



Reverse Engineering Techniques for Virtual Reconstruction of Defective Skulls: an Overview of Existing Approaches

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ABSTRACT

The surgical process adopted to repair cranial defects using an implant, typically called Cranioplasty, has seen an abrupt increase in recent years due to the introduction of Reverse Engineering (RE) and Additive Manufacturing (AM) techniques. By adopting these techniques, CT/MRI data can be used to reconstruct, in a pre-operative stage, the 3D anatomy of the defective skull in order to design a patient-specific digital model of the prosthesis. The so-designed cranial plate can be then fabricated via AM, in a suitable metal alloy, and implanted. This allows for a perfect fit of the implant during the actual surgery, reducing the risks for the patient and increasing the efficacy of the treatment. This paper reviews existing approaches for the virtual reconstruction of defective skulls, and a basic classification, proposing four different classes of strategies (Mirroring, Surface Interpolation, Template-Based and Slice-based techniques) is provided. The findings of the study suggest that the reconstruction of skull defects is still an open problem, due to the complexities imposed by surface that needs to be retrieved (i.e. the human anatomy). All the presented approaches share weaknesses and limits, which are discussed in the article. Finally, possible directions to improve the existing techniques are briefly presented.

Keywords: Reverse Engineering, Biomedical Engineering, Skull Reconstruction, Cranioplasty.

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1 INTRODUCTION

Nowadays, Reverse Engineering (RE) and Additive Manufacturing (AM) techniques are pushing the boundary of cost-efficiency, convenience, and customization in medical applications [36, 37, 43]. The ability to generate 3D models from patient data allows to create preoperatively custom prosthetics and implants. This approach represents a radical evolution for surgical planning and simulation on the patient-specific anatomy.

For these reasons, clinical applications of these technologies are actively being investigated and considerable developments were recently achieved [15, 33].

Despite the potentialities, there is still a long way to overcome existing technical and ethical difficulties for being considered standard techniques when applied in the medical field [34]. An important factor that limits the application of RE & AM in medicine is the amount of time and effort required to segment and reconstruct the region of interest (ROI). Time spent in postprocessing reduces the cost-effectiveness of using these approaches and limits their usefulness. In the typical framework, ROI is processed and reconstructed with advanced RE techniques starting from standard diagnostic imaging such as Computed Tomography (CT) and Magnetic Resonance Imaging (MRI). In particular, the geometric reconstruction of anatomical surfaces, able to fit a patient-specific ROI, is one of the most addressed research topics.

In this context, the present study aims at exploring existing algorithms to reconstruct the anatomical shape of defective skulls. A defective skull can be the result of a trauma or a surgical craniotomy (e.g. for a tumor) and is usually treated with the aid of a cranial implant (i.e. cranioplasty).

The digital reconstruction of the missing skull surface is a fundamental step for defining the cranial implant and, therefore, it has been tackled by several studies. The attainment of a valid reconstruction is fundamental not only for functionality but also for aesthetic and psychological reasons.

All the methods available in literature share the typical framework for the computer-aided design of any medical device that is shown in Fig. 1; different data sources can be exploited during the shape reconstruction phase (i.e. DICOM or STL files). Therefore, this work is focused only on the surface reconstruction task given for assured the availability of a 3D model (e.g. stl file) or a set of 2D slices (DICOM file).

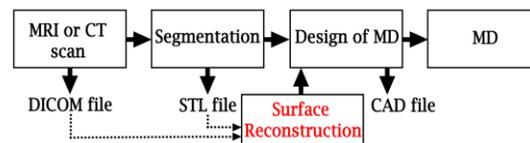


Figure 1: Typical Medical Device (MD) CAD framework.

Most representative works analyzed in this review fall under four main categories, depending on the reconstruction strategy adopted: (1) mirroring; (2) surface interpolation; (3) deformed template; (4) slice-based reconstruction. Accordingly, the following sections adhere to this classification in order to present an organized description of the state of the art. It is important to note that most of the presented methods, due to the highly complex structure of human skull, can only be used for the reconstruction of the cranium vault.

2 MIRRORING-BASED METHODS

Historically, research investigating the reconstruction of skull defects has first focused on the exploitation of the skull symmetry, w.r.t. the sagittal plane, to retrieve missing geometry. This approach, called “mirroring”, proposes the reflection of the non-defective side of the skull onto the defective one to reconstruct the missing surface (Fig. 2). The first systematic mirroring approach was presented in literature in the early ‘90s [30]; the authors describe several medical applications for 3D anatomical digitized data and assess the potential advantages attainable by applying the mirroring technique in cranioplasty, for the generation of titanium implants.

More recently, interesting case studies are presented in [31] and [14]. Both the papers present the results obtained applying state of the art RE software tools to: 1) process the original STL data, 2) identify and mirror defective parts of the skull and 3) wrap the healthy surface upon the defect to produce the final result. Boolean operations are used in [31] to isolate the set of points required to reconstruct the defective area.

The usefulness of the mirroring-based approach, regardless of its simplicity, is proved by the wide number of works using this method [1, 6, 17, 23, 25, 26, 39]. Unfortunately, the typical implementation of the method requires several manual operations that are the computation of the symmetry plane, the isolation of the healthy region corresponding to the defect, and the adjustment of the reconstructed patch on the defective side of the skull. These operations are not trivial since the human skull is not perfectly symmetrical. In this context, most recent research is oriented towards the development of advanced strategies for the automatic identification of the symmetry plane in highly asymmetrical anatomies [10], and for the adaptation of the reconstructed patch upon the defective area. With

this respect, an effective smoothing strategy has been recently presented in [13], where a Laplacian smoothing, combined with a Delaunay triangulation, is used to retrieve the patch of the missing part.

It is important to note that some elements severely limit the efficacy of the mirroring-based approach: firstly, it can be applied only with reference to the treatment of unilateral skull damages. Whenever the defect crosses the sagittal plane, no useful geometry information can be extracted from the original data. Moreover, in all cases, the procedure relies on a user for its execution and its steps, which cannot be easily automatized, are time-consuming.

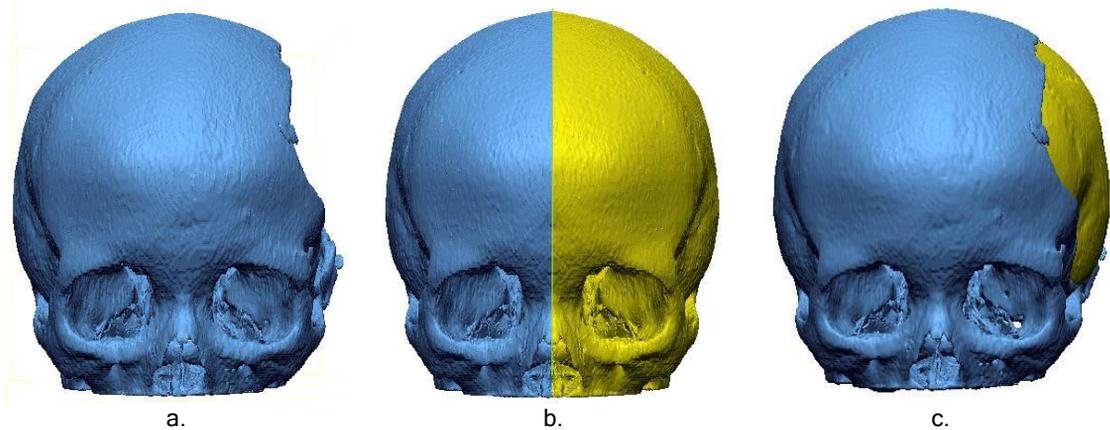


Figure 2: Example of the results obtained applying the “mirroring” approach: (a) the starting defective skull; (b) the reflection of the non-defective side; (c) the reconstructed patch (in yellow).

3 SURFACE INTERPOLATION-BASED METHODS

A different approach is based on surface interpolation. It pursues the generation of a smooth approximation of the skull shape across the defect region. The result is a mathematical surface characterized by a certain degree of continuity w.r.t. the defect edge.

For the specific geometry of the skull and the defect boundaries, the interpolating function must be able to work even when the interpolation centers do not form a regular grid. Furthermore, for ensuring a coherent reconstruction, the surface must provide at least a C1 continuity in order to avoid creases. For these reasons, Carr et al. [3] and Zhou et al. [42] indicate the Radial Basis Functions (RBFs) as an appropriate choice due to the few restrictions imposed on the geometry of the interpolation centers and its capacity to guarantee a C1 continuity. In [3], RBFs are fitted to depth maps of the skull’s surface, obtained from CT data using ray-tracing techniques. In particular, the surface interpolation uses the vertices of the defect’s boundary region as the centers of the RBFs. Carr identifies in the Thin Plate Spline (TPS) the best choice among the RBFs alternatives, since it “is the smoothest C1 interpolant in the sense that it minimizes the energy functional”.

As an alternative, other authors propose different approximation methods for the skull reconstruction.

Chong et al. have proposed in [7] a semi-automatic hole repairing algorithm using quartic Bézier surface approximation starting from an initial triangulation obtained with a genetic algorithm. The method starts with the hole identification, by simply checking for connected boundary edges that form a closed loop. Then, the triangulation of the defected area, using a genetic algorithm, is performed to obtain a guide for the subsequent approximated Bézier Gregory patch. At the end, triangular meshes are created using a customized advancing front method and projected to the Bézier surfaces.

These approaches guarantee the main advantage of ensuring the continuity at the boundary. Furthermore, the resulting surface is mathematically defined, so it could be evaluated at any desired resolution. Despite these advantages, a significant limitation for interpolation approaches is the lack of constraints inside the defect region. For this reason, [3] and [7] highlight that the surface near to the defect margin has less reconstruction errors with respect to the center. Usually, the larger is the hole, the greater is the internal error. To partially overcome this drawback for large holes, [3] suggests the partitioning of the defect. Alternatively, the use of a template to provide information on the curvature inside the defect is suggested in [7]. Even using these strategies, however, the surface interpolation-based methods are not able to properly reconstruct large defect areas.

The same issue is described in [24]; the paper highlights that, dealing with large holes, it is usually impossible to control the shape only with the boundary points. As a result, the reconstructed surface results flat (see the example of Fig. 3). Therefore, they use the points around the hole to get the shape of the adjacent area and generate the surface, and then adjust the insertion points in this surface to generate the new points. Finally, they repeat the two steps to adjust the shape and repair the holes. They also adopt a template matching method to repair particular part (e.g. nose shape).

A different surface interpolation approach based on NURBS is presented in [4]. The authors start with an initial mesh of the patch surface defined over the skull defect area. The mesh points might be obtained either from points mirrored on the opposite side of the skull or from points sketched by doctors. By interpolating such mesh points with NURBS surfaces, a NURBS-format patch is obtained. Accordingly, the patch reconstruction requires a strong user interaction.

Several commercial reverse engineering software offer holes-filling tools based on the surface interpolation methods [38], but the problems faced are the same of those discussed above: the wider the hole, the flatter the reconstructed patch is.

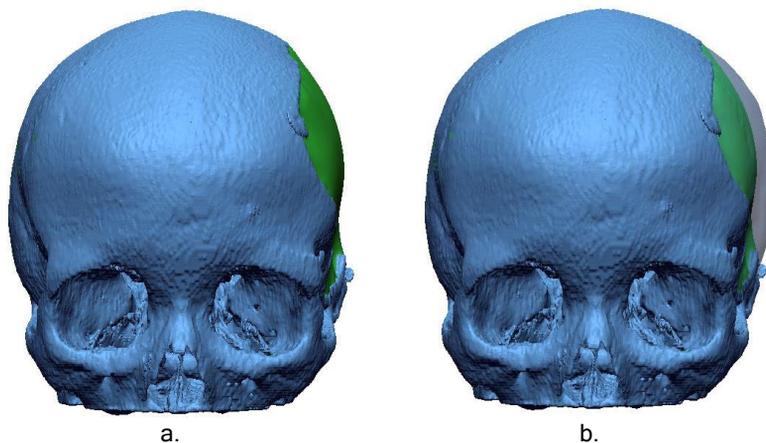


Figure 3: (a) the defective part reconstructed by surface interpolation can lead to a too flat patch; (b) the comparison between the patch obtained with the surface reconstruction technique (in green) and using the mirroring technique (in transparency).

4 DEFORMED TEMPLATE-BASED METHODS

This class of methods makes use of an a-priori generated 3D template of the human skull to model the missing cranial area. Typically, the template is extracted from a database of 3D skull models using statistical tools (e.g. Procrustes analysis [20]) and/or cephalometric analysis [21]; as a result, a reference shape for the cranial vault is obtained and can be used to guide the reconstruction of the region of interest. The adaptation of the template upon the defective skull is typically guided by suitable landmarks, which map the two models. Several strategies, which differ in the algorithms and mathematical tools used for the adaptation as well as in the level of user interaction required, can be identified at the state of the art.

Marreiros et al. [32] propose an approach based on geometric morphometrics to guide a surface interpolation that is performed using RBFs. For unilateral defects, the healthy symmetrical surface can be used as a template, hence realizing a hybrid mirroring/deformed template-based method. Alternatively, a database-extracted template is required. Their approach is specifically tailored for the reconstruction of large defects (i.e. $>100 \text{ cm}^2$). The process starts with a manual segmentation of the original CT data, performed to isolate the cranial bone as well as to remove artifacts and small bone regions. Subsequently, anatomical landmarks need to be placed upon the defective skull. Seventeen standard landmarks (see Fig. 4) are manually identified; starting from this initial set, additional landmarks are mapped on the cranial surface using a ray-casting approach. Symmetry and/or template geometries are used for the generation of landmarks in the defective region, by means of a Thin-Plate Spline (TPS) relaxation process. Obtained landmarks are interpolated by 2D RBFs, allowing “the construction of a depth map

centered at the (manually selected) missing landmarks of the defective skull". The generated surface is then used to create a mesh that closely fits the defect boundary.

The method presents two principal limitations: the defect area needs to be properly covered by an appropriate number of landmarks, and it needs to be described by a well-defined perimeter in order to avoid leaking effects. Moreover, the deformation process proves to be computationally expensive.

A similar approach is presented by Dean et al. in [8, 9]; the authors make use of a TPS-warp algorithm to map a template skull surface image upon the defective one. The process starts with a semi-automatic identification, based on manually selected landmarks, of the defect margins. A set of globally located skull landmarks, identified on both the defective skull and the template, are used to guide a first-pass warp operation that adapts the template onto the defective cranium. An additional set of landmarks, located in the defect area, is automatically generated via ray-casting and used to guide a second warp operation, thereby improving the result. In order to avoid the flattening of the patch, additional landmarks, extracted from the template, are added inside the defect area.

An alternative approach, with respect to TPS-based ones, is presented by Wu et al. in [40]. The authors propose an anatomical-constrained deformation process based on radial scaling. Both mirroring and a 3D retrieval approach, performed using a database of skull models, are considered as possible sources for the reference template model used to guide the reconstruction. A statistically-evaluated "average skull" is not considered by the authors. The paired point matching method is then used to guide the binding of corresponding landmarks between the defective and reference models. Alternatively, a user-guided approach could be adopted. The actual deformation is performed adaptively at each point: using known radial distances of corresponding landmarks, the authors compute local scaling factors. Finally, scaling factors of the defect area points are estimated via interpolation and used to compute the missing surface.

A significant attempt towards the automatization of the reconstruction process is proposed by Fuessinger et al. in [16]. In particular, a statistical shape model (SSM), able to minimize the manual interaction required by a surgeon for the creation of cranial implants, is proposed. The method is based on a manual approach to attain the identification of the defective area and to place landmarks on the patient skull. These are used to map the skull to a database of 131 CT scans of healthy crania. Using the landmarks correspondences, the target surface is aligned to the mean shape of the SSM; an iterative closest point (ICP) algorithm is used to refine the alignment. A new SSM, evaluated on a subset of skull shapes characterized by minimal deviation w.r.t. the patient skull, is then generated. The SSM is subsequently refined using an elastic ICP based on smoothed displacement fields. The final model is obtained by fitting the SSM to the target model using a TPS deformation guided by additional semi-landmarks.

Overall, the studies presented in this section provide evidence that template-based approaches are the most suitable for the reconstruction of large holes in the skull and represent a valid strategy to tackle bilateral defects. By adopting this strategy, a possible notable lack of information in the patient CT data is well-compensated by external sources. On the other hand, the performances of this approach highly depend on the quality of the template model and, specifically, by its similarity to the patient skull. Albeit significant efforts have been spent to improve the automatization of template-based processes, the human interaction remains essential. For instance, all the presented processes rely on a manual selection of landmarks. Moreover, given the lack of objective techniques for the placement of reference points, this step is prone to introduce alignment errors.

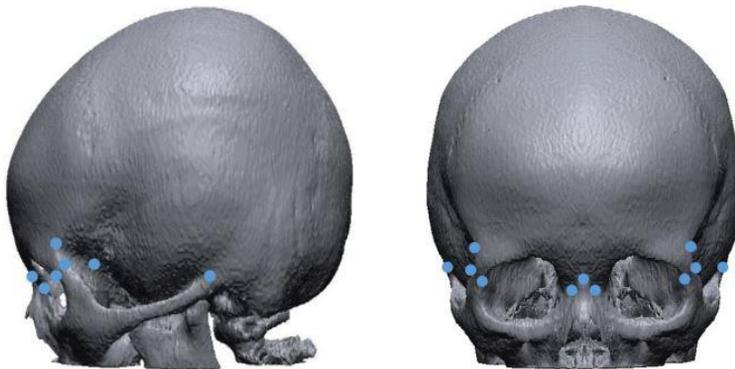


Figure 4: Anatomical Landmarks (blue) used in [32].

5 SLICE-BASED METHODS

The last class of methods adopts a slice-by-slice approach for reconstructing the skull defect. The original 2D diagnostic CT slices are used to extract the bone contour. The idea is to push a mathematical curve to fit the bone contour by minimizing the energy of a functional (see Fig. 5 for an example). Since in the single slice the geometry of the skull is almost elliptical [35], the curve in each image can be modeled starting from an oval shape.

As widely recognized, the Active Contour Models (ACM), also known as Snakes, are evolving curves driven by a minimization of the internal and external energies. The characteristics of ACM enable the generated curve to closely match the skull border. Liao et al. in [27] and [28] successfully applied ACM for medical application, but the authors mainly use Snakes in image segmentation and noise elimination rather than directly for skull modeling. The actual surface reconstruction is based on a multiresolution image registration between the defective skull and a previously-acquired CT image of the intact patient one. Evidently, this approach can be applied only whenever a CT scan of the healthy skull of the patient is available.

To the best of authors' knowledge, the only works that use Snakes for the skull modeling are [5] and [29]. After filtering out the inner and outer skull borders, in each CT slice suitable arcs can be computed using snakes. Finally, all the previously processed CT images are stacked to build the 3D skull model.

An approach based on ellipses that is capable to perform a self-adjustment upon the bone curvature is proposed in [2, 35]. These methods propose a Particle Swarm Optimization algorithm [32] and Genetic Algorithm [2] adjustment in order to find the best solution for each tomographic slice. Both the papers propose the concept of "super-ellipse" to recover the parameters fitting the skull shape in each CT slice. The arcs describing the missing bone shapes for each slice are recovered from the final configuration of the ellipse. Once the solution is found for each slice, the whole 3D missing information can be virtually rebuilt. An important open issue for this method is the "union problem" between healthy bone and reconstructed patch.

Another approach is proposed by [41], who apply Level Set Functions. A new hybrid level set model based on edge and region information (without re-initialization) is proposed in the article. The processed image is segmented using the novel hybrid level set method according to the skull and brain tissue information to obtain the complete inner contour of the skull. The outer contour is obtained starting from the initial curve by means of an offset operation. It needs to be pointed out that, by using the brain tissue profile resulting from the segmentation to determine the skull shape in the defect area, acceptable result could not be achieved. In other words, depending on the patient' condition, the brain shape could not correspond to the desired skull inner contour.

In [18] a procedure to create outer surface meshes of intact bones, starting from 2D bone contour is presented. Considering each slice, the bone contour is classified according to three different variants of "loops". The classification is built depending on the distance between the start and endpoint of the loops, the percentage of enclosed polyline points, and the global/local property of the loop with respect to the entire contour area. A "loop removal" procedure to obtain close curves defining the outer shape of the skull bone is subsequently applied; such procedure is tailored for each type of loop identified for each slice. The algorithm automatically detects each defect zone. The defect is reshaped by a closed spline approximating the bone contour (using a periodic least-squares approximation method). A thin plate smoothing spline is then evaluated only for the enclosed surface entities. Starting from the spline set, a triangulated surface representation is built.

An alternative approach is defined in [22], where the missing bone is created by a 3D orthogonal neural network. For each CT slice, the inputs are the horizontal coordinate X_i of the healthy bone and the CT image number, that is transformed as spatial coordinate Z_i . After the neural network has been properly trained, vertical coordinate Y_i of the missing pixels within the defect are derived.

Despite the potentialities of this class of approaches, some of these methods are affected by the same problem discussed for the Surface Interpolation class, that is the lack of information inside the defect area. Consequently, whenever a large-hole reconstruction is faced, the information available only for the boundary, namely the curvature, is not sufficient for an effective reconstruction of the original shape.

6 DISCUSSION AND CONCLUSIONS

The aim of the present research was to survey the state of the art in defective skulls reconstruction starting from standard diagnostic imaging. Several strategies to address the problem have been identified and discussed. The proposed classification is based on four categories: mirroring, surface interpolation, deformed template, and slice-based reconstruction; evidently, a strict classification cannot be entire defined, as some methods [26, 32, 40]

exploit tools that could be referred to more than one strategy. For instance, the mirroring strategies are widely used to extract missing data on the defective area to be used as input in other techniques.

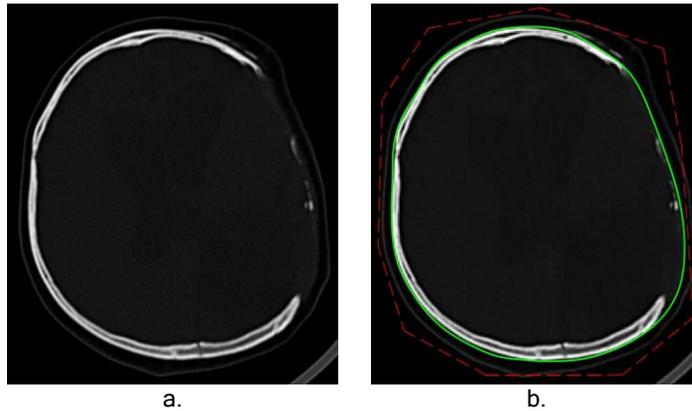


Figure 5: A slice in a TC of a defective skull (a) and the resulting boundary (green), fitted on the bone surface, obtained by ACM starting from a coarse approximation (red).

The findings of this study suggest that the problem is still open, as proved by the recentness of published works. Indeed, a definitive solution has yet to be found, as all of the proposed approaches are affected by significant, although different, drawbacks (see Tab. 1). A fundamental condition for the application of most methods is that a previous definition of complex geometric reference features is required, i.e. the skull symmetry plane. Furthermore, the high user-dependency of existing strategies is another limiting factor. Future work, in this direction, could be oriented towards the implementation of automatic segmentation techniques (e.g. guided by ACM [19]). Evidently, the development of automatic techniques for all the tasks described in this paper (e.g. automatic landmarks positioning, as proposed in [11, 12] for other anatomical parts) is not trivial due to the complex surfaces that define the human skull anatomy and the lack of precise landmarks. Despite that, continued efforts are needed to make reconstruction approaches more accessible to the medical staff, automatizing the entire procedure, hence removing the need of a user with advanced CAD skills.

<i>Skull Virtual Reconstruction strategy</i>	<i>Strengths</i>	<i>Drawbacks</i>	<i>References</i>
Mirroring-Based Methods	<ul style="list-style-type: none"> • Simple and Effective • Exploits accurate patient data 	<ul style="list-style-type: none"> • High user interaction • Possibility of dealing only with unilateral defects • Continuity between the healthy skull and the reconstructed patch not assured 	[1] [6] [13] [14] [17] [23] [25] [26] [30] [31] [39]
Surface Interpolation-Based Methods	<ul style="list-style-type: none"> • Continuity between the healthy skull and the reconstructed patch is assured • Patch reconstructed with a mathematically-defined surface (retrieved data is not-discrete) 	<ul style="list-style-type: none"> • The wider the hole, the more difficult it is to reconstruct a correct shape of the skull because of the lack of constraints inside the defect region 	[3] [4] [7] [24] [42]
Deformed Template-Based Methods	<ul style="list-style-type: none"> • Continuity between healthy skull and reconstructed 	<ul style="list-style-type: none"> • High user interaction • High computational cost • Use of generic data as 	[8] [9] [16] [20] [21] [32] [40]

	patch. • Possibility of dealing with any kind of defect.	reference, not related to the patient	
Slice Based Methods	• Continuity between healthy skull and reconstructed patch is assured • Patch reconstructed with a mathematically-defined surface (retrieved data is not-discrete)	• Lack of the information inside the defect area • Need to stack the curves obtained slice by slice	[2] [5] [18] [22] [28] [29] [35] [41]

Table 1: Comparison of advantages and disadvantages of different Skull Virtual Reconstruction strategies.

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