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HIGH QUALITY GEOMETRIC RECONSTRUCTION OF HUMAN MANDIBLE

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Abstract
This paper explores the reverse engineering of the relationship between a lower tooth and the lower mandible, along with potential finite element analysis methods. The primary focus of the study is to develop a high-quality computer model of the mandible with precise, continuous spline surfaces and to subsequently examine the tooth-bone relationship using this more accurate geometric model. Many of the studies reviewed employ a highly simplified model, where the individual layers of tooth and mandible bone are not distinctly analyzed. In contrast, our research emphasizes the reverse engineering of the tooth's integration into the mandible, enabling us to decompose the model into layers and conduct a comprehensive computer simulation of the entire structure. This approach allows us to assign different material properties to various regions of the model during the finite element analysis. This procedure is done by using scanned 3D (3-Dimensional) data in a mechanical CAD system the PTC Creo 8.

Keywords:
reverse engineering, lower tooth, mandible, high quality, CT scan, NURBS curve, NURBS surface

1 INTRODUCTION

In medical imaging, geometric reconstructions are essential for visualizing and analyzing anatomical structures and functional properties of tissues [Fill 2011]. These reconstructions enable precise modeling of spatial structures based on data derived from various imaging modalities. The classification of medical geometric reconstructions can be approached from several perspectives [Giannini 2004]. One common approach is to classify based on the type of reconstruction method. For instance, Computed Tomography (CT) reconstructions utilize X-ray absorption data to reconstruct spatial structures and tissues visible in CT images. Positron Emission Tomography (PET) reconstructions, on the other hand, model and reconstruct the distribution and activity of isotopes based on PET images, while Magnetic Resonance Imaging (MRI) reconstructions employ signals measured in magnetic fields to reconstruct the spatial arrangement of tissues.

Another classification method is based on the type of reconstruction algorithm used. Iterative reconstructions iteratively determine the reconstructed image to fit the measured data, offering flexibility and accuracy, whereas analytical reconstructions use predefined analytical formulas for faster but potentially less adaptable image reconstruction. Reconstruction methods can also be categorized by their purpose. Anatomical reconstructions focus on reconstructing the anatomy of the human body, such as the brain or heart, while functional reconstructions target the spatial representation of tissue or organ functions, like metabolism or blood flow [Habelitz 2001]. Additionally, reconstruction methods can be classified based on the applied mathematical and physical principles.

Linear reconstructions use linear models for image reconstruction, while non-linear reconstructions employ non-linear models, providing greater flexibility for handling complex data.

Understanding these classifications aids in selecting the optimal reconstruction method for specific imaging tasks, thereby enhancing the accuracy and applicability of medical diagnoses and treatments.

The reverse engineering method and finite element analysis (FEA) are well-suited for this study because they allow for the precise reconstruction and detailed modeling of the mandible based on CT scans. Reverse engineering enables the accurate capture of the complex geometry of the mandible, ensuring that the model reflects the true anatomical structure. Finite element analysis further contributes by allowing us to simulate and analyze the mechanical behavior of the mandible under various conditions, providing insights into stress distribution and structural integrity [Christoph 2023]. Together, these methods facilitate a comprehensive understanding of the tooth-bone relationship, supporting the research goals of accurately modeling and analyzing the mandible's biomechanical properties [Dong-Xu 2011].

Bezier curves are pivotal in medical image reconstruction due to their capability to fit curves smoothly and accurately to points or contours in images. The process typically involves several steps, beginning with the selection of points along the image where the curve will be fitted. Once these points are identified, the Bezier curve is fitted by linking the selected points and positioning control points to shape and smooth the curve. The curve fitting process involves adjusting the parameters of the Bezier curve to match the selected points. After fitting the curve, there is usually a need to evaluate and refine it to enhance smoothness and accuracy by modifying control points. The fitted Bezier curves can then be applied in various tasks such as image segmentation and contour delineation, facilitating accurate reconstruction of structures in medical images, which is crucial for diagnostics and surgical planning.

Iterative PET image reconstruction is another advanced technique that enhances accuracy and image quality compared to traditional methods by iteratively refining the distribution and activity of radiotracers. The process begins with preparing data measured by PET detectors, which indicate the activity of radiotracers in the examined area. The reconstruction algorithm starts with an initial estimate of the activity distribution and continuously updates the image to better match the measured data. This iterative process is repeated until the reconstructed image closely aligns with the actual data. Iterative PET reconstructions are particularly useful in various medical applications, such as cancer research and treatment, where accurate imaging of tumor location and activity is crucial. They are also valuable in neuroimaging for diagnosing and monitoring neurological diseases like Alzheimer's and in cardiology for assessing heart muscle activity and blood flow. Thus, iterative PET reconstruction is vital for producing accurate and reliable images, contributing significantly to early disease detection and effective treatment planning.

2 PROCESSING OF COMPUTER TOMOGRAPHY IMAGES

Computed tomography (CT) images are detailed depictions of body parts or organs obtained during CT examinations. These images are created using X-ray radiation, which different tissues and organs absorb to varying degrees [Gradl 2016]. The collected data is processed by a computer and converted into 3D or 2D images, used by physicians for diagnosing and treating health problems [Tianran 2010]. Processing CT images involves several steps to extract valuable information about the examined area or organs.

The first step is data collection and preparation of scans. During CT scans, measurements of X-rays passing through the examined area are taken, and this data is digitally recorded to create multiple cross-sectional images for further processing. Image enhancement and reconstruction follow, involving noise reduction, image sharpening, and application of reconstruction algorithms to create three-dimensional images from cross-sectional data.

Next is image segmentation, where processed CT images are divided into different regions or structures, allowing the separation of different organs or tissues and a more accurate determination of their spatial arrangement. Image registration and alignment are often necessary to compare CT scans taken at different times or using different modalities, enabling the tracking of temporal changes and determining agreements or discrepancies between images.

Through the analysis of processed CT images, physicians obtain critical information about the condition of the examined area or organs, aiding in diagnosis and treatment planning. Quantitative analysis and research of processed CT images allow for evaluating anatomical and pathological characteristics, estimating therapeutic efficacy, and predicting disease prognosis. Advances in processing techniques help produce increasingly accurate and informative images, essential for managing and improving patients' health [Gradl 2016].

In both CT and magnetic resonance imaging (MRI), images are composed of voxels representing specific regions of the examined space, containing detailed information about the tissues or organs studied. The size and resolution of the voxel determine the image's level of detail and spatial resolution: the smaller the voxel, the more detailed the image, though this increases demands on image processing and storage.

Voxel-based morphometry is an image processing method that utilizes voxel elements in imaging. This method allows for the quantitative analysis of the morphology and size of the brain or other organs. The process begins with data acquisition and preparation, where CT or MRI scans digitally capture the three-dimensional arrangement of organs and structures. Image enhancement and processing involve noise reduction, sharpening, and other techniques to optimize images for further analysis.

Segmentation methods are then applied to separate organs and structures of interest, identifying different volumetric elements such as brain regions, tumors, or other anatomical structures. Morphometric analysis characterizes these segmented volumetric elements by quantitative features such as volume, surface area, shape, or other morphological parameters, enabling comparison and evaluation in various pathological conditions or diseases. Statistical analyses of quantitative morphometric data help uncover changes in organs, such as those due to aging or diseases.

Voxel-based morphometry is widely used in neurological research, diagnosis, and monitoring of nervous system diseases, as well as in assessing therapeutic efficacy. The method provides detailed information about the anatomy of organs and structures, contributing to the understanding and treatment of diseases.

3 3D PARAMETRIC RECONSTRUCTION OF MANDIBLE

In this article, we have created a high-quality solid model based on a CT scan. For scanning, we used a Gendex GXDP-800 machine and then used the Gendex VixWin Platinum clinical software to process the CT image. The purpose of the reconstruction was to provide a high-quality model that can be subjected to simulation studies in the future. Figure 1 shows the reconstructed mandible and lower teeth based on the CT scan in a 1:1 ratio. The scanned mandible is 107.7 mm wide, 72.5 mm high and 83.1 mm deep.

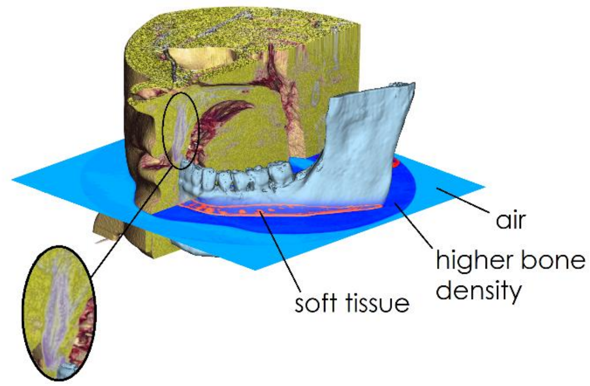

Fig. 1: The model of the mandible and lower dentition based on CT scan.

The visualization was performed using CT segmentation software. On the left side of the figure, the CT scan is displayed. The CT scan thoroughly scans the shape and captures points wherever material is detected, resulting in a three-dimensional image. Unlike 2D images, which consist of pixels, CT scans comprise spatial points called voxels.

In Figure 1, the image is composed of voxels, indicating that it consists of 3D points. The voxels have a very small extent, approximately one-tenth of a millimeter, creating a highly dense representation. The voxels in Figure 1 are color-coded. In CT scans, each point is assigned a shade, typically in grayscale. However, the medical software we used can determine the material properties associated with each grayscale shade. [Katarzyna 2022]

In Figure 1, the gray areas represent bony structures according to the material properties we set, the soft tissues are shown in yellow, and boundaries are marked by prominent red or yellow edges. Thus, Figure 1 depicts a voxel array that can be sectioned at any point. Through segmentation, a specific part of the voxel array can be isolated, such as a tooth in our case. The segmented tooth is also shown in a zoomed area in Figure 1.

In the zoom-in area shows the region with higher bone density with the lighter gray, known as cortical bone, and the spongy bone with the darker gray, and the soft tissue containing nerves with the yellow color. Segmentation refers to the process of isolating parts with specific properties, retaining only those voxels that represent high bone density regions, such as tooth enamel and cortical bone.

In the medical software previously mentioned, physicians examine cross-sectional views. An example of such a cross-section is shown at the bottom of Figure 1. This section is also a result of segmentation but uses a more contrasting color scheme: all soft tissues are displayed in blue, while high-density bone areas are shown in red and yellow. Lower-density bone areas appear red, and higher-density areas are yellow.

The CT software allows for segmentation settings that differentiate voxels with various properties even within a cross-section. Therefore, by adjusting the segmentation appropriately in 2D cross-sections, different property areas are displayed in distinct colors. In creating Figure 1, special attention was given to clearly delineating high bone density regions.

The 3D model of the mandible was created by transferring the CT scan slices into a 3D space. Based on these slices, points were generated in the 3D space, which were then connected to form curves. Surfaces were subsequently constructed over these curves. This process is illustrated in Figure 2.

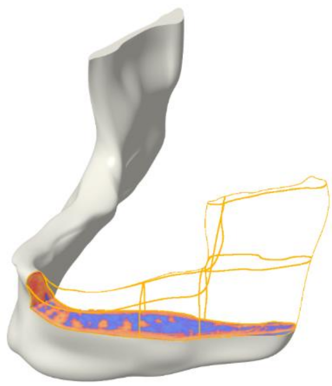

Fig. 2: NURBS curves.

Figure 3 displays the original CT scan.

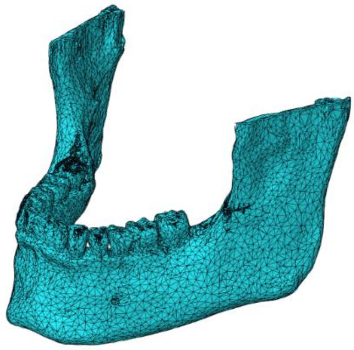

Fig. 3: CT scan model of the mandible.

This scan provides a detailed cross-sectional view of the mandible, captured using X-ray imaging. The CT scan offers high-resolution images that allow for the precise visualization of different tissues and structures.

Figure 4 presents both the original CT scan and the final 3D model we created.

Fig. 4: The merged CT scan and model reconstructed with NURBS curves.

It demonstrates how well the surfaces of our model align with the mesh surfaces displayed from the CT scan data. This alignment confirms that we have achieved a high-quality, highly accurate modeling process. The figure provides visual evidence of the precision and fidelity of our reconstruction, highlighting the effectiveness of our techniques in creating a reliable 3D representation of the mandible.

Figure 5 showcases the final model, specifically the outer surface of the cortical bone.

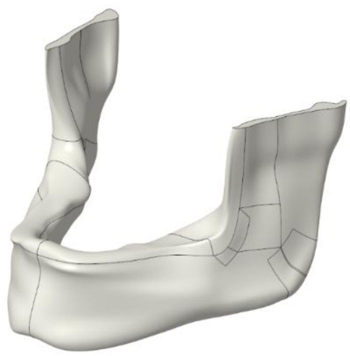

Fig. 5: The final model.

This model represents the high-density regions of the mandible, providing a detailed and accurate depiction of the cortical structure. The outer surface captured in this model is essential for various analyses and simulations, demonstrating the effectiveness of our reconstruction process in preserving critical anatomical details.

Figure 6 displays a sagittal slice extracted from the CT scan, which has been integrated into the model space.

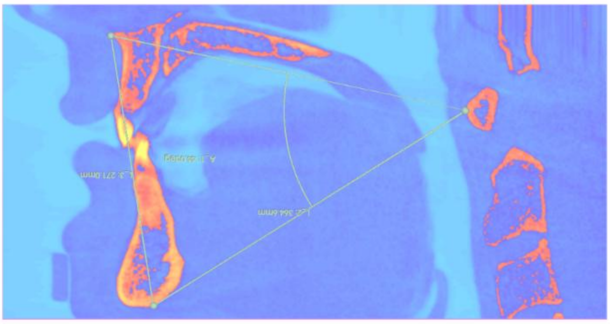

Fig. 6: Sagittal slice of the mandible.

This integration allows for a direct comparison between the 2D imaging data and the 3D reconstructed model, facilitating a detailed examination of the anatomical structures within their spatial context.

A sagittal slice is a type of anatomical plane used in medical imaging that divides the body into left and right sections. This slice is oriented vertically and runs parallel to the sagittal suture of the skull. Sagittal slices are particularly useful for examining structures and organs in a longitudinal view, providing detailed insights into the body's internal anatomy. They are commonly used in CT and MRI scans to visualize and analyze the spatial relationships and conditions of tissues and organs.

Figure 7 displays a cortical slice extracted from high-resolution CT scans of the human mandible.

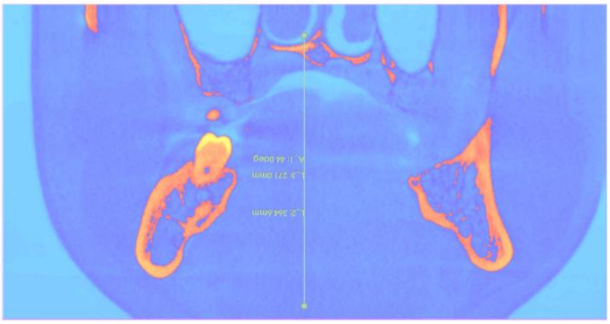

Fig. 7: Cortical slice of the mandible.

The cortical slice on a CT scan refers to a specific image slice that displays the cortical bone surrounding the teeth. This slice provides a detailed view of the outer layer of bone tissue, highlighting its thickness, density distribution, and overall structure. Dentists use this information to assess the integrity of the cortical bone around teeth, which is critical for understanding dental health, planning surgeries like dental implants, and evaluating bone quality for various dental procedures.

Figure 8 presents an axial slice extracted from high-resolution CT scans of the mandible.

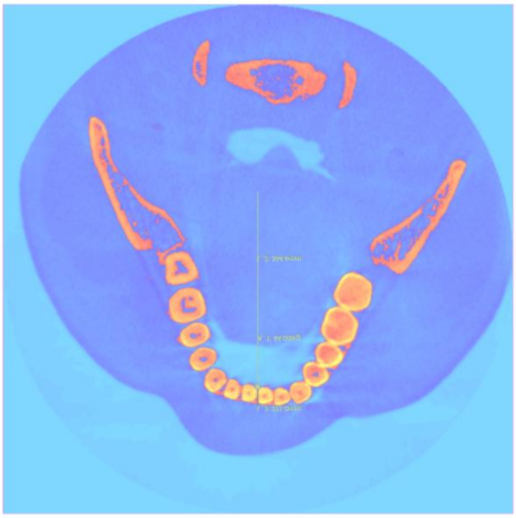

Fig. 8: Axial slice of the mandible.

This slice provides a cross-sectional view of the mandibular bone at a specific anatomical level, showcasing detailed anatomical structures such as the mandibular canal, alveolar ridge, and trabecular bone pattern.

Figure 9 displays a composite view, termed as the orion slice, showcasing sagittal, cortical, and axial slices derived from CT scans of the lower mandible, along with a corresponding 3D model.

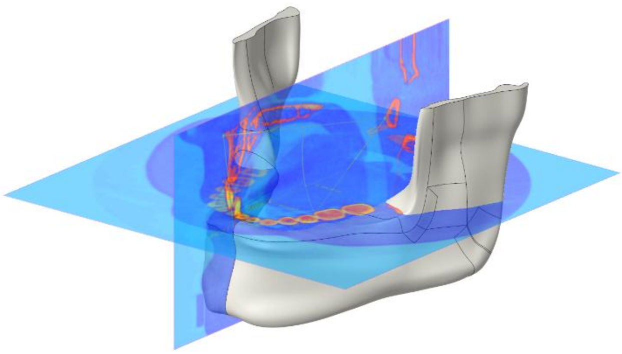

Fig. 9: Orion slice of the mandible.

These slices are integrated to construct a comprehensive 3D model of the mandible, enabling a holistic visualization and analysis of its anatomical characteristics. The inclusion of teeth in the CT slices aids in accurately modeling the lower mandible, ensuring precise representation of dental anatomy and spatial relationships. This approach facilitates detailed biomechanical studies, surgical planning for dental implants, and comprehensive assessments of mandibular health and pathology.

Figure 9 exemplifies the utility of integrating multiple CT slices into a cohesive 3D model, demonstrating their collective role in enhancing our understanding of mandibular morphology and supporting clinical decision-making in dentistry.

Figure 10 illustrates curves constructed from the sectional views of the mandible.

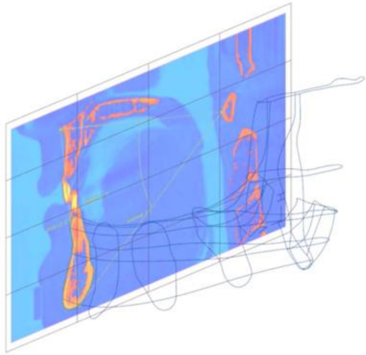

Fig. 10: Curves built by sections of the mandible.

These curves demonstrate the meticulous process of extracting and refining anatomical features from the CT scans. Specifically, they represent NURBS curves that conform closely to the contours observed in the respective CT sections.

NURBS curves are particularly suitable for representing complex shapes like those found in bone structures. They are defined by control points that influence their shape and curvature, ensuring a smooth and natural fit to the underlying bone anatomy. In areas where specific points of the curve are not defined, the curve is guided by energy minimization principles to accurately match the bone's configuration.

In our study, the application of NURBS curves has proven effective in capturing the intricate details of the mandible, reflecting its natural contours and structural integrity. This methodological approach enhances the fidelity of our 3D reconstruction, facilitating precise biomechanical simulations, surgical planning, and morphometric analyses crucial for advancing clinical dentistry and research.

Figure 11 showcases surfaces generated from NURBS curves constructed from sectional views of the mandible.

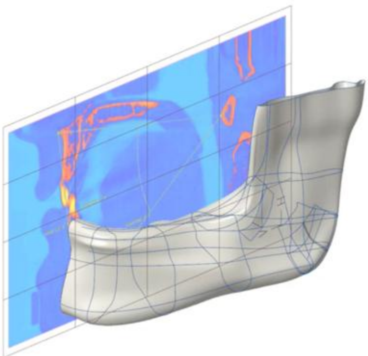

Fig. 11: Curves built by sections with surfaces of the mandible.

NURBS curves, previously extracted from CT scans, have been utilized to create these surfaces.

NURBS surfaces are formed by interpolating or approximating the curves, ensuring smooth transitions and accurate representation of the mandibular anatomy. These surfaces accurately capture the complex geometry and curvature of the mandible, integrating information from multiple sectional views into a cohesive 3D model. The use of NURBS surfaces enhances the fidelity of our model, enabling detailed visualization and analysis of the mandibular structure for various clinical and research applications.

Figure 12 depicts the modeled internal cavity of the lower mandible based on CT scans, specifically highlighting the spongiosa region.

Fig. 12: Spongiosa of the mandible.

In our study, it was paramount to differentiate between the cortical and spongiosa parts of the mandible. This differentiation allows us to assign different material properties during simulations, leading to more accurate results.

The spongiosa, or trabecular bone, plays a crucial role in the mandible's structural integrity by providing internal support and contributing to its flexibility and resilience. In contrast, the cortical bone offers protective strength and rigidity to the mandible [Zhang 2014]. By accurately modeling these distinct regions, we can simulate various scenarios, such as mechanical loading or surgical interventions, with greater precision and realism.

In reality, the cortical and spongiosa regions of the mandible possess different material properties, including hardness, elasticity, and density. These properties influence the mandible's response to external forces and are crucial for understanding its biomechanical behavior under different conditions. Figure 12 exemplifies our approach to integrating anatomical accuracy and material heterogeneity into computational models, advancing our ability to predict and optimize treatments in clinical dentistry and related fields.

Figure 13 displays a sagittal sectional view model created based on the sagittal slice extracted from CT scans.

Fig. 13: Sagittal slice on the 3D model of the mandible.

This specific sagittal slice, previously mentioned in our study, served as a foundational element for our 3D model of the mandible.

The sagittal slice provided critical anatomical details and spatial relationships necessary for accurately reconstructing the mandibular structure. By meticulously following and replicating this slice in our model, we ensured a high level of precision in depicting the mandible's sagittal profile and internal architecture. This included faithfully representing features such as the mandibular body, ramus, and dental structures visible in the original CT scan.

The fidelity with which we traced and modeled the sagittal slice is essential for several reasons. Firstly, it allows for precise anatomical analysis and measurements, supporting clinical evaluations and treatment planning in dentistry. Secondly, it enhances the reliability of biomechanical simulations and virtual surgical procedures conducted on the model, providing insights into how the mandible responds to different mechanical forces or surgical interventions.

Figure 13 exemplifies our approach to leveraging detailed imaging data to construct accurate 3D representations of mandibular anatomy, highlighting our commitment to capturing and utilizing anatomical data effectively in dental research and practice.

Figure 14 depicts a 3D model of the mandible cut along the axial slice extracted from CT scans.

Fig. 14: Axial slice on the 3D model of the mandible.

The axial slice served as another fundamental basis for our modeling process, providing crucial insights into the internal structure and spatial relationships within the mandible. By aligning our 3D model precisely with the axial slice, we ensured accurate representation of anatomical features such as the mandibular canal, alveolar ridge, and tooth roots visible in the CT scan.

Figure 15 presents a 3D model of the mandible cut along the coronal slice derived from CT scans.

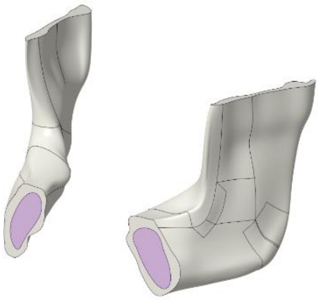

Fig. 15: Coronal slice on the 3D model of the mandible.

Figure 16 presents a composite view where the original geometry of the mandible, the voxel data extracted from CT scans, and its tessellated surface are inserted into a sectional view.

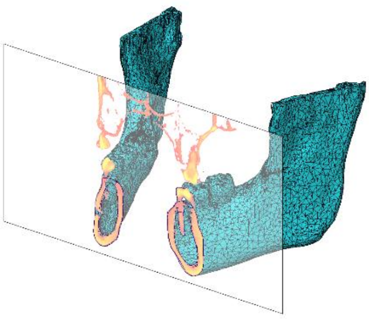

Fig. 16: The original geometry superimposed on the section.

This visualization highlights the transformation process from raw voxel data obtained from CT scans to a detailed tessellated surface representation of the mandible.

The original geometry represents the anatomical structure of the mandible as visualized in the CT scan. Voxel data, which consists of three-dimensional pixels (voxels) derived from the scan, captures the density and spatial arrangement of tissues within the mandible. The tessellated surface is generated from this voxel data through a process known as surface reconstruction, where the surface is approximated by connecting neighboring voxels to form a continuous and smooth representation.

Figure 17 showcases our CAD model of the mandible, meticulously constructed using NURBS curves and surfaces derived from CT scans.

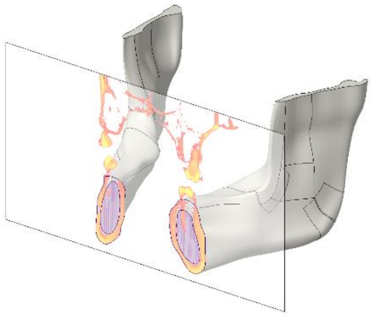

Fig. 17: The geometry with CAD data.

This process involved integrating detailed sectional views obtained from CT imaging to create a highly precise and high-quality representation of mandibular anatomy.

The CAD model accurately captures the intricate details and spatial relationships observed in the original CT sections. By utilizing NURBS curves and surfaces, we ensured smooth transitions and precise fitting of anatomical features such as the mandibular body, ramus, dental arch, and surrounding bone structures. This approach not only enhances the visual fidelity of the model but also supports accurate measurement and analysis of mandibular dimensions and morphology.

The inclusion of all three components in figure 16 and 17 allows for a comprehensive comparison and validation of the modeled mandibular geometry against the original CT data. This verification step ensures that the tessellated surface accurately reflects the anatomical details and spatial relationships observed in the voxel data, thereby enhancing the fidelity and reliability of our 3D model.

Figure 16 and 17 exemplifies our approach to integrating advanced imaging techniques with computational modeling to translate voxel data into a clinically relevant 3D representation of mandibular anatomy. This methodology supports precise anatomical analysis, virtual surgical planning, and biomechanical simulations essential for advancing dental research and clinical practice.

4 CONCLUSIONS

The CAD modeling process described is essential for several applications in dental research and clinical practice. Firstly, it facilitates advanced anatomical visualization, enabling detailed examination of the mandible's internal and external structures. Secondly, it serves as a foundation for virtual surgical planning, where clinicians can simulate procedures like dental implant placement or orthognathic surgeries with confidence in the accuracy of the model.

This methodology supports precision dentistry by providing tools for detailed analysis, treatment planning, and patient-specific care.

The ultimate goal of this study is to simulate tooth implantation and placement within the model, enabling realistic data extraction for virtual testing of specific teeth or tooth arrangements. Initially, the study has focused on reverse engineering and modeling the mandible based on CT images, excluding the teeth. The next steps in this research involve the comprehensive reconstruction of the teeth, as well as the upper jaw and its teeth, ensuring the same high level of accuracy. Following these reconstructions, finite element analyses will be performed on the complete models to assess their mechanical behavior under various conditions, as this has not yet been done for the existing mandible model.

Future plans include expanding the study to simulate the effects of different types of dental prosthetics within these models. By comparing the behavior of various prosthetic designs across different reconstructed mandible models, we aim to provide valuable insights that can assist dentists in determining the most suitable prosthetic method for individual patients. This will help tailor treatments to specific anatomical variations, improving patient outcomes. Ultimately, this research will contribute to more accurate and clinically relevant simulations, as the models will consider the mandible's capacity for deformation, leading to more realistic predictions of prosthetic performance and longevity.

5 PRIMARY CONCEPTS

Bézier curves: A Bézier curve is a mathematical curve widely used in computer graphics and geometric modeling. It is defined by a set of control points connected by straight lines. The shape of the curve is determined by these control points, and the curve always remains within the convex hull of the points.

Voxel-based morphometry: Voxel-based morphometry (VBM) is a neuroimaging analysis technique that allows for the investigation of differences in brain anatomy, particularly gray matter volume, by comparing the density of brain tissue at the voxel level. VBM involves the preprocessing of brain scans, such as MRI images, where each brain is spatially normalized to a standard template, segmented into different tissue types, and then statistically analyzed to detect local changes in brain structure across groups or conditions.

Segmentation methods: In reverse engineering, a segmentation method refers to the process of dividing a complex 3D model into smaller, more manageable sections or segments. This is typically done to simplify the analysis and reconstruction of the object, allowing for more accurate modeling of its individual components. Segmentation helps in identifying distinct features or regions of the object, which can then be separately analyzed, reconstructed, or optimized before being combined into the final reverse-engineered model.

NURBS: The Non-Uniform Rational B-Splines are mathematical representations used in computer graphics and CAD (Computer-Aided Design) for generating and representing curves and surfaces. NURBS allow for the creation of complex shapes with great precision and flexibility by using control points, weights, and knots to define the shape. Unlike simpler spline curves, NURBS can accurately model both standard geometric shapes, like circles and ellipses, and freeform surfaces, making them highly versatile for 3D modeling.

CT scan: The CT scan, also known as Computed Tomography, thoroughly scans the shape and captures points wherever material is detected, resulting in a three-dimensional image.

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