular large defect: A simulated study," *Materials Science and Engineering: C*, vol. 104, p. 109934, 2019.

[18] N. Yoda, K. Zheng, J. Chen, Z. Liao, S. Koyama, C. Peck, M. Swain, K. Sasaki, and Q. Li, "Biomechanical analysis of bone remodeling following mandibular reconstruction using fibula free flap," *Medical engineering & physics*, vol. 56, pp. 1–8, 2018.

[19] R. C. Wong, H. Tideman, M. Merkx, J. Jansen, S. Goh, and K. Liao, "Review of biomechanical models used in studying the biomechanics of reconstructed mandibles," *International journal of oral and maxillofacial surgery*, vol. 40, no. 4, pp. 393–400, 2011.

[20] I. Stavness, A. G. Hannam, J. E. Lloyd, and S. Fels, "Towards predicting biomechanical consequences of jaw reconstruction," in *Conf Proc IEEE Eng Med Biol Soc*, vol. 2008, 2008, p. 4567.

[21] A. Kimura, T. Nagasao, T. Kaneko, T. Tamaki, J. Miyamoto, and T. Nakajima, "Adaquate fixation of plates for stability during mandibular reconstruction," *Journal of Cranio-Maxillofacial Surgery*, vol. 34, no. 4, pp. 193–200, 2006.

[22] J. J. Lang, M. Bastian, P. Foehr, M. Seebach, J. Weitz, C. von Deimling, B. J. Schwaiger, C. M. Micheler, N. J. Wilhelm, C. U. Grosse *et al.*, "Improving mandibular reconstruction by using topology optimization, patient specific design and additive manufacturing?—a biomechanical comparison against miniplates on human specimen," *PloS one*, vol. 16, no. 6, p. e0253002, 2021.

[23] R. C. Wong, H. Tideman, M. A. Merkx, J. Jansen, and S. M. Goh, "The modular endoprosthesis for mandibular body replacement. part 2: Finite element analysis of endoprosthesis reconstruction of the mandible," *Journal of Cranio-Maxillofacial Surgery*, vol. 40, no. 8, pp. e487–e497, 2012.

[24] M. Seebach, F. Theurer, P. Foehr, C. v. Deimling, R. Burgkart, and M. F. Zaeh, "Design of bone plates for mandibular reconstruction using topology and shape optimization," in *World Congress of Structural and Multidisciplinary Optimisation*. Springer, 2017, pp. 2086–2096.

[25] D. C. Koper, C. A. Leung, L. C. Smeets, P. F. Laeven, G. J. Tuijthof, and P. A. Kessler, "Topology optimization of a mandibular reconstruction plate and biomechanical validation," *journal of the mechanical behavior of biomedical materials*, vol. 113, p. 104157, 2021.

[26] A. Van Kootwijk, V. Moosabeiki, M. C. Saldivar, H. Pahlavani, M. Leeflang, S. K. Niar, P. Pellikaan, B. Jonker, S. Ahmadi, E. Wolvius *et al.*, "Semi-automated digital workflow to design and evaluate patient-specific mandibular reconstruction implants," *journal of the mechanical behavior of biomedical materials*, vol. 132, p. 105291, 2022.

[27] Y.-W. Shen, Y.-S. Tsai, J.-T. Hsu, M.-Y. Shie, H.-L. Huang, and L.-J. Fuh, "Biomechanical analyses of porous designs of 3d-printed titanium implant for mandibular segmental osteotomy defects," *Materials*, vol. 15, no. 2, p. 576, 2022.

[28] T. Korioth and A. Hannam, "Effect of bilateral asymmetric tooth clenching on load distribution at the mandibular condyles," *The Journal of Prosthetic Dentistry*, vol. 64, no. 1, pp. 62–73, 1990.

[29] T. Ying, D. M. Wang, J. Tong, C. T. Wang, and C. P. Zhang, "Three-dimensional finite-element analysis investigating the biomechanical effects of human mandibular reconstruction with autogenous bone grafts," *Journal of Cranio-Maxillofacial Surgery*, vol. 34, no. 5, pp. 290–298, 2006.

[30] P. Schuller-Götzburg, M. Pleschberger, F. Rammerstorfer, and C. Krenkel, "3d-fem and histomorphology of mandibular reconstruction with the titanium functionally dynamic bridging plate," *International journal of oral and maxillofacial surgery*, vol. 38, no. 12, pp. 1298–1305, 2009.

[31] W. Z. Wu, J. Zhao, L. Zhang, N. Feng, and D. W. Rosen, "Customized titanium plate virtual design and deformation simulation analysis of human lateral mandible defect," in *Applied Mechanics and Materials*, vol. 157. Trans Tech Publ, 2012, pp. 227–230.

[32] M. Jędrusik-Pawłowska, M. Kromka-Szydek, M. Katra, and I. Niedzielska, "Mandibular reconstruction: biomechanical strength analysis (fem) based on a retrospective clinical analysis of selected patients," *Acta of Bioengineering and Biomechanics*, vol. 15, no. 2, 2013.

[33] P. Li, Y. Tang, J. Li, L. Shen, W. Tian, and W. Tang, "Establishment of sequential software processing for a biomechanical model of mandibular reconstruction with custom-made plate," *Computer methods and programs in biomedicine*, vol. 111, no. 3, pp. 642–649, 2013.

[34] Y.-W. Chang and P.-H. Liu, "Biomechanical effects of screw fixation in second mandibular reconstruction plate," in *2013 35th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*. IEEE, 2013, pp. 3167–3170.

[35] W. Z. Wu, L. Zhang, J. Zhao, X. T. Qu, D. Zhao, Y. Zhang, and W. S. Wang, "The fatigue simulation analysis of customized implanted titanium plate for human mandible bone reconstruction," in *Applied Mechanics and Materials*, vol. 300. Trans Tech Publ, 2013, pp. 1067–1070.

[36] P. Li, L. Shen, J. Li, R. Liang, W. Tian, and W. Tang, "Optimal design of an individual endoprosthesis for the reconstruction of extensive

mandibular defects with finite element analysis," *Journal of Cranio-Maxillofacial Surgery*, vol. 42, no. 1, pp. 73–78, 2014.

[37] P. Bujtár, J. Simonovics, K. Váradi, G. K. Sándor, and C. Avery, "The biomechanical aspects of reconstruction for segmental defects of the mandible: a finite element study to assess the optimisation of plate and screw factors," *Journal of Cranio-Maxillofacial Surgery*, vol. 42, no. 6, pp. 855–862, 2014.

[38] N. Narra, J. Valášek, M. Hannula, P. Marcián, G. K. Sándor, J. Hyttinen, and J. Wolff, "Finite element analysis of customized reconstruction plates for mandibular continuity defect therapy," *Journal of biomechanics*, vol. 47, no. 1, pp. 264–268, 2014.

[39] M. Pinheiro and J. Alves, "The feasibility of a custom-made endoprosthesis in mandibular reconstruction: implant design and finite element analysis," *Journal of Cranio-Maxillofacial Surgery*, vol. 43, no. 10, pp. 2116–2128, 2015.

[40] A. Al-Ahmari, E. A. Nasr, K. Moiduddin, S. Anwar, M. A. Kindi, and A. Kamrani, "A comparative study on the customized design of mandibular reconstruction plates using finite element method," *Advances in Mechanical Engineering*, vol. 7, no. 7, p. 1687814015593890, 2015.

[41] A. Jahadakbar, N. Shayesteh Moghaddam, A. Amerinatanzi, D. Dean, H. E. Karaca, and M. Elahinia, "Finite element simulation and additive manufacturing of stiffness-matched niti fixation hardware for mandibular reconstruction surgery," *Bioengineering*, vol. 3, no. 4, p. 36, 2016.

[42] K. Mehle, A. W. Eckert, D. Gentzsch, S. Schwan, C. M. Ludtka, and W.-D. Knoll, "Evaluation of a new peek mandibular reconstruction plate design for continuity defect therapy by finite element analysis," *International Journal of New Technology and Research*, vol. 2, no. 7, p. 263461, 2016.

[43] S.-M. Park, D. Lee, J.-W. Lee, Y. Kim, L. Kim, and G. Noh, "Stability of the permanently bent plates used in mandibular reconstructive surgery," in *2016 38th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*. IEEE, 2016, pp. 2198–2201.

[44] S. Dahake, A. Kuthe, S. Kulkarni, and M. Mawale, "Finite element analysis of customized implant in mandibular reconstruction after tumor resection with and without using customized surgical osteotomy guide," *The International Journal of Medical Robotics and Computer Assisted Surgery*, vol. 14, no. 1, p. e1854, 2018.

[45] E. A. Nasr, A. M. Al-Ahmari, K. Moiduddin, M. Al Kindi, and A. K. Kamrani, "A digital design methodology for surgical planning and fabrication of customized mandible implants," *Rapid Prototyping Journal*, vol. 23, no. 1, pp. 101–109, 2017.

[46] K. Moiduddin, S. Anwar, N. Ahmed, M. Ashfaq, and A. Al-Ahmari, "Computer assisted design and analysis of customized porous plate for mandibular reconstruction," *Irbm*, vol. 38, no. 2, pp. 78–89, 2017.

[47] C.-H. Wu, Y.-S. Lin, Y.-S. Liu, and C.-L. Lin, "Biomechanical evaluation of a novel hybrid reconstruction plate for mandible segmental defects: A finite element analysis and fatigue testing," *Journal of Cranio-Maxillofacial Surgery*, vol. 45, no. 10, pp. 1671–1680, 2017.

[48] D. Luo, X. Xu, C. Guo, and Q. Rong, "Fracture prediction for a customized mandibular reconstruction plate with finite element method," in *Advanced Computational Methods in Life System Modeling and Simulation*. Springer, 2017, pp. 86–94.

[49] K. O. Sanal, B. Özden, and B. Bas, "Finite element evaluation of different osteosynthesis variations that used after segmental mandibular resection," *Journal of Craniofacial Surgery*, vol. 28, no. 1, pp. 61–65, 2017.

[50] R. Gutwald, R. Jaeger, and F. M. Lambers, "Customized mandibular reconstruction plates improve mechanical performance in a mandibular reconstruction model," *Computer Methods in Biomechanics and Biomedical Engineering*, vol. 20, no. 4, pp. 426–435, 2017.

[51] K. Moiduddin, "Implementation of computer-assisted design, analysis, and additive manufactured customized mandibular implants," *Journal of Medical and Biological Engineering*, vol. 38, no. 5, pp. 744–756, 2018.

[52] S.-M. Park, J.-W. Lee, and G. Noh, "Which plate results in better stability after segmental mandibular resection and fibula free flap reconstruction? biomechanical analysis," *Oral surgery, oral medicine, oral pathology and oral radiology*, vol. 126, no. 5, pp. 380–389, 2018.

[53] S. Hoefert and R. Taier, "Mechanical stress in plates for bridging reconstruction mandibular defects and purposes of double plate reinforcement," *Journal of Cranio-Maxillofacial Surgery*, vol. 46, no. 5, pp. 785–794, 2018.

[54] K. Moiduddin, S. H. Mian, H. Alkhalefah, and U. Umer, "Digital design, analysis and 3d printing of prosthesis scaffolds for mandibular reconstruction," *Metals*, vol. 9, no. 5, p. 569, 2019.

[55] S.-N. Huang, M.-Y. Shie, Y.-W. Shen, J.-T. Hsu, H.-L. Huang, and L.-J. Fuh, "Biomechanical assessment of design parameters on a self-developed 3d-printed titanium-alloy reconstruction/prosthetic implant for mandibular segmental osteotomy defect," *Metals*, vol. 9, no. 5, p. 597, 2019.

[56] K.-j. Cheng, Y.-f. Liu, J. H. Wang, J. C. Jun, X.-f. Jiang, R. Wang, and D. A. Baur, "Biomechanical behavior of mandibles reconstructed with fibular grafts at different vertical positions using finite element method," *Journal of Plastic, Reconstructive & Aesthetic Surgery*, vol. 72, no. 2, pp. 281–289, 2019.

[57] M. B. Kucukguven and M. Akkocaoğlu, "Finite element analysis of stress distribution on reconstructed mandibular models for autogenous bone grafts," *Technology and Health Care*, vol. 28, no. 3, pp. 249–258, 2020.

[58] X. Li, C. Jiang, H. Gao, C. Wang, C. Wang, and P. Ji, "Biomechanical analysis of various reconstructive methods for the mandibular body and ramus defect using a free vascularized fibula flap," *BioMed Research International*, vol. 2020, 2020.

[59] S. Kargarnejad, F. Ghalichi, M. P. Mohammad, and A. Garajei, "Evaluation of failure of a titanium conventional plate in mandibular reconstruction and improve the performance with fibula free flap," *Journal of Craniomaxillofacial Research*, pp. 67–75, 2020.

[60] S. Kargarnejad, F. Ghalichi, M. Pourgol-mohammad, I. Oskui, and A. Garajei, "Biomechanical evaluation of reconstructed extensive mandibular defects by different models using finite element method," *Journal of Mechanics in Medicine and Biology*, vol. 20, no. 08, p. 2050053, 2020.

[61] S. Prasadh, S. Suresh, K. L. Hong, A. Bhargav, V. Rosa, and R. C. W. Wong, "Biomechanics of alloplastic mandible reconstruction using biomaterials: The effect of implant design on stress concentration influences choice of material," *Journal of the mechanical behavior of biomedical materials*, vol. 103, p. 103548, 2020.

[62] K.-j. Cheng, Y.-f. Liu, R. Wang, J.-x. Zhang, X.-f. Jiang, X.-t. Dong, and X. Xu, "Topological optimization of 3d printed bone analog with pekk for surgical mandibular reconstruction," *Journal of the mechanical behavior of biomedical materials*, vol. 107, p. 103758, 2020.

[63] C. Wu, K. Zheng, J. Fang, G. P. Steven, and Q. Li, "Time-dependent topology optimization of bone plates considering bone remodeling," *Computer Methods in Applied Mechanics and Engineering*, vol. 359, p. 112702, 2020.

[64] S. Kargarnejad, F. Ghalichi, M. Pourgol-Mohammad, and A. Garajei, "Mandibular reconstruction system reliability analysis using probabilistic finite element method," *Computer Methods in Biomechanics and Biomedical Engineering*, vol. 24, no. 13, pp. 1437–1449, 2021.

[65] J. Kang, J. Zhang, J. Zheng, L. Wang, D. Li, and S. Liu, "3d-printed peek implant for mandibular defects repair-a new method," *Journal of the Mechanical Behavior of Biomedical Materials*, vol. 116, p. 104335, 2021.

[66] Q. Shi, Y. Sun, S. Yang, J. Van Dessel, H.-T. Lübbers, S. Zhong, Y. Gu, M. Bila, T. Dormaar, J. Schoenaers *et al.*, "Failure analysis of an in-vivo fractured patient-specific ti6al4v mandible reconstruction plate fabricated by selective laser melting," *Engineering Failure Analysis*, vol. 124, p. 105353, 2021.

[67] Q. Shi, Y. Sun, S. Yang, J. Van Dessel, H.-T. Lübbers, S. Zhong, Y. Gu, M. Bila, and C. Politis, "Preclinical study of additive manufactured plates with shortened lengths for complete mandible reconstruction: Design, biomechanics simulation, and fixation stability assessment," *Computers in Biology and Medicine*, vol. 139, p. 105008, 2021.

[68] W.-m. Peng, K.-j. Cheng, Y.-f. Liu, M. Nizza, D. A. Baur, X.-f. Jiang, and X.-t. Dong, "Biomechanical and mechanostat analysis of a titanium layered porous implant for mandibular reconstruction: The effect of the topology optimization design," *Materials Science and Engineering: C*, vol. 124, p. 112056, 2021.

[69] H. Farajpour, F. Bastami, M. Bohlouli, and A. Khojasteh, "Reconstruction of bilateral ramus-condyle unit defect using custom titanium prosthesis with preservation of both condyles," *Journal of the Mechanical Behavior of Biomedical Materials*, vol. 124, p. 104765, 2021.

[70] S. Zhong, Q. Shi, Y. Sun, S. Yang, J. Van Dessel, Y. Gu, X. Chen, H.-T. Lübbers, and C. Politis, "Biomechanical comparison of locking and

non-locking patient-specific mandibular reconstruction plate using finite element analysis," *Journal of the Mechanical Behavior of Biomedical Materials*, vol. 124, p. 104849, 2021.

[71] G. Muftuoglu, B. Bayram, and P. Aydin, "Comparison of locking and non-locking reconstruction plate-screw system in lateral mandibular defects by finite element analysis," *Journal of Stomatology, Oral and Maxillofacial Surgery*, vol. 122, no. 4, pp. e65–e69, 2021.

[72] T.-S. Lin, T.-F. Chiu, J.-T. Hsu, C.-C. Chen, L.-R. Chang, and H.-L. Huang, "Biomechanical evaluation and factorial analysis of the 3-dimensional printing self-designed metallic reconstruction plate for mandibular segmental defect," *Journal of Oral and Maxillofacial Surgery*, vol. 80, no. 4, pp. 775–783, 2022.

[73] K. Zheng, N. Yoda, J. Chen, Z. Liao, J. Zhong, C. Wu, B. Wan, S. Koyama, K. Sasaki, C. Peck *et al.*, "Bone remodeling following mandibular reconstruction using fibula free flap," *Journal of Biomechanics*, vol. 133, p. 110968, 2022.

[74] R. Liu, Y. Su, W. Yang, X. Dang, C. Zhang, R. Du, and Y. Zhong, "Novel design and optimization of porous titanium structure for mandibular reconstruction," *Applied Bionics and Biomechanics*, vol. 2022, 2022.

[75] B. T. Jung, W.-H. Kim, B. Kim, and J.-H. Lee, "Biomechanical integrity of hydroxyapatite/poly-l-lactide fixation system in mandibular body reconstruction with deep circumflex iliac artery free flap," *Journal of Materials Research and Technology*, vol. 18, pp. 4662–4671, 2022.

[76] S. Zhong, Q. Shi, J. Van Dessel, Y. Gu, Y. Sun, S. Yang, and C. Politis, "Biomechanical validation of structural optimized patient-specific mandibular reconstruction plate orienting additive manufacturing," *Computer Methods and Programs in Biomedicine*, vol. 224, p. 107023, 2022.

[77] H. Cui, L. Gao, J. Han, and J. Liu, "Biomechanical analysis of mandibular defect reconstruction based on a new base-fixation system," *Computer Methods in Biomechanics and Biomedical Engineering*, pp. 1–11, 2022.

[78] B. M. Ferguson, A. Entezari, J. Fang, and Q. Li, "Optimal placement of fixation system for scaffold-based mandibular reconstruction," *Journal of the Mechanical Behavior of Biomedical Materials*, vol. 126, p. 104855, 2022.

[79] B. Wan, N. Yoda, K. Zheng, Z. Zhang, C. Wu, J. Clark, K. Sasaki, M. Swain, and Q. Li, "On interaction between fatigue of reconstruction plate and time-dependent bone remodeling," *Journal of the Mechanical Behavior of Biomedical Materials*, vol. 136, p. 105483, 2022.

[80] R. Liu, Y. Su, W. Yang, K. Wu, R. Du, and Y. Zhong, "A novel design method of gradient porous structure for stabilized and lightweight mandibular prosthesis," *Bioengineering*, vol. 9, no. 9, p. 424, 2022.

[81] P. Ruf, V. Orassi, H. Fischer, C. Steffen, G. N. Duda, M. Heiland, K. Kreutzer, S. Checa, and C. Rendenbach, "Towards mechanobiologically optimized mandible reconstruction: Cad/cam miniplates vs. reconstruction plates for fibula free flap fixation: A finite element study," *Frontiers in Bioengineering and Biotechnology*, vol. 10, 2022.

[82] Y. Li, Y. Hu, H. Chen, X. Meng, D. Chen, H. Gu, Q. Chen, Z. Mu, and Z. Li, "A novel conceptual design of a biomimetic oral implant and its biomechanical effect on the repairment of a large mandibular defect," *Medicine in Novel Technology and Devices*, vol. 15, p. 100147, 2022.

[83] C. Zhong, Y. Zhao, H. Xing, Q. Lai, R. Xue, T. Song, X. Tang, K. Zhu, and Y. Deng, "Assembly of 3d-printed ti scaffold and free vascularized fibula using a customized ti plate for the reconstruction of mandibular defects," *Bio-Design and Manufacturing*, vol. 5, no. 2, pp. 424–429, 2022.

[84] H. Wu, L. Chao, Y. Yi, C. Jiao, L. Shen, G. Wu, J. Zhao, L. Wang, J. Meng, C. Wang *et al.*, "Design and 3d printing of integrated bionic porous ceramic maxillofacial prosthesis," *Journal of Materials Science*, pp. 1–14, 2022.

[85] A. Erdemir, T. M. Guess, J. Halloran, S. C. Tadepalli, and T. M. Morrison, "Considerations for reporting finite element analysis studies in biomechanics," *Journal of biomechanics*, vol. 45, no. 4, pp. 625–633, 2012.

[86] R. T. Hart, V. V. Hennebel, N. Thongpreda, W. C. Van Buskirk, and R. C. Anderson, "Modeling the biomechanics of the mandible: a three-dimensional finite element study," *Journal of biomechanics*, vol. 25, no. 3, pp. 261–286, 1992.

[87] L. Giovannelli, J. Ródenas, J. Navarro-Jimenez, and M. Tur, "Direct medical image-based finite element modelling for patient-specific simulation of future implants," *Finite Elements in Analysis and Design*, vol. 136, pp. 37–57, 2017.

[88] J. E. Lloyd, I. Stavness, and S. Fels, "Artisynth: A fast interactive biomechanical modeling toolkit combining multibody and finite element simulation," *Soft tissue biomechanical modeling for computer assisted surgery*, pp. 355–394, 2012.

[89] S. A. Maas, B. J. Ellis, D. S. Rawlins, and J. A. Weiss, "Finite element simulation of articular contact mechanics with quadratic tetrahedral elements," *Journal of biomechanics*, vol. 49, no. 5, pp. 659–667, 2016.

[90] D. D. McErlain, J. S. Milner, T. G. Ivanov, L. Jencikova-Celerin, S. I. Pollmann, and D. W. Holdsworth, "Subchondral cysts create increased intra-osseous stress in early knee oa: a finite element analysis using simulated lesions," *Bone*, vol. 48, no. 3, pp. 639–646, 2011.

[91] W. C. Parr, T. Wang, C. Tan, M. J. Dan, W. R. Walsh, and P. Morberg, "Fatigue implications for bending orthopaedic plates," *Injury*, vol. 52, no. 10, pp. 2896–2902, 2021.

[92] P. D. N. Borges, A. Forte, T. Vincent, D. Dini, and M. Marenzana, "Rapid, automated imaging of mouse articular cartilage by microct for early detection of osteoarthritis and finite element modelling of joint mechanics," *Osteoarthritis and cartilage*, vol. 22, no. 10, pp. 1419–1428, 2014.

[93] J. E. Johnson, P. Lee, T. E. McIff, E. Bruce Toby, and K. J. Fischer, "Computationally efficient magnetic resonance imaging based surface contact modeling as a tool to evaluate joint injuries and outcomes of surgical interventions compared to finite element modeling," *Journal of Biomechanical Engineering*, vol. 136, no. 4, 2014.

[94] S. C. Dogru, E. Cansiz, and Y. Z. Arslan, "A review of finite element applications in oral and maxillofacial biomechanics," *Journal of mechanics in medicine and biology*, vol. 18, no. 02, p. 1830002, 2018.

[95] B. B. J. Merema, J. Kraeima, H. H. Glas, F. K. Spijkervet, and M. J. Witjes, "Patient-specific finite element models of the human mandible: Lack of consensus on current set-ups," *Oral diseases*, vol. 27, no. 1, pp. 42–51, 2021.

[96] C. Zannoni, R. Mantovani, and M. Viceconti, "Material properties assignment to finite element models of bone structures: a new method," *Medical engineering & physics*, vol. 20, no. 10, pp. 735–740, 1999.

[97] L. M. Mathieu, T. L. Mueller, P.-E. Bourban, D. P. Pioletti, R. Müller, and J.-A. E. Månson, "Architecture and properties of anisotropic polymer composite scaffolds for bone tissue engineering," *Biomaterials*, vol. 27, no. 6, pp. 905–916, 2006.

[98] S. Pai, V. Bhat, V. Patil, N. Naik, S. Awasthi, and N. Nayak, "Numerical three-dimensional finite element modeling of cavity shape and optimal material selection by analysis of stress distribution on class v cavities of mandibular premolars," *Journal of International Society of Preventive & Community Dentistry*, vol. 10, no. 3, p. 279, 2020.

[99] B. C. Yemineni, J. Mahendra, J. Nasina, L. Mahendra, L. Shivasubramanian, and S. B. Perika, "Evaluation of maximum principal stress, von mises stress, and deformation on surrounding mandibular bone during insertion of an implant: a three-dimensional finite element study," *Cureus*, vol. 12, no. 7, 2020.

[100] D. S. Ryan, S. Domínguez, S. A. Ross, N. Nigam, and J. M. Wakeling, "The energy of muscle contraction. ii. transverse compression and work," *Frontiers in Physiology*, vol. 11, p. 538522, 2020.

[101] C. Rungsiyakull, J. Chen, P. Rungsiyakull, W. Li, M. Swain, and Q. Li, "Bone's responses to different designs of implant-supported fixed partial dentures," *Biomechanics and modeling in mechanobiology*, vol. 14, pp. 403–411, 2015.

[102] D. Lin, Q. Li, W. Li, N. Duckmanton, and M. Swain, "Mandibular bone remodeling induced by dental implant," *Journal of biomechanics*, vol. 43, no. 2, pp. 287–293, 2010.

[103] A. G. Hannam, I. Stavness, J. E. Lloyd, and S. Fels, "A dynamic model of jaw and hyoid biomechanics during chewing," *Journal of Biomechanics*, vol. 41, no. 5, pp. 1069–1076, 2008.

[104] A. G. Hannam, I. K. Stavness, J. E. Lloyd, S. S. Fels, A. J. Miller, and D. A. Curtis, "A comparison of simulated jaw dynamics in models of segmental mandibular resection versus resection with alloplastic reconstruction," *The Journal of Prosthetic Dentistry*, vol. 104, no. 3, pp. 191–198, 2010.

[105] I. Stavness, A. G. Hannam, J. E. Lloyd, and S. Fels, "Predicting muscle patterns for hemimandibulectomy models," *Computer Meth-*

ods in Biomechanics and Biomedical Engineering, vol. 13, no. 4, pp. 483–491, 2010.

[106] W. Schupp, M. Arzdorf, B. Linke, and R. Gutwald, "Biomechanical testing of different osteosynthesis systems for segmental resection of the mandible," *Journal of oral and maxillofacial surgery*, vol. 65, no. 5, pp. 924–930, 2007.

[107] R. Drake, A. W. Vogl, and A. W. Mitchell, *Gray's anatomy for students E-book*. Elsevier Health Sciences, 2009.

[108] B. Sagl, M. Schmid-Schwap, E. Piehslinger, M. Kundi, and I. Stavness, "A dynamic jaw model with a finite-element temporomandibular joint," *Frontiers in Physiology*, vol. 10, p. 1156, 2019.

[109] B. Sagl, M. Schmid-Schwap, E. Piehslinger, X. Rausch-Fan, and I. Stavness, "The effect of tooth cusp morphology and grinding direction on tmj loading during bruxism," *Frontiers in Physiology*, p. 1829, 2022.

[110] A. Wall and T. Board, "The compressive behavior of bone as a two-phase porous structure," *Classic Papers in Orthopaedics*, pp. 457–460, 2014.

[111] J. Rice, S. Cowin, and J. Bowman, "On the dependence of the elasticity and strength of cancellous bone on apparent density," *Journal of biomechanics*, vol. 21, no. 2, pp. 155–168, 1988.

[112] P. Ducheyne, L. Heymans, M. Martens, E. Aernoudt, P. de Meester, and J. C. Mulier, "The mechanical behaviour of intracondylar cancellous bone of the femur at different loading rates," *Journal of Biomechanics*, vol. 10, no. 11-12, pp. 747–762, 1977.

[113] M. Martens, R. Van Audekercke, P. Delport, P. De Meester, and J. Mulier, "The mechanical characteristics of cancellous bone at the upper femoral region," *Journal of biomechanics*, vol. 16, no. 12, pp. 971–983, 1983.

[114] J. Keyak, I. Lee, and H. Skinner, "Correlations between orthogonal mechanical properties and density of trabecular bone: use of different densitometric measures," *Journal of biomedical materials research*, vol. 28, no. 11, pp. 1329–1336, 1994.

[115] C. Field, Q. Li, W. Li, M. Thompson, and M. Swain, "Prediction of mandibular bone remodelling induced by fixed partial dentures," *Journal of biomechanics*, vol. 43, no. 9, pp. 1771–1779, 2010.

[116] M. H. Smith, C. H. Schrag, S. P. Chandarana, J. G. Cobb, T. W. Matthews, C. D. Mckenzie, and J. L. Matthews, "Novel plate design to improve mandibular and maxillary reconstruction with the osteocutaneous fibula flap," *Plastic and Reconstructive Surgery Global Open*, vol. 7, no. 1, 2019.

[117] R. Gutwald, R. Jaeger, and F. M. Lambers, "Customized mandibular reconstruction plates improve mechanical performance in a mandibular reconstruction model," *Computer methods in BiomeChaniCs and BiomediCal engineering*, vol. 20, no. 4, pp. 426–435, 2017.

[118] T.-S. Lin, T.-F. Chiu, J.-T. Hsu, C.-C. Chen, L.-R. Chang, and H.-L. Huang, "Biomechanical evaluation and factorial analysis of the 3-dimensional printing self-designed metallic reconstruction plate for mandibular segmental defect," *Journal of Oral and Maxillofacial Surgery*, vol. 80, no. 4, pp. 775–783, 2022.

[119] M. Lisiak-Myszke, D. Marciniak, M. Bieliński, H. Sobczak, Ł. Garbacewicz, and B. Drogoszewska, "Application of finite element analysis in oral and maxillofacial surgery—a literature review," *Materials*, vol. 13, no. 14, p. 3063, 2020.

[120] H. Cook, "Immediate reconstruction of the mandible by metallic implant following resection for neoplasm." *Annals of the Royal College of Surgeons of England*, vol. 42, no. 4, p. 233, 1968.

[121] Y.-f. Liu, Y.-y. Fan, X.-f. Jiang, and D. A. Baur, "A customized fixation plate with novel structure designed by topological optimization for mandibular angle fracture based on finite element analysis," *Biomedical engineering online*, vol. 16, no. 1, pp. 1–17, 2017.