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Systematic Review of Image Segmentation Programs in Craniomaxillofacial Surgery

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Abstract

Image segmentation has a significant role in the virtual planning, execution, and evaluation of craniomaxillofacial (CMF) surgical procedures. This systematic review aims to evaluate and compare the image segmentation programs frequently used in the field of CMF surgery. A precise search strategy was employed to recognise suitable studies across several databases, using specific inclusion criteria and keywords. Various image segmentation programs that use different techniques, including thresholding, edge-based methods, region-based methods and machine learning-based methods, were investigated. Results were screened through Preferred Reporting Items for Systematic Reviews and Meta-Analyses. A total of 94 reports on the use of virtual surgical planning from January 1, 2014, to June 1, 2023, were obtained. The identified image segmentation programs were analysed, including factors such as program features, strengths, limitations, supported image modalities, and clinical applications. A qualified assessment of these programs was conducted on the basis of parameters such as segmentation accuracy, processing speed, robustness, user-friendliness and integration capabilities. The review also addresses challenges faced by current segmentation programs and outlines future directions for advancement, including the standardised validation metrics and the integration of artificial intelligence. Surgical procedures were assigned into seven categories for analysis: cranial reconstructions, facial rejuvenation, orthognathic surgery, trauma repair, tumour resection, cleft lip and palate and patient specific implant. Amongst the software that could be used for bone segmentation in CMF region, eight software programs are most frequently used. Results showed that the Materialise suite was the most widespread tool for bone segmentation programs, with a prevalence of 50%, followed by the 3D slicer. This review underlines the principal significance of image segmentation in CMF surgery and offers valuable insights for clinicians and researchers to make informed decisions regarding the selection and utilisation of image segmentation programs.

Keywords: *Image segmentation; Craniomaxillofacial surgery; Surgical planning; Segmentation programs; medical imaging; Computer-aided surgery; Image analysis; Surgical navigation.*

1. Introduction

Software plays an integral role in the diagnosis and treatment of patients; this role is like that of many medical or surgical devices. Craniomaxillofacial (CMF) surgery, a specialised field within the broader domain of surgical interventions, involves sophisticated procedures aimed at addressing a wide array of CMF pathologies, including trauma, congenital anomalies and tumours [1]. The precision and effectiveness of such surgeries are considerably influenced by the details provided by medical images, particularly in the context of image segmentation. Image segmentation is the process of dividing medical images into distinct anatomical regions of interest, which are crucial in CMF surgery. It has an important role in surgical planning, intraoperative navigation, and outcome assessment [2]. Literature provides acceptable evidence that image segmentation and virtual surgical planning have remarkable effect on the accuracy of bone cutting. This progression helps divide and reconstruct the craniofacial skeleton, with a focus on compatibility and a proper fit of anatomical parts; it has also allowed the design of patient-specific implants that are personalised to the individual morphological variations of each patient [3–5].

Virtual surgical planning is an important development in the field of craniofacial surgery, where it enhances the accuracy of preoperative planning, possibly resulting in more accurate reconstructions. In other words, it may significantly reduce operating time, increase clinical and patient outcomes, and increase surgical efficiency by planning the operations.

The development of medical imaging techniques like computed tomography (CT) and magnetic resonance imaging (MRI) has led to an increase in the need for automated and semi-automated image analysis approaches. Thus, various segmentation methods, such as thresholding, region-based methods, edge-based methods and machine learning-based methods, were developed [6]. These techniques facilitate defining pathological regions, outlining and detecting critical structures and easing three-dimensional reconstruction that improves surgeons' understanding of complex anatomical structures [7]. The integration of specialised software capable of effective and precise image segmentation has become essential in modern CMF surgical practice [8]. Simulated surgical scenarios using virtual and augmented reality technologies have been widely used in CMF surgery. These tools help surgeons practice complex surgical procedures in a virtual environment before performing them. Surgeons can receive feedback during surgery by using these technologies, where computer graphics are used to import geometric data taken from volumetric imaging of patients, such as CT and MRI [9]. In CMF surgery, these programs are used in any step of the digital workflow, including segmentation of required structures, reconstruction of three-dimensional models and creation of implants or structures that are ready for printing [10]. These programs could be used to simulate surgical planning of osteotomies and soft tissue, design surgical guides and moulds, create implantable prosthetic devices and evaluate distance and angle measurements [11–14].

1.1. Image Segmentation Techniques in CMF Surgery

Many segmentation techniques are used in medical image segmentation, which is an important step in modern CMF surgery. They improve the understanding of anatomical structures and many pathological cases. These techniques have been used to detect and segment regions of interest. The most frequently used techniques are thresholding, region-based methods, edge-based methods and machine learning-based methods.

Thresholding is a technique where pixel intensity values are utilised to differentiate between different adjacent regions [15]. This method is very useful when dealing with images that have distinct intensity peaks. In CMF surgery, thresholding is mostly used to segment bone from soft tissues. However, it is not very efficient in cases of presence of variations in tissue intensity due to noise, artifacts or anatomical abnormalities [16, 17].

An image is segmented into regions on the basis of predetermined characteristics such as texture or intensity. This step most frequently performed using watershed and region-growing segmentation methods. In CMF surgery, region-based methods can help improve the segmentation of complex structures with varying densities or images with lower contrast that do not have distinct differences in densities and variations between adjacent structures such as tumours or vascular structures. Although these techniques are sensitive to the original seed points, the parameters may have to be fine-tuned because of their ability to identify minute nuances [18].

The edge-based technique relies on detecting boundaries between different adjacent structures by detecting abrupt changes in pixel intensity [19]. Techniques like canny edge detector is manipulated to help outline structures that have well-defined edges or boundaries, such as blood vessels or bones. However, identifying edges or contours in low-contrast images can be difficult, leading to some mistakes in boundary detection [20].

Machine learning, particularly convolutional neural networks, has become increasingly important in many areas of modern life, especially in the segmentation of medical images, due to its ability to learn complex patterns from a large number of datasets. Machine learning shows great promise in CMF surgery for segmenting anatomical features and abnormalities. It can be applied across varying anatomical features and adapted to the differences among patients, but this method requires extensive training data and significant computational resources. In addition, the decision-making process may not be transparent [21, 22].

Whilst each of these segmentation techniques has several benefits and drawbacks, their applicability varies depending on a number of variables, including surgical scenarios and image quality. As a result, these methods rely on the case, the level of accuracy needed and the available computational resources.

The available literature does not provide a comprehensive review of all image segmentation software used in CMF surgery. Comparative studies that assessed the performance of various segmentation techniques in this region and the rapid technological advancements are lacking. This study aimed to fill this gap by systematically reviewing a wider range of segmentation methods and comparing the available programs' features, strengths and limitations, thus allowing for identification of areas of improvement [23].

This review aimed to provide clinicians, researchers, and other healthcare professionals who specialised in the craniofacial region a comprehensive understanding of segmentation programs, including their features, strengths, limitations and possible effects on clinical practice. By analysing the features of the current segmentation programs, this review aimed to illustrate their clinical usefulness, evaluate their performance and outline their capability for further advancements in this critical aspect of virtual surgical planning and implementation.

2. Methodology

2.1. Search Strategy

Electronic databases like PubMed, Scopus, IEEE Xplore, and Web of Science were investigated. A combination of free-text and Medical Subject Headings (MeSH) terms was employed in the search. 'Surgical planning', 'image segmentation', 'craniomaxillofacial surgery' and 'segmentation programs' were amongst the terms mentioned. The search period was restricted from January 1, 2014, to June 1, 2023.

2.2. Criteria for Inclusion and Exclusion

All articles included in this study were checked for eligibility and duplicates, and all titles and abstracts were scanned for suitability by two independent reviewers. The inclusion criteria consisted of articles published between January 1, 2014, and June 1, 2023. A specific exclusion criterion was applied. Thus, this work focused on bone segmentation performed on the CMF region for surgical purposes.

Studies that reported on original research or case studies addressing the use of image segmentation programs in CMF surgery and provided a thorough explanation of the segmentation program's results were included. Articles in English and those involving CT imaging modality were included. Studies were excluded if they were review articles, conference abstracts or editorials.

2.3. Study Selection

In the initial search, a total of 1940 articles were detected. Two independent reviewers screened the titles and abstracts to identify potentially relevant studies [24]. The full texts of these articles were then evaluated to determine their appropriateness for this study on the basis of the predetermined inclusion and exclusion criteria. Any discrepancies were discussed and resolved through discussion and consensus.

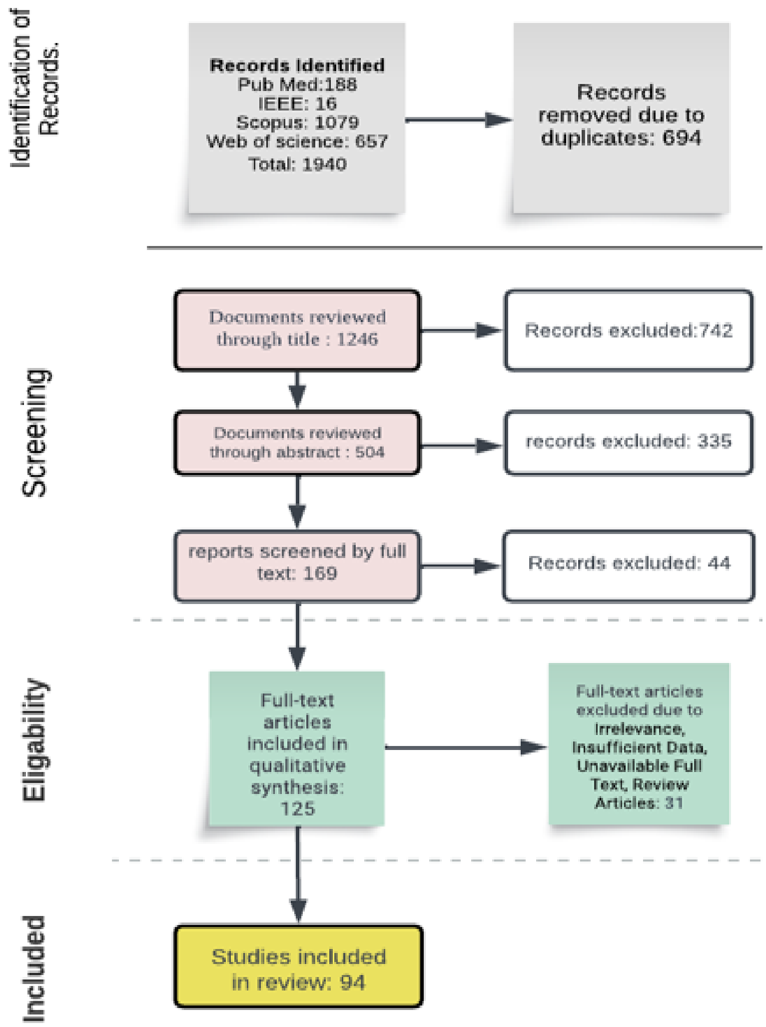

Fig. 1. PRISMA Flowchart for Article Selection

2.4. Data Extraction and Synthesis

From the selected studies, a standardised data extraction method was developed and used to extract appropriate information. The extracted data involved details about the segmentation programs, anatomical regions studied, image modalities, segmentation techniques employed, outcome measures and reported results to provide a comprehensive understanding of the classifications for individual procedures within the context of CMF surgery. Table 1 outlines various categories and their respective surgical procedures as a guide to understand the scope of this review. The data collection involved a qualitative analysis of the included studies, focusing on the programs' features, limitations, strengths and clinical applications.

3. Results and Discussion

Comparing the performance and features of different segmentation programs is important for medical professionals and scholars to make subjective choices regarding their selection. Different programs were assessed in accordance with the key components necessary for their successful utilisation in CMF surgery.

Table 1,
Definitions Outlining the Classifications for Individual Procedures

Category	Definition	Surgical Procedures
Cranial reconstructions	Surgical procedures involving the restoration and reshaping of the cranial vault to address congenital anomalies, trauma, or tumours	Cranioplasty and fronto-orbital advancement
Facial rejuvenation	Surgical interventions addressing fractures and injuries of the facial bones caused by trauma.	Facelift, blepharoplasty, and brow lift
Orthognathic surgery	Surgical corrections of skeletal discrepancies in the jaw, aiming to improve functional and aesthetic harmony.	Maxillary osteotomy and mandibular osteotomy
Trauma repair	Surgical interventions addressing fractures and injuries of the facial bones caused by trauma.	Zygomaticomaxillary complex repair and nasal fracture reduction
Tumour resection	Procedures targeting the removal of benign or malignant tumours affecting the craniofacial region.	Mandibulectomy and maxillectomy
Cleft lip and palate	Surgical interventions addressing congenital cleft lip and palate anomalies for improved function and appearance.	Lip repair and palate repair
Patient-specific implant	Procedures involving the design and placement of custom implants tailored to a patient's unique craniofacial anatomy.	Craniomaxillofacial implant placement

3.1. Prevalence of Different Software Packages

Amongst the software packages analysed in the selected studies, Mimics by Materialise was the most frequently utilised, appearing in approximately 25 papers, which is approximately 26.6% of the total. Following closely was ProPlan CMF, also by Materialise, which was cited in 20 papers (21.2%). The 3D Slicer from Harvard University had a strong presence in 18 papers (19.2%). Dolphin by Dolphin Imaging and Management Solutions was the software of choice in nine papers (9.6%), followed by the Geomagic Family from 3D Systems, with eight papers referencing it (8.5%). Amira was mentioned in four papers (4.3%), Rhino3D Medical was mentioned in four papers (4.3%) and MeVisLab was mentioned in two papers (2.1%). These percentages from highest to lowest represent the frequency of use to segment CMF bones in papers included in this review.

Various software packages were referenced, and they were categorised as distinct and less commonly reported category because each had fewer than one or two references. The frequency of use of the most common segmentation programs is displayed in Figure 2. On the one hand, no software was considered better or more accurate when it had a higher mention rate in the research area. On the other hand, the higher percentage could reflect more useful features or better compatibility with specific tasks.

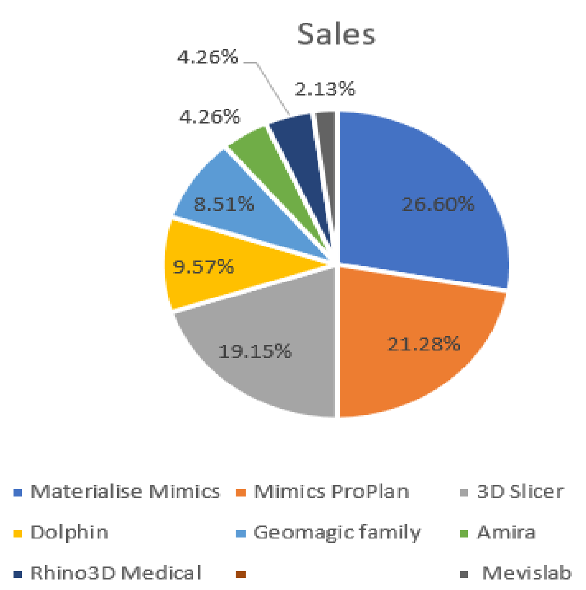

Fig. 2. Prevalence of different software packages.

3.1. Usefulness of Different Segmentation Software Packages

Comparing the features and performance of several segmentation programs is essential for physicians and researchers to make well-informed decisions on which segmentation software to use. As shown in Table 2, various programs were evaluated on the basis of key factors mentioned in the reviewed articles. For each factor, a performance satisfaction of above 80% was assumed to be high, moderate if the satisfaction was 50%–80% and variable if the performance ranged between 30% and 50%. These factors are essential for their effective utilisation in CMF surgery.

The first and most important criterion is the accuracy of image segmentation, which is an essential feature in medical image analysis and segmentation. It contributes to the success of the following procedures: Mimics by Materialise is based on thresholding, region growing and manual segmentation. ProPlan CMF by Materialise uses similar techniques as Mimics but it is adapted specifically for CMF applications. The 3D Slicer uses various segmentation algorithms such as thresholding, region growing, and edge-based methods. It also allows integration of machine learning models for segmentation tasks, allowing for advanced and automated segmentation. The Dolphin by Dolphin Imaging and Management Solutions uses techniques like thresholding and manual segmentation. The Geomagic Family from 3D Systems combines thresholding, edge detection, and manual segmentation for accurate 3D reconstruction and modelling. In general, these software applications often use a combination of image segmentation techniques, targeted to the specific needs of their respective fields. They may also integrate machine learning or artificial intelligence (AI)-based algorithms for more automated, precise and efficient segmentation processes. The choice of technique can depend on factors like the type of imaging modality, the anatomical structures of interest and the required level of accuracy and detail needed [25–27].

Real-time applications depend on programs with good processing capabilities. An AI-based medical segmentation software can improve efficiency, reduce scan time and patient dose and provide accurate and fast results in various medical imaging applications. Programs like Mimics, Rhino and ReLUS offer interactive processing, enabling surgeons for immediate segmentations adjustment [28–89].

User-friendliness is a very important feature, especially in intraoperative intervention. Programs like Mimics, ProPlan CMF, 3D Slicer and Geomagic Family make intuitive interfaces a priority that enables users to interact with functions and criteria available in segmentation programs [30, 31]. User-friendliness lowers the requirement for training health professionals and makes products easier to use. Amira, MeVisLab and Rhino3D Medical are some of the platforms that, albeit having a larger toolbox, could take some extra time and effort for users to become experts with using them [32].

One of the most crucial requirements for any segmentation technique is its ability to effectively handle noise and artifacts, guaranteeing accurate segmentations from defective images. AI-driven programs, such as Relu virtual patient creator, are designed to handle noisy input and are less affected by artifacts, but this method may lead to some issues in precision and accuracy, where it depends on ready-learning anatomical templates. Programs, such as Materialise Mimics, Proplan CMF, and 3D Slicer, may offer filtering and correction options to resolve the effects of noise and artifacts [33, 34].

Integration with other medical segmentation software enhances the program's workflow and makes it easier to use. Programs, such as Mimics, ProPlan CMF, Geomagic Studio and Geomagic Freeform, offer options to export 3D models to be employed on other platforms. Open-source platforms, such as 3D Slicer, enable the development and modification of custom workflows, thereby improving compatibility with available tools [35, 36].

Accessibility and cost play a significant role, especially for institutions that have limited budgets, researchers and students. Open-source platforms like 3D Slicer offer cost-effective solutions with many capabilities. Commercial programs like Mimics, ProPlan CMF, Geomagic Studio, Geomagic Freeform and Dolphin may provide a wide variety of features but at a higher cost. Although each program is superior in certain aspects, the final decision depends on the specific clinical needs; the existing resources; and the desired balance amongst speed, accuracy, ease of use and cost consistency.

Table 2,
Evaluation of various programs based on key factors essential for their effective utilisation in craniomaxillofacial surgery.

Software	Prevalence	Accuracy of Segmentation	Processing Speed	User-friendliness	Robustness to Noise/Artifacts	Integration with Other Software	Accessibility
Mimics by Materialise	High	High	Moderate	High	High	Yes	High
ProPlan CMF by Materialise	Moderate	High	Moderate	High	High	Yes	High
3D Slicer	High	High	Variable	High	High	Yes	High
Dolphin by Dolphin Imaging	Moderate	High	Variable	Good	High	Yes	Moderate
Geomagic Family by 3D Systems	Moderate	Moderate	Variable	High	Moderate	Yes	High
Amira	Moderate	High	Variable	Moderate	High	Yes	Moderate
Rhino3D Medical	Low	High	Variable	Medium	High	Yes	Moderate
MeVisLab	Moderate	High	Variable	Needs special training	High	Yes	Moderate

4. Conclusion

Despite progress in image segmentation programs for CMF surgery, several challenges and limitations persist. Recognising these challenges and drawing a path toward future development is essential for improving the efficacy and reliability of segmentation tools.

As the field of image segmentation continues to develop, challenges, such as noise handling, integration, and validation, will be addressed through innovations in AI, standardised metrics, and personalised approaches. These advancements will undoubtedly reshape the landscape of CMF surgery, enabling continued progress in patient care and surgical excellence.

This literature review highlights the medical software frequently used to segment bones in CMF region. However, further investigation is required to examine the accuracy of these software programs.

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مراجعة منهجية لبرامج تقسيم الصور في جراحة الوجه والفكين

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المستخلص

يلعب تقسيم الصور دورًا مهمًا في التخطيط الافتراضي والتنفيذ وتقييم الإجراءات الجراحية في مجال جراحة الوجه الفكين. تهدف هذه المراجعة المنهجية إلى تقييم ومقارنة برامج تقسيم الصور المستخدمة بشكل متكرر في هذا المجال. تم اعتماد استراتيجية بحث دقيقة لتحديد الدراسات المناسبة عبر عدة قواعد بيانات، باستخدام معايير إدراج محددة وكلمات مفتاحية ذات صلة. تم التحقيق في برامج تقسيم الصور التي تعتمد على تقنيات مختلفة، مثل تقنيات تحديد العتبات(Thresholding) ، وطرق تحديد الحواف(Edge-based methods) ، وطرق تحديد المناطق(Region-based methods) ، بالإضافة إلى الطرق القائمة على التعلم الآلي .
تم فحص النتائج وفقًا لبيان "عناصر التقرير المفضلة للمراجعات المنهجية والتحليلات التلوية(PRISMA) "، حيث تم تحديد ٩٤ دراسة تقرر اختيار الدراسات التي استخدمت التخطيط الجراحي الافتراضي في الفترة ما بين ١ يناير ٢٠١٤ و١ يونيو ٢٠٢٣. أجريت دراسة تحليلية لبرامج تقسيم الصور المحددة، مع التركيز على ميزات البرامج ونقاط القوة والضعف وأنواع الصور المدعومة والتطبيقات السريرية. تم إجراء تقييم مؤهل لهذه البرامج بناءً على معايير مثل دقة التقسيم، سرعة المعالجة، الصلابة، سهولة الاستخدام وقدرات التكامل مع البرامج الأخرى.
تناقش المراجعة أيضًا التحديات التي تواجهها برامج التقسيم الحالية وتحدد اتجاهات التطوير المستقبلية، بما في ذلك معايير التحقق القياسية ودمج الذكاء الاصطناعي.
تم تقسيم الإجراءات الجراحية إلى سبع فئات لتحليلها، وهي: إعادة بناء الجمجمة، تجديد الوجه، جراحة تقويم الفكين، إصلاح الإصابات، استئصال الأورام، إصلاح الشفة الأرنبية والحنك، وتصميم زراعة مخصصة للمريض .توجد العديد من البرامج التي يمكن استخدامها لتقسيم العظام في منطقة الفكين والوجه، إلا أن هناك ثمانية برامج تُعد الأكثر استخدامًا في هذا المجال. أظهرت النتائج أن حزمة برامج "Materialise"هي الأداة الأكثر انتشارًا لتقسيم العظام بنسبة ٥٠٪، تليها أداة "3D Slicer"تسلط هذه المراجعة الضوء على الأهمية الأساسية لتقسيم الصور في جراحة الفكين والوجه وتقدم رؤى قيمة للأطباء والباحثين لاتخاذ قرارات مستنيرة بشأن اختيار واستخدام برامج تقسيم الصور.