3D DEEP LEARNING FOR SKULL IMPLANT DESIGN

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INTRODUCTION

- Advancements in 3D deep learning are transforming medical imaging and cranioplasty by automating cranial implant design and reconstruction.
- AI-driven methods offer a faster, automated alternative to traditional, time-consuming implant modeling, requiring less expertise.
- Research shows deep learning enhances efficiency and accuracy in implant design, ensuring better anatomical fit and reduced surgery times.
- These innovations highlight the potential of AI to automate complex 3D tasks across medical and engineering fields, paving the way for personalized medical treatments.

THREE-DIMENSIONAL DEEP LEARNING TO AUTOMATICALLY GENERATE CRANIAL IMPLANT GEOMETRY

CHIEH-TSAI WU, YAO-HUNG YANG & YAU-ZEN CHANG

BACKGROUND:

- Traditional skull reconstruction methods, like the mirror operation, are inadequate for asymmetrical skulls or complex defects.
- Advances in deep learning for 2D image inpainting and 3D modeling have paved the way for this research.
- Current 3D inpainting techniques need improvement in resolution and shape complexity to be clinically effective.

OBJECTIVES:

1. **Develop a 3D deep learning framework to:**
    - Automatically generate complete cranial models from defective ones
    - Use the generated complete model to create implant geometry for cranioplasty

2. **Address limitations of traditional mirror-based implant design methods:**
    - Handle defects crossing the plane of symmetry
    - Account for natural skull asymmetry

3. **Create a computationally efficient system for clinical use**

METHODOLOGIES :

- Used an enhanced 3D autoencoder architecture
- Trained on pairs of complete cranial models and corresponding models with simulated defects
- Input/output resolution: 112 x 112 x 40 voxels (upper part of cranium)
- Used data augmentation to expand 73 skull models to 7,154 training samples
- Applied various 3D masks (ellipsoids, cylinders) to create simulated defects for training

RESULTS :

- Achieved volumetric error rates <8.2% on simulated test cases
- Can handle defects up to 35% of skull volume
- Successfully used to generate implant for clinical case (12-year-old boy)
- Little to no post-processing is needed to eliminate noise in generated implants

DEEP LEARNING-BASED FRAMEWORK FOR AUTOMATIC CRANIAL DEFECT RECONSTRUCTION AND IMPLANT MODELING

MAREK WODZINSKI , MATEUSZ DANIOL , MIROSLAW SOCHA , DARIA HEMMERLING ,MACIEJ STANUCH , ANDRZEJ SKALSKI

BACKGROUND:

- Cranial implants are essential for repairing skull defects caused by surgeries like craniectomy or trauma.
- Traditional methods for designing and producing these implants are slow, requiring days to weeks and often necessitating follow-up surgeries.
- There is a need to automate this process to reduce time and improve patient outcomes.
- Advances in deep learning (DL) and 3D printing technologies provide an opportunity to streamline cranial implant design.

OBJECTIVES:

- Develop a fast, robust, and fully automatic method for cranial defect reconstruction and implant modeling.
- Use deep learning to automate the segmentation and reconstruction of skull defects.
- Create a method that can generate 3D-printable implant models automatically.
- Evaluate the method using quantitative metrics and qualitative assessments through 3D printing and mixed reality visualization.

METHODOLOGIES:

- Developed a comprehensive pipeline including data preprocessing, defect reconstruction using a modified U-Net architecture, defect refinement, and implant modeling.
- Implemented cross-case data augmentation using imperfect image registration to diversify the training dataset.
- Used a variational autoencoder (VAE) for further data augmentation, enhancing the robustness and accuracy of the model.
- Developed an iterative defect refinement and implant modeling procedure to ensure clinical suitability and prepare models for 3D printing.

RESULTS:

- The method showed superior performance in quantitative evaluations, with high accuracy metrics across different datasets.
- Successfully validated the method’ s clinical applicability through 3D printing and mixed reality demonstrations, confirming the implants' practical utility.
- The pipeline allows for real-time application during surgeries, potentially enabling 3D printing directly in the operating room.
- The research contributes significantly to personalized medicine by automating cranial implant design, making the process faster and more accessible.

CREATING HIGH-RESOLUTION 3D CRANIAL IMPLANT GEOMETRY USING DEEP LEARNING TECHNIQUES

CHIEH-TSAI WU, YAO-HUNG YANG & YAU-ZEN CHANG

OBJECTIVES:

- Develop a deep learning approach to automatically generate high-resolution 3D cranial implant geometry from defective skull models.
- Create a system that can produce implants suitable for clinical use while reducing training time.
- Improve upon existing methods by generating higher resolution implant models (512 x 512 x 384 voxels).

METHODOLOGIES:

- Developed a two-stage deep learning system for cranial implant generation.
- Produced high-resolution (512 x 512 x 384) implants suitable for clinical use.
- Achieved rapid implant generation time of under 10 minutes.
- Demonstrated effectiveness in both numerical studies and surgical practice.

RESULTS:

- Achieved SDI values above 90% for most defects; maintained SDI above 80% for large defects.
- Successfully applied the system in a clinical case, producing a well-fitting implant with better symmetry.
- Reduced surgery time and improved aesthetic outcomes with smooth implant transitions.

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CUSTOM IMPLANT DESIGN FOR LARGE CRANIAL DEFECTS

FILIPE M. M. MARREIROS, Y. HEUZÉ, M. VERIUS, C. UNTERHOFER, W. FREYSINGER & W. RECHEIS

OBJECTIVES:

- Introduce a computer-aided design (CAD) tool for designing implants for large skull defects (>100 cm^2).
- Develop a semiautomatic method for generating patient-specific implants with high accuracy.
- Create a complete and coherent software CAD pipeline for implant design.

METHODOLOGIES:

- Developed a CAD tool combining geometric morphometrics and radial basis functions (thin-plate splines) for implant generation.
- Created a method that uses symmetry and the best fitting shape to estimate missing data directly within radiologic volume data.
- Implemented a boundary fitting approach for accurate implant placement.
- Achieved high accuracy in implant design, with 89.29% of missing landmarks having an error less than or equal to 1 mm.
- The CAD pipeline offers a complete solution from CT data to final implant design,

RESULTS:

- TPS relaxation quickly stabilized after about 10 iterations, with errors dropping significantly, showing the skull shape was well-represented.
- Best results came from using symmetry, with most landmarks having errors under 1 mm, and 89% of them within this range.
- This method outperformed previous ones, working well for both one-sided and two-sided defects.
- It might struggle with poorly covered defect areas, but it's great for other smooth bone reconstructions and has potential in anthropology.

IMPROVING DEEP LEARNING-BASED AUTOMATIC CRANIAL DEFECT RECONSTRUCTION BY HEAVY DATA AUGMENTATION

MAREK WODZINSK , KAMIL KWARCIAK , MATEUSZ DANIOL, DARIA HEMMERLING

BACKGROUND:

- Personalized cranial implants reduce patient wait times but are costly and time-consuming.
- Deep learning methods face challenges due to heterogeneity in skull shapes and difficulty obtaining ground truth.
- Data augmentation improves model generalizability for cranial defect reconstruction.
- SkullBreak and SkullFix synthetic datasets are used to overcome the lack of real ground truth data.

OBJECTIVES:

- Evaluate the effectiveness of various data augmentation techniques for cranial defect reconstruction.
- Improve the generalizability of deep learning models to real clinical data.
- Achieve high reconstruction accuracy using synthetic datasets and advanced augmentation methods.
- Benchmark and combine different augmentation strategies to find the optimal approach.

METHODOLOGIES:

- Employed heavy data augmentation techniques, including geometric transformations and image registration.
- Integrated various generative models like VAEs, GANs, and latent diffusion models.
- Performed ablation studies to assess the impact of dataset size and augmentation strength.
- Evaluated augmentation methods by training a deep convolutional network for cranial defect reconstruction.

RESULTS:

- The proposed method outperformed state-of-the-art techniques, setting a new benchmark.
- Combined augmentation strategies resulted in significant improvements in reconstruction accuracy.
- The approach was validated on real clinical cases, demonstrating high generalizability.
- The study confirmed that extensive data augmentation is crucial for reliable cranial defect reconstruction.

CRANEXT: AUTOMATIC RECONSTRUCTION OF SKULL IMPLANTS WITH SKULL CATEGORIZATION TECHNIQUE

THATHAPATT KESORNSRI, NAPASARA ASAWALERTSAK , NATDANAI TANTISEREEPATANA ,PORNNAPAS MANOWONGPICHATE ,

BACKGROUND:

- Existing skull reconstruction techniques often struggle to generalize to diverse clinical cases, limiting their effectiveness.
- Traditional methods are time-consuming, sensitive to image quality, and rely heavily on manual intervention.
- Recent advancements in deep learning, especially ConvNeXt architecture, offer potential improvements in reconstruction quality and efficiency.
- The paper introduces CraNeXt, a novel model for automatic skull implant design, aimed at reducing model size while maintaining high reconstruction accuracy.

OBJECTIVES:

- Create a lightweight, efficient model for skull implant reconstruction using ConvNeXt.
- Implement skull categorization to enhance implant accuracy and anatomical fit.
- Combine synthetic and clinical datasets to boost model generalizability.
- Compare CraNeXt’s performance against existing state-of-the-art methods.

METHODOLOGIES:

- Used the ConvNeXt backbone for a more efficient and lightweight model.
- Applied skull categorization to improve defect localization during training.
- The model was trained on a combined dataset of synthetic skull data (SkullBreak) and a large in-house clinical dataset, enhancing its generalizability.
- Performance was evaluated using metrics such as Dice coefficient, 95th percentile Hausdorff distance, and the newly proposed Surface Hausdorff distance (SdH).

RESULTS:

- CraNeXt significantly reduced model size while achieving a dice score of 0.7969, demonstrating high accuracy in skull reconstruction.
- The skull categorization technique improved model performance, particularly in handling complex cranial defects.
- The combination of synthetic and clinical data resulted in better generalization and applicability of the model to real-world clinical scenarios.
- The Surface Hausdorff distance (SdH) was introduced as a more effective metric for assessing the contour accuracy of the reconstructed implants.

DEEP LEARNING FOR CRANIOPLASTY IN CLINICAL PRACTICE: GOING FROM SYNTHETIC TO REAL PATIENT DATA

OLDŘICH KODYM, MICHAL ŠPANĚL, ADAM HEROUT

BACKGROUND:

- Joint reconstruction of skull patches and cranial implants is tackled using multi-task learning.
- 3D printable implants have advantages over traditional methods, but require skilled CAD modeling.
- Automatic skull reconstruction methods have shown promise but are mostly untested on real patient data.
- There's a need for methods that can leverage both synthetic and clinical data for skull reconstruction.

OBJECTIVES:

- Develop a multi-task learning model for simultaneous skull patch and implant reconstruction.
- Introduce a curvature-based metric to evaluate surface fit along defect borders.
- Validate the model on real clinical data, bridging the gap between synthetic and real datasets.
- Design a method that can be integrated into semi- or fully automatic clinical cranial implant design workflows.

METHODOLOGIES:

- Used a cascade of multi-branch volumetric CNNs for simultaneous training on two types of cranioplasty data.
- Introduced a new Gaussian curvature-based metric for evaluating defect border reconstruction.
- Trained and tested models on a combination of Skullbreak synthetic data and real patient data.
- Applied data augmentation techniques, including rescaling, to address differences between datasets.

RESULTS:

- Achieved an average surface distance of 0.67 mm for reconstructed skull patches on a clinical test set of 75 defective skulls.
- Reduced the defect border Gaussian curvature error by 12% compared to a baseline model trained on synthetic data only.
- Produced 3D printable cranial implant shapes with a Dice coefficient of 0.88 and a surface error of 0.65 mm.
- Demonstrated that the proposed method's outputs reach good quality and can be considered for clinical use in cranial implant design workflows.

TOWARDS CLINICAL APPLICABILITY AND COMPUTATIONAL EFFICIENCY IN AUTOMATIC CRANIAL IMPLANT DESIGN

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BACKGROUND:

- Cranial implants are critical for surgical repair of skull defects, typically requiring extensive time for offline generation.
- The AutoImplant II challenge addressed the need for automated, efficient implant design with immediate availability.
- The challenge built on AutoImplant I by including real clinical cases and focusing on clinical and computational requirements.
- Deep learning models have proven effective for skull shape completion but face challenges in generalizing from synthetic to clinical data.

OBJECTIVES:

- Develop automated solutions for cranial implant design that meet clinical standards and computational efficiency.
- Improve generalizability of deep learning models from synthetic to real clinical skull defect cases.
- Evaluate the clinical applicability of deep learning models through expert assessment and new metrics.
- Encourage advancements in skull shape completion by introducing diverse defect patterns and high-resolution imaging data.

METHODOLOGIES:

- Three challenge tracks focused on diverse synthetic defects, clinical cases, and generalizability improvement in skull shape completion.
- Evaluation metrics included Dice similarity coefficient, 95th percentile Hausdorff distance, and the newly introduced bDSC.
- Participants used various deep learning architectures, such as U-Nets and sparse convolutional networks, tailored to the specific requirements of each track.
- Post-processing techniques were proposed to adjust implant thickness and borders, ensuring clinical feasibility.

RESULTS:

- The top submissions effectively bridged the gap between synthetic and clinical datasets, showing improved generalizability.
- Quantitative metrics were moderately correlated with clinical assessments, highlighting the importance of expert evaluation.
- The new bDSC metric provided a stronger correlation with clinical feasibility compared to traditional metrics.
- The challenge outcomes underscored the need for further advancements in both clinical applicability and computational efficiency in cranial implant design.

CRANIAL IMPLANT PREDICTION BY LEARNING AN ENSEMBLE OF SLICE-BASED SKULLCOMPLETION NETWORKS

BOKAI YANG , KE FANG , AND XINGYU LI(B)

BACKGROUND:

- Cranial defects often result from physical or pathological damage and require reconstructive surgery called cranioplasty.
- Earlier methods involved using universal covers, leading to poor aesthetic outcomes and incomplete recovery.
- Customized implants designed for specific patients have improved cranioplasty outcomes but require complex procedures and long waiting times.
- Recent advancements in machine learning and deep learning aim to automate the cranial implant design process, reducing time and improving patient outcomes.

OBJECTIVES:

- Create a method for skull implant prediction that is both fast and accurate, reducing reliance on manual intervention.
- Address overfitting and computational resource limitations in 3D volume analysis by using 2D slices for implant prediction.
- Combine multiple neural network outputs to improve prediction accuracy and robustness.
- Ensure that the method works well with a variety of skull defect cases, including those with complex shapes and locations.

METHODOLOGIES:

- Used data from the AutoImplant 2021 challenge, consisting of 570 training cases and 100 evaluation samples, all represented as $512 \times 512 \times 512$ binary volumes.
- Developed a CNN for local information processing and an RNN to capture continuity between adjacent slices, leveraging both for implant prediction.
- Averaged the outputs of six 3D implant volumes generated from different slice orientations to improve prediction robustness.
- Designed computationally efficient filters to remove noise from the predicted implants, enhancing the final output quality.

RESULTS:

- Achieved higher Dice similarity scores and reduced Hausdorff distances, indicating better implant prediction accuracy.
- Improved visual completeness and smoothness of implants through the ensemble strategy, making them more suitable for clinical use.
- Outperformed baseline methods that used single models or did not account for global skull information.
- Plans to refine impurity removal methods and explore more sophisticated RNN architectures to further enhance performance.

AUTOMATIC SKULL DEFECT RESTORATION AND CRANIAL IMPLANT GENERATION FOR CRANIOPLASTY

JIANNING LI A,D,G,H,⋆, GORD VON CAMPE B, ANTONIO PEPE A,D,G,
CHRISTINA GSAXNER A,D,G,

BACKGROUND:

- Cranioplasty repairs skull defects using cranial implants after surgeries or trauma.
- Traditional implant design is slow and requires expensive manual tools.
- Automation is needed to speed up the implant design process.
- Advances in deep learning and 3D printing enable faster, automated implant creation.

OBJECTIVES:

- Develop a fully automatic, fast, and reliable method for cranial defect restoration and implant modeling using deep learning.
- Formulate skull defect restoration as a 3D volumetric shape completion task.
- Use CNNs to automatically complete the shape of the skull and design the implant.
- Create a training dataset using healthy skulls with synthetic defects to train the model without requiring manual annotations.

METHODOLOGIES:

- Constructed a database of 167 high-resolution healthy skulls, injected with synthetic defects to simulate real-life scenarios
- Developed an encoder-decoder style network with two variants, M1 and M2, utilizing skip connections to improve reconstruction quality.
- Used a novel patch-based training strategy to handle high-resolution and spatially sparse data.
- Implemented overlapping and non-overlapping cropping methods to maximize the model's learning capacity.

RESULTS:

- High scores in Dice and Jaccard similarity indices for skull and implant reconstructions, proving the method's accuracy.
- Visual inspection and 3D printing confirm that the implants fit well with the skull defects, providing a good match for clinical needs.
- The automatic approach is faster and more consistent compared to manual CAD-based methods, making it a valuable tool in surgical planning and execution.
- Potential to transform cranial implant design in clinical settings.

CONCLUSION

- 3D deep learning techniques are revolutionizing cranial implant design by automating geometry generation.
- These AI-driven methods use large datasets of 3D medical images to learn complex skull shapes and defects.
- Automation in implant design reduces the time and expertise needed, improving implant fit and patient outcomes.
- Success in cranial reconstruction highlights AI's potential in automating 3D geometry tasks across industries.

THANK YOU

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