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***RESEARCH ARTICLE***

**THEROLE OF VIRTUAL DESIGN AND 3D PRINTING FOR RECONSTRUCTION:WORKING ALGORITHM AND ITS APPLICATIONS**

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***Abstract***

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Reconstruction of Maxillofacial defects following complex resection is common challenge encountered by many maxillofacial surgeons.The important objectives are to restore the normal anatomy and function with proper adaptation in these complex defects. The introduction ofcomputer aided design (CAD) and 3D printing technology has significantly facilitated greater predictability with improved efficiencies in surgical procedures and prosthetic reconstruction. This paper reviews the concept of virtual surgical planningand 3D technology in surgical proceduresand its broad clinical application in oral & maxillofacial surgery.



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## Introduction:-

Modern virtual surgical planning and 3D printing technologyhas significantly facilitated the outcome of various maxillofacial complex resection procedures by preoperative fabrication of surgical guide, 3D printed model surgeryresulting in tactile feedbacks greatly enhance the understandingof anatomical details, especially the spatial relationship of surrounding structures[1,2].

Computer aided design (CAD) and 3D printing technologies contributed in rehabilitation of such defects corrected throughreconstruction ofmaxillofacial customized implants, patient specific implants (PSI), postoperative fabrication of surgical guides for implant retained prosthesis etc [3-5].

VSP is a pre-operative planning which includes the visualization of a surgical procedure in a 3D imaging computer software. There are several advantages of VSP, including improved diagnostic accuracy and additional benefits to simulate the surgery in the virtual environment [6-8]. This can facilitate the surgery with cutting or drilling guides which accurately fits to the anatomical landmarks fabricated through different kinds of medical imaging technologies includingCT, CBCT, MRI, intraoral scanners, ultrasound etc. In some occasion it may necessitate to combine different imaging methods by data fusion [9,10].

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## A description of the work-flow for virtual planning in Cranio-Maxillofacial Surgery

The steps in virtual planning are dependent on the specific applicatione.g:-orthognathic surgery,CMF reconstruction, trauma, dental or craniofacialimplants, but a typical work flow consists of the following steps:

1. Image modality
2. Data acquisition (CT/CBCT, intraoral scanning, 3D photos).
3. Image processing including segmentation.
4. Preoperative planning and virtual surgery.
5. Guide/template/PSI design.
6. Guide/template/PSI manufacturing via Rapid Processing (RP).

Selection of appropriate imaging technique is most important step. It depends on two important quality of imaging data i.e spatial and contrast resolution.Spatial resolution in CT is the ability to distinguish between object or structures that differ in density i.e nerve canal within the mandible.Contrast resolution refers to the ability of any imaging modality to distinguish between differences in image intensity i.e fat strandings vs normal adipose tissue [11]. The inherent contrast resolution of a digital image is given by the number of possible pixel values, and is defined as the number of bits per pixel value.

Computed tomography (CT)scanning - high spatial resolution but limited contrast resolution.
Cone beam computed tomography (CBCT) –high spatial resolutionwith less radiation exposure at the cost ofpoorcontrast resolution [12].

Due to above characteristics, CT scans are recommended for oral and maxillofacial cases as it involve bones and teeth.MRI is indicated, if detailed soft tissue evaluation is required as it has superior contrast resolution compared with CT scans [13].

Depending on the complexity of the case, intraoperative navigation and finalconfirmation with an intraoperative CT may be an addition to the presentedalgorithm. Figure 1 shows an exampleof a standard workflow for a commerciallyavailable VSP system.

The image data is imported in a Digital Imaging and Communication inMedicine (DICOM) format into a VSP software. This can be a commercialsoftware, such as Materialise, Planmeca or Brainlab. The planningmay be based on the communication with a computer engineer or via an inhousesolution where the surgeon performs all the relevant processing andanalysis steps in the workflow. Before the planning and simulation can start, it is important to perform different kinds of image processing steps, including reorientation of the CT data, segmentation of the anatomical structures of interest (e.g., skull, mandible, teeth, soft tissue, nerves and vessels).

In planning for orthognathic surgery, the next step is to create a composite model of the skull with all necessary information. Currently, none of the existing CMF imaging techniques can capture a competent 3D model of all structures (e.g., facial skeleton, dentition and soft tissue) with the quality required. Hence, there is often a need for combining and merging different 3D imaging techniques. The virtual model of the skull can then be used to simulate surgical situations and perform measurements. The pre-processing steps and merging of different imaging sources are normally performed by a computer engineer/scientist and need to be approved by the surgeon before the relevant guide or implant can be designed and manufactured.

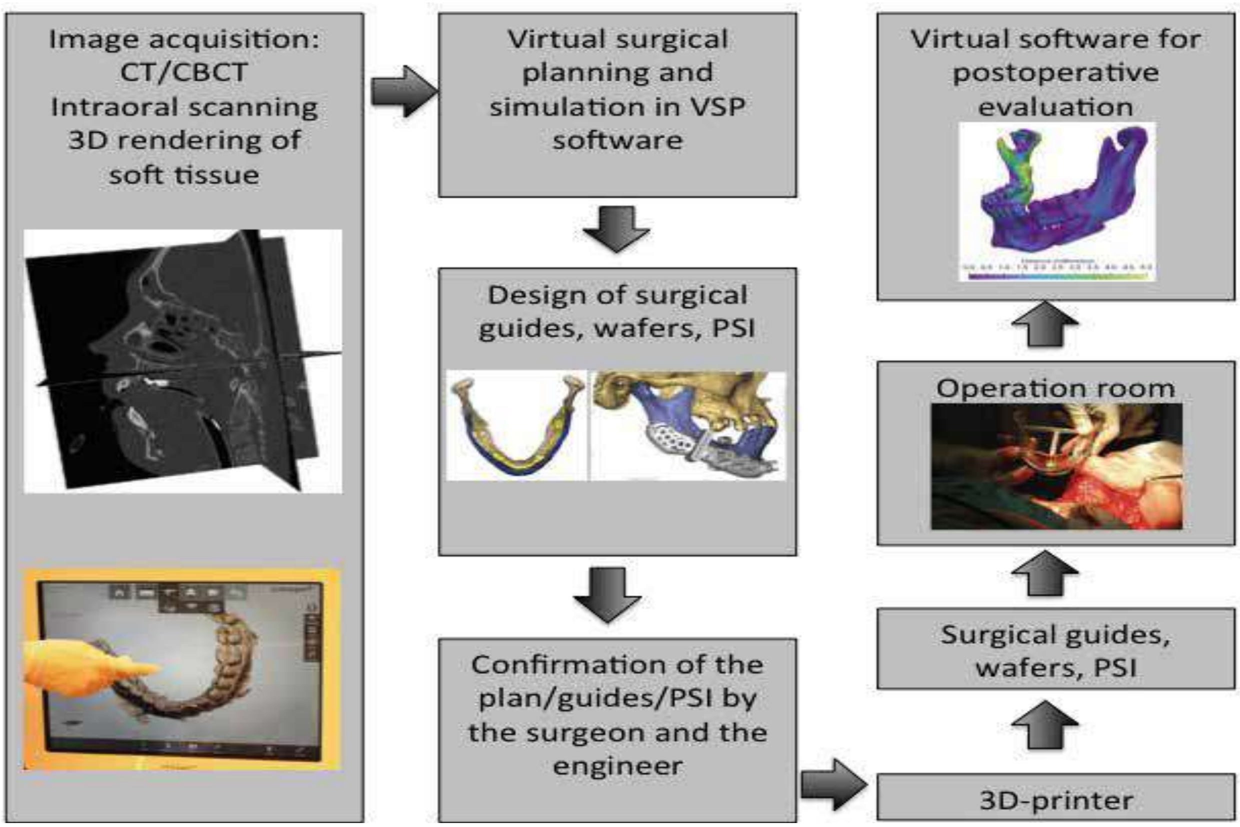


**Figure 1**:- An example of a standard workflow in VSP.

It is a substantial challenge to have an efficient work-flow and communication in VSP. Likewise, it is crucial to develop a fast and reliable protocol given the greaterurgency often required when working with trauma and oncological cases. The costs for using VSP are significant, both when done with an external partner, as well as investing in and maintaining an in-house setup. This concerns investments into software, hardware for production of models, guides and patient-specific implants (PSI) [6].

**Clinicalapplication virtual surgical planningand 3D printing in Maxillofacial surgery**

Maxillofacial surgery has witnessed greater progress following introduction of VSD and 3D printing.VSP have been used in various procedures including maxillofacial trauma, orthognanthic surgery, total joint replacement (TJR) pathology and reconstruction. From complex facial skeleton reconstruction to improvement of aesthetics and functional performances is extremely challenging.Following acquisition of the patient's anatomy using required imaging technique, a patient specific treatment plan could be designed. VSP coupled with surgical navigation is noted to be most useful in in orbital reconstruction owing to the limitations insurgical access, the relationship to surrounding vital structures, and the strict demand for function and aesthetics of the eye[14].VSP is ideal for orthognanthic surgical planning as it provides precise and predictable movements compared to model surgery [15]. VSPguides resection marginsin maxillofacial pathologies along with visualisation of vital structuresand designing cutting guides to prevent inadvertent injury.

**Table 1:-** Summary applications of VSP and 3D technology in oral & maxillofacial surgery.

| | Application | References |
|---|---|---|
| Maxillofacial trauma ModelMid face–30-32 Mandible - 19 | Pre-bendingof fixation plates on | Orbit - 16-18, 20-24 |
| | Customized plate fabricationbased | Orbit -29 |

| | | |
|---|---|---|
| | on VSP | Mid face–30, 33 |
| Mandible- 25, 26-28 | | |
| Orthognanthic surgery | Composite models | 34,35,36 |
| Splints and cutting guides | 37-42 | |
| Tumor resection | Osteotomy guides | 43, 44-45 |
| Total joint replacement | Design of cutting guides for TJR | 46-49 |
| | VSP and custom made implants | 50, 51,52 |

**3D planning andprinting technology in maxillofacial trauma**

VSP provides the direct 3D visualisation of complex fracturesby fabrication of 3D model and appropriate plan can be instituted by 3D manipulation,Patient specific designs and customize bending of fixation plates for easy fixation and reduce the operative period[53].Jaime Castro-Núñez et. al [54] used virtual planning in two cases to reduce the fracture of severely atrophic mandible.The displaced segments were virtually reduced using mirror images and the midline of the maxilla. 3D models were fabricated for preoperative contouring of 2.5-mm reconstruction plates.Fracture segments were reduced and stabilized with 2.5-mm reconstruction plates under general anesthesia.Average treatment time for both patients was a little over 2 hours with good reduction.

Aditya Mohan Alwala et. al [55] treated pan facial trauma with multiple facial bones fracture treated by surgical planning on additive manufactured medical model to adapt the mini plates to be prior to the surgery [fig 2]. The operating time was reduced significantly and the adaptation of the mini plates was accurate. The pre-determined position also aided in good reduction of the bony segments and reduced the chance of postoperative plate breakage.

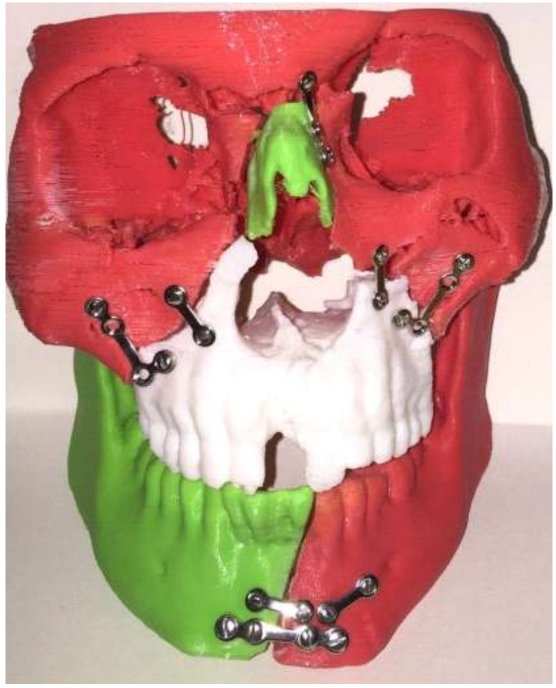

**Figure 2:-** 3D model by additive manufacturing and preoperative adaptation of miniplates.

Alan Scott Herford et. al in a case report of patient with orbital floor fracture treated with virtual surgical planning and custom-made implant used for orbital floor reconstruction [Fig 3], Postoperative CT showed excellent positioning of the implant, especially when compared to the unaffected side (Fig. 8). Both orbital and maxillary sinus volume and borders had been re-established.

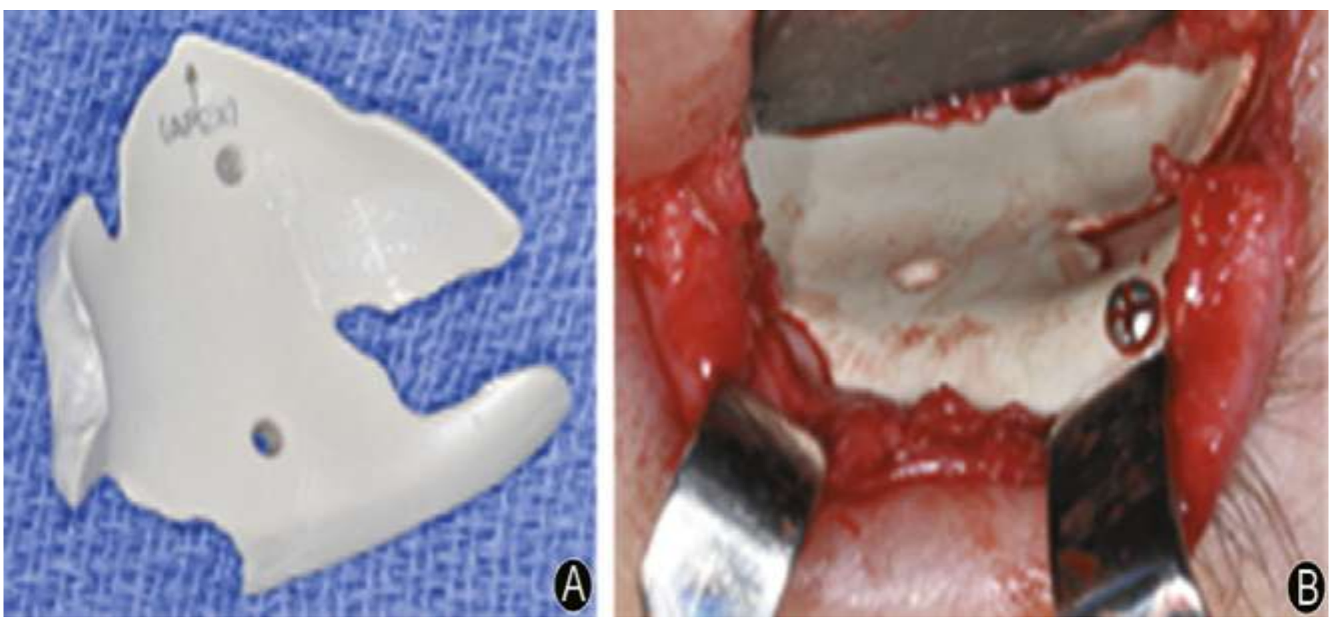


**Figure 3:- A:** Patient 3D implant, removed from the stereolithic model; **B:** The placement of the 3D implant in the bone defect.

**3D planning and printing technology in orthognanthic surgery**

Traditionally, 2D cephalogram dental cast models mounted on fully adjustable articulators, and face-bow registration were used for surgical planning [57].However, the manual-based procedures are time-consuming and have shown non-controllable errors and interlaboratory differences.Compared to the traditional method, the digital-based occlusal splint provides high accuracy, reliability and consistency, as well as improved quantitative control and efficiency. Custom osteotomy guides can be designed to achieve surgical maneuvers that are as close to the 3D planningguides can be designed to achieve surgical maneuvers that are as close to the 3D planningandreproduce the desired occlusal relation, perform the osteotomies and retain both the maxillaand the mandible in their new positions until the designed plating is attached.

Sang-Jeong Lee et. Aldeveloped the complete digital workflow fororthognathic patients [fig .4]provides efficient and streamlined procedures for orthognathic surgery andshows high surgical accuracy with efficient image data sharing and close collaboration [58].

Nan Zhang et. al [59] studied 30 patients for accuracy of VSPtwo-jaw orthognathic surgery via quantitative comparison of preoperative planned and postoperative actual skull models. He concluded thatvirtual surgical planning and 3-D-printed surgical templates facilitated the diagnosis, treatment planning, and accurate repositioning of bony segments in two-jaw orthognathic surgery.

Zavattero Emanuele et. al [60] conducted a study to test the accuracy of computer-aided orthognathic surgery comparing the virtual surgical planning with the three-dimensional (3D) outcome.An overall high degree of accuracy between the virtual plan and the postoperative result was found.

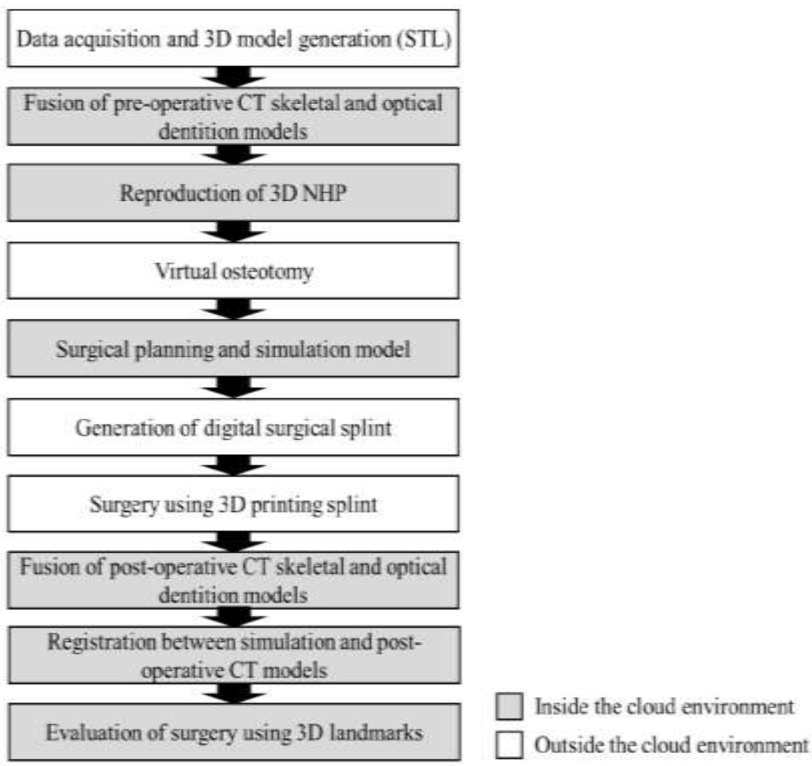


**Figure 4:-**Overall procedure used for orthognathic surgery using a 3D printing splint with fullydigitalized planning, simulation, and evaluation.Abbreviations; STL- Standard triangle language, NHP- Natural head position.

**3D planning and printing technology inMaxillofacial pathology/ tumor resection and reconstruction**

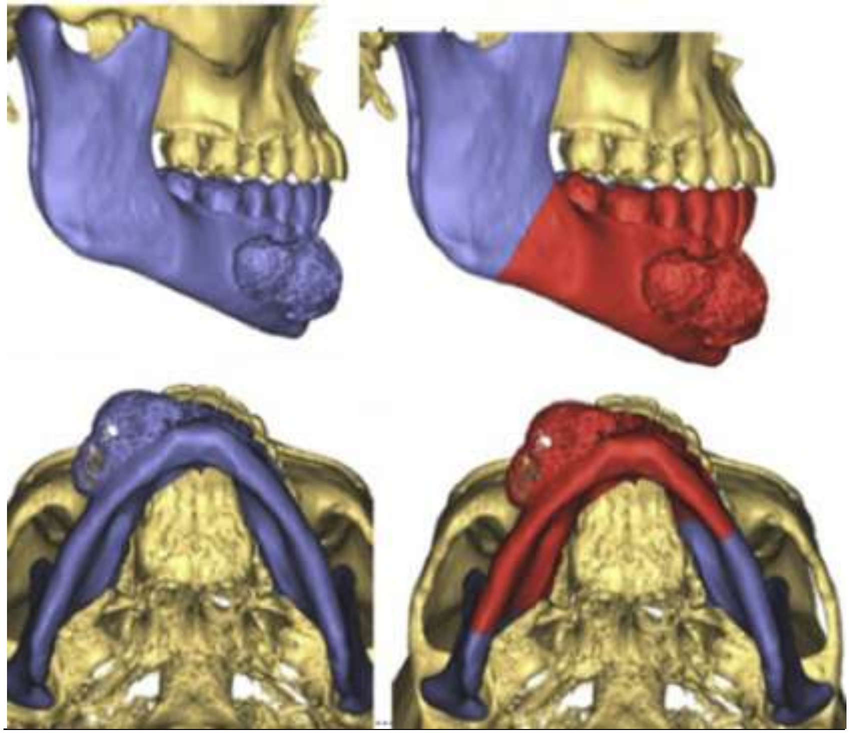

**Figure 5:-** The resection margins are defined and viewed on virtual model.

VSP is used in managing maxillofacial pathology/tumor due to its ability to virtually visualize pathology and guide the location of resection margins [fig 5]. This application is especially valuable for surgical resections of the midface and large tumors that have altered anatomical landmarks [61-63]. Challenges associated with midface pathology include the difficulty of removing tumors within the maxillary sinus or nasal cavity, where osteotomies are often performed without direct visualization of the tumor. Surgical planning allows for greater confidence in performing such resections when visual cues are absent. Additionally, cutting guides can be designed with consideration for the proximity to vital skull base structures, thereby minimizing the risk of inadvertent injury. The integration of real-time 3D navigation and VSP further enhances these benefits by providing immediate feedback to confirm the position of guides and planned osteotomies.

Current studies demonstrate the benefits of VSP and navigation by reporting a statistically significant difference in 91% of patients in obtaining a clear margin along deep tumor margins with an accuracy of less than 5 mm difference of the actual resection margin compared with the planned margin [64,65].

Bernstein [66] and colleaguesand Foley and colleagues [67] compared 224 osteotomies madewith 3D-navigated virtual cutting guides and 224 without navigation and found that osteotomies made with 3D navigation to be more accurate.

**3D planning and printing technology in Maxillofacial pathology/ tumor resection and reconstruction**

Temporomandibular joint (TMJ) is often affected by a wide spectrum of disorders, including extra-articular and intra-articular pathologies which usually present with various clinical symptoms including pain in the preauricularregion, limitation of mouth opening, malocclusion,or jaw deformity [68, 69]. The former is typically managednon-surgically, whereas the latter is often managed surgically.Some of the intra-articular TMJ diseases, includingend-staged TMJ osteoarthritis, severe idiopathic condylarresorption, TMJ ankylosis, comminuted condylarfracture, and part of TMJ tumors, have to be treated bysimultaneously removing the lesion and joint together,with primary joint reconstruction to restore its anatomicstructure and function as much as possible.

Prosthetic total joint replacement surgery is theindicated treatment for severe degenerative joint conditions of theTMJ when conservative treatment is not effective. It reduces pain and restore jaw function of above mentionedconditions. The limitations of current commercially available prosthetic TMJ components is the limited capacity of standard implant sizes to conform to the wide range of jaw morphologies and bone pathologies that present clinically, while maintaining adequate fixation under physiological loading.

TMJ prosthesis preparation prior to surgerybyJiSi Zheng et. al [70]
**1.** CT scan of the entire mandible, maxilla, and TMJ for allpatients (0.625 mm slice thickness).

**2.** Processing CT data with DICOM format to createthe 3D craniomaxillofacial model in Mimics software18.0 (Materialize Co, Leuven, Belgium).

**3.** Cutting the lower part of the eminence and entirecondyle with the aid of Mimics software.

**4.** Designing the prosthesis (including the glenoid fossa,condylar head, and mandibular handle components)by using 3-Matic research software 9.0 (MaterializeCo, Leuven, Belgium). The main principles of theTMJ prosthesis design are focusing on the followingpoints:-

(1) The dimension and slope of the articularsurface of the fossa component are ascertained basedon the TMJ anatomy database. (2) The bony surface of the fossa partis customized to match the anatomic configurationof the glenoid fossa, zygomatic arch, and remainingarticular eminence; (3)The condylar head componentis cylinder-like shaped with a hollow structure, whichis perfectly fitted in with the predefined cone frustumon the top of the mandibular handle componentaccording to the machine taper connection mechanism[71,72](4) The inner surface of the handlecomponent is also customized to fit with the externalsurface of the mandibular ramus [73].

**5.** Manufacturing the three components of the prosthesis:The fossa component is fabricated from ultrahigh-molecular-weight polyethylene (UHMWP, GB/T19701.2) by 5-axis milling device (DMU60, DGM,Germany). The condylar head component is fabricatedfrom the cobalt-chromium-molybdenumalloy (Co–Cr–Mo alloy, YY0117.3) by 5-axis millingdevice. The mandibular component is fabricatedfrom titanium alloy (Ti6Al4 V alloy, GB/T13810) by a3D-printing machine (Arcam A1, MÖlnda, Sweden).
Then, all of the components are polished and themedial surface of the mandibular handle is treatedwith the sandblasting technique.

**6.** Fitting the prosthesis in the 3D skull model beforesterilizing and packaging: The three components ofthe prosthesis are fitted in the 3D model to checkwhether the stability and accuracy of each individualcomponent are the same with the models in Mimicssoftware.

**7.** Sterilization and packaging of the prosthesis: All TMJprosthesis components are provided clean and nonsterileand therefore, no additional cleaning prior tosterilization is needed. The glenoid fossa componentis sterilized utilizing ethylene oxide gas sterilization,and the condylar head and mandibular componentsare sterilized using steaming sterilization.

Afterward,The TMJ prosthesis components are repackagedagain. The simple processing procedure is showed in[Fig.6].

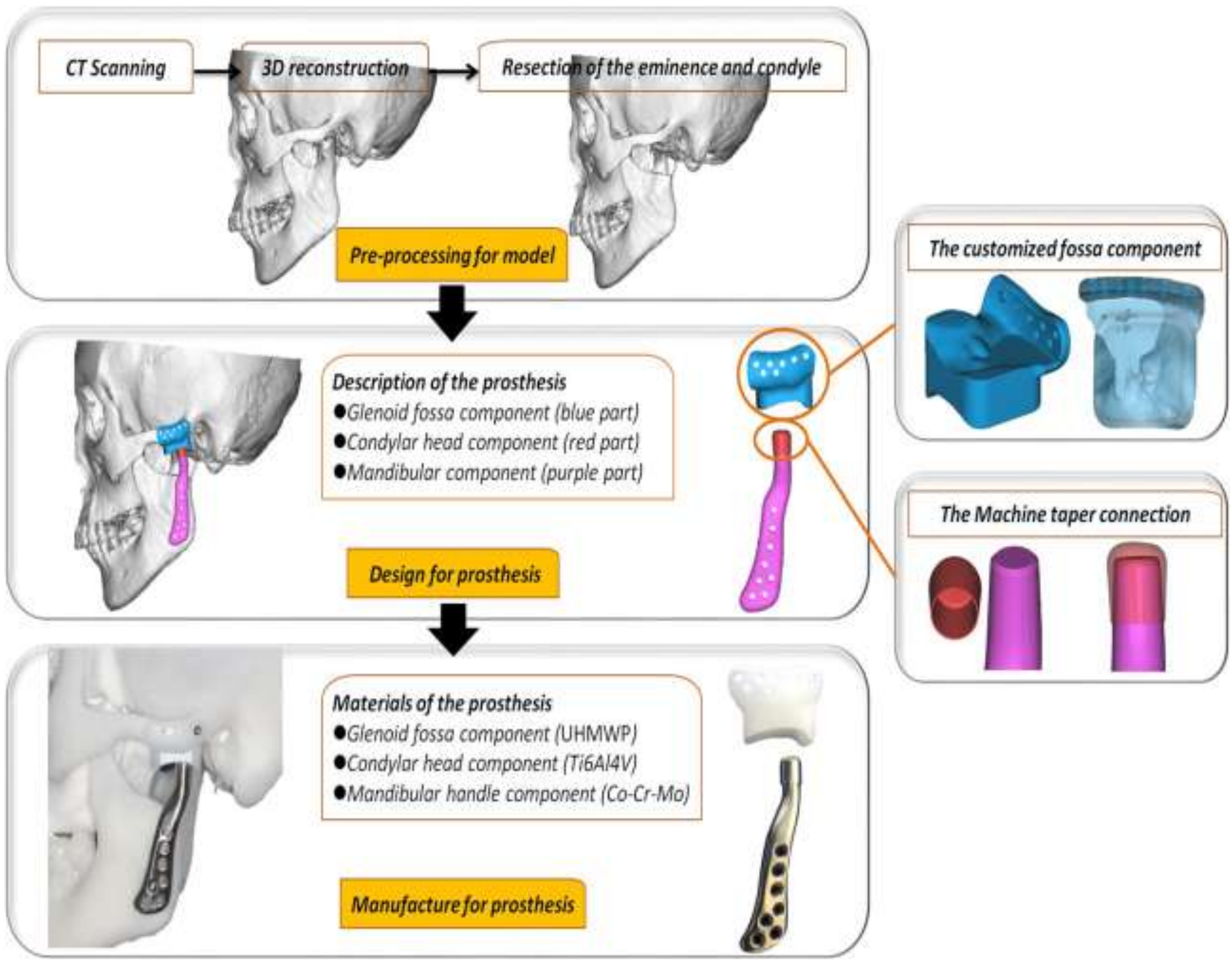


**Figure 6:-** The processing of the new TMJ prosthesis. [JiSi Zheng et.al].

David C. Ackland et. al designed customized TMJ prosthetic device in a 58 year old patient with modified design called ‘ Melbourne’ prosthetic TMJ designfor the patient with end stage osteoarthritis using VSP and 3D printing and concluded The maximum condylar stresses, screwstress and mandibular stress at the screw-bone interface were lower in the Melbourne prosthetic TMJ(259.6 MPa, 312.9 MPa and 198.4 MPa, respectively) than those in the Biomet Microfixation device(284.0 MPa, 416.0 MPa and 262.2 MPa, respectively) during the maximum-force bite, with similar trends alsoobserved during the chewing bite with no complication identified [74].

Xuzhuo Chen et. al evaluate the biomechanical behavior of 3D printed customized three-dimensional (3D)printing total temporomandibular joint (TMJ) prostheses by means of finite element analysisfrom CT imaging ofChinese patient with the end-stage osteoarthrosis in the right TMJ.The stress distribution on the custom-made total TMJ prosthesis and the strain distribution on the mandible were analyzed by loading maximal masticatory force. The results showed that customized 3D-printed total TMJ prostheses exhibit uniform stress distribution without changing the behavior of the opposite side natural joint [75].

**Future Prospective**

The existing computational tools for computer assisted surgical plannig lack sufficient precision, suffer from observer variability, and are prone to time-consuming processes [76].By incorporating artificial intelligence (AI)-based networks into surgical workflows, it is possible to overcome the limitations imposed by conventional computer-aided surgical planning (CASP) approaches. The utilization of AI, specifically machine and deep learning algorithms, enables the performance of cognitive functions that can reduce the workload of surgeons and greatly enhance the practice of precision medicine in CASP[77–79].

However, the implementation of AI-based CASP is currently limited to specialized hospitals due to the complexity of software programs and the requirement of experienced staff in both medical imaging and maxillofacial surgery [80,81].

## Limitations

The implementation of 3D technologies in implant design and manufacture is ushering a new revolution into the OMFS field. The advantages of the 3D-based revolution in OMFS are obvious and well-established: efficiency, accuracy and reaching an optimal clinical outcome.

Barriers to the effective use of VSP are associated with the inherent delays associated with current manufacturing capabilities and human error. The turnover between VSP planningsession to delivery of implant/guides can range between 7 to 14 days for pre-bent and milled hardware, whereas 3Dprinted plates and laser sintered hardware canbeproduced in14to17days.These limitations are due to the logistics involved in the processing, quality control, and transportation of the prostheses.

## Compliance with Ethical Standards

**Conflict of interest:**
The authors declare that they have no conflict ofinterest.

**Ethical Approval:**
The ethical clearance for conducting the study was obtained from ethical committee of the institution.

**Informed Consent:**
Informed consent was obtained from all individual participants included in the study.

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