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Enhanced Clinical CT Image Resolution through Multi-Planar Reconstruction for Improved Bone-Implant Simulations

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Abstract: Clinical computed tomography (CT) plays a critical role in patient-specific implant planning; however, its standard resolution is often insufficient for precise biomechanical simulations. We suggest a multi-planar reconstruction pipeline that fuses three image-plane reconstructions to increase the effective resolution. Clinical CT datasets of human femoral heads are processed by converting DICOM images into the Visualization Toolkit (VTK) format, followed by voxel-wise simple mean intensity integration to enhance the image resolution. Quantitative evaluations using intensity profiles and statistical analysis confirmed that the proposed method not only preserves global consistency but also reveals essential local variations in bone structure. The enhanced resolution facilitates more accurate geometric extraction and material mapping for subsequent finite element analyses.

Keywords: Computed Tomography, Femoral Head Datasets, ParaView Pipeline, Patient-Specific Implants

1 Introduction

Total hip replacement (THR) is a common intervention wherein surgeons replace the damaged or worn components with prostheses. In current clinical practice, implant selection relies on multiple 2D X-ray images of the pelvis and femur, which trained professionals visually assess. While this approach has been standard for decades, it may lead to suboptimal implant geometry selection and reduced range of motion, implant interference, dislocation, or early failure [1].

Recent advances in patient-specific implant design have demonstrated the potential for more accurate, personalized treatment strategies [1, 2]. However, these in silico methods depend critically on the quality of the underlying medical images. Clinical computed tomography (CT) scans, which form the basis for simulation workflows, are typically acquired at a lower resolution to minimize X-ray exposure and patient risk. This low resolution often fails to capture fine details such as the trabecular bone structure, compelling researchers to rely on simplified computational models that omit these critical features [3].

Our work introduces a novel multi-planar reconstruction technique to enhance the effective resolution of clinical CT images. Our approach yields higher-fidelity representations of bone geometry by combining image reconstructions along the three coordinate axes (axial, coronal, and sagittal). This enhanced resolution facilitates cleaner geometry extraction and establishes a more robust baseline for generating accurate material data in subsequent finite element analyses.

2 Materials and Methods

2.1 Tissue Samples

In collaboration with the Clinic for Orthopedics and Trauma Surgery at Klinikum Heidenheim, Germany, 28 human femoral heads were obtained from patients undergoing THR. The collection of these samples was approved by the Ethics Committee of the State Medical Chamber of Baden-Württemberg under the application F-2020-118, ensuring that all ethical requirements are fulfilled.

After extraction, each femoral head was labeled with a unique number and securely stored in a locked room at the Institute of Biomaterials and Biomolecular Systems, University of Stuttgart, for subsequent experiments. Storing the samples at -80 °C preserves the tissue integrity, following protocols previously validated for assessing the impact of storage on elastic properties [4]. Detailed donor demographics-including gender, age, and body weight-are available in our earlier publication [5].

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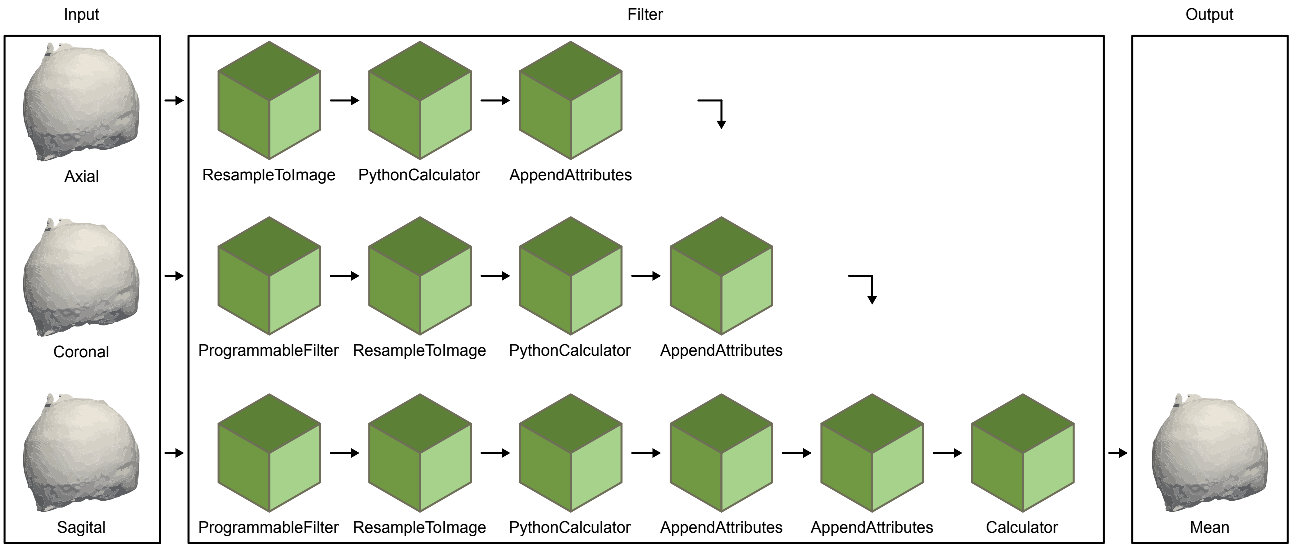

Fig. 1: Combination pipeline implemented in ParaView.

2.2 Clinical CT Scanning

In addition to storing the femoral head samples for later experiments, we acquired clinical CT scans of all specimens in the collaborating hospital following a standardized protocol. Femoral heads labeled 1 to 20 are scanned using a Siemens SOMATOM Sensation 64 CT scanner, while those labeled 22 to 44 are imaged using a Siemens SOMATOM Confidence CT scanner. We then reconstructed the raw datasets scanned on the Siemens SOMATOM Sensation 64 CT scanner using two distinct statistical iterative reconstruction kernels: a smooth standard reconstruction kernel (B40f) and a sharpening reconstruction kernel (B60f). The datasets scanned on the Siemens SOMATOM Confidence CT scanner rely on a Br38 kernel (regular body kernel for soft tissue visualization) and a Br51 kernel (regular body kernel with low-dose CT for bone visualization). We exported the resulting datasets in the DICOM format, following clinical standards [6, 7].

The spatial resolution and image spacing vary between the scanners. For instance, the CT scan of femoral head number 1 has an image spacing of 0.17 mm $\times$ 0.17 mm $\times$ 0.60 mm and was reconstructed with kernel B60f. Femoral head number 22 has an image spacing of 0.23 mm $\times$ 0.23 mm $\times$ 0.60 mm and was reconstructed with kernel Br51.

Furthermore, the acquired scans are publicly accessible through the data repository of the University of Stuttgart (DaRUS)[1] under the CC BY 4.0 license [8]. The data is published according to the FAIR principles (findable, accessible, interoperable, reusable) [9].

2.3 Resample-Combine Method Pipeline

We combine multiple reconstructions acquired in different imaging planes to ehance the image's resolution. Based on discussions with medical staff, we adopted a method that integrates standard clinical protocols with minimal disruption to routine practice, which entails reconstructing the CT image data orthogonally to the three principal axes: axial, coronal, and sagittal.

The processing pipeline consists of two main stages. First, the raw DICOM images are converted into VTK format using the 3D Slicer application (RRID:SCR_005619). In the second stage, a pipeline implemented in ParaView (RRID:SCR_002516) combines the three image orientations using a simple mean calculation, as illustrated in Fig. 1.

The procedure begins by loading the three orientation VTK files of the femoral head. Next, the spatial bounds and center points are computed to define a unified sampling domain. Resampling filters ensure spatial alignment and consistent grid dimensions across all datasets.

To correct misalignment, a `ProgrammableFilter` applies geometric transformations. Specifically, each image volume is first centered by translating its minimum bounds to the origin. A first rotation is performed using a `vtkTransformFilter`, with the angle derived from the inverse cosine of the x-component of a reference vector. The rotation axis consists of the y and z components, correcting for any initial misorientation. A second rotation further refines alignment based on the dot product between an intermediate and secondary reference vectors. After alignment, we translate the volume back to its original spatial position.

1 https://darus.uni-stuttgart.de/

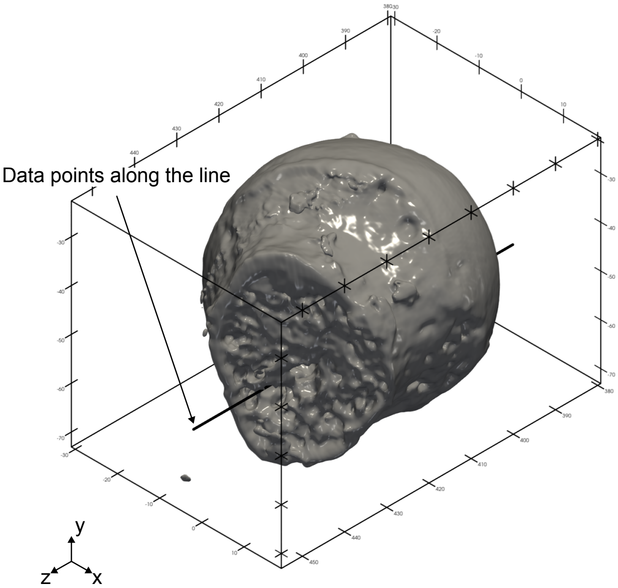

Fig. 2: Recombined volume of femoral head number 1 with an overlaid data line indicating the region used for generating intensity profiles.

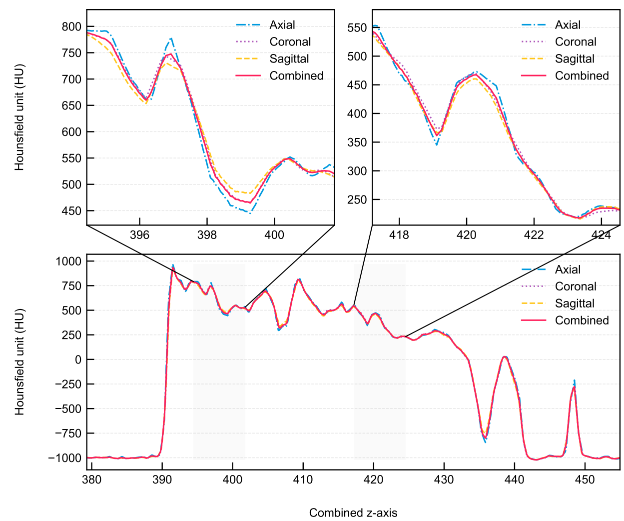

Fig. 3: Intensity profiles from the resample-combine method for femoral head number 1 with kernel B40f. While global trends are consistent, local discrepancies between reconstructions are observable.

Next, scalar intensity fields are extracted using the `PythonCalculator` filter. We then merge the dataset and compute a simple mean. Finally, the processed geometry is send to the finite element method preprocessor ANSA (RRID:SCR_016283) [10]. In ANSA, further processing includes mesh optimization, reassembly of fractured bone segments, and volume meshing. Implant geometries, typically provided in CAD format, can also be meshed and integrated. Loads and boundary conditions are then defined in preparation for subsequent simulations.

3 Results and Discussion

The clinical CT datasets from all 28 cases were reconstructed in the three orientations, following the resample-combine method described in Section 2.3. Fig. 2 illustrates the overall outline of the combined data volume along with a volume rendering of femoral head number 1 (reconstructed with the B40f kernel). This figure also displays the location of the data line used to generate the intensity profiles shown in Fig. 3.

The line chart in Fig. 3 presents a plot of the resampled Hounsfield unit values along the specified data line along the z-axis across the volume. Globally, the intensity values show strong consistency across the three reconstructions. However, upon closer inspection, particularly within zoomed sections of the plot, local discrepancies become evident. Regions corresponding to local maxima and minima display variations that reflect inherent differences between images reconstructed along different planes.

Tab. 1 provides a statistical summary of these differences by listing the 25th percentile, median (50th percentile), and 75th percentile for intensity differences between pairs of reconstruction planes. Although the consistency observed in the line plot holds across the whole dataset, the table highlights that the extent of variability differs substantially between femoral heads. For example, the maximum deviation for femoral head number 1 is 3.1 %, whereas for femoral head number 2 the maximum deviation reaches 5.2 %.

Our results indicate that while the resample-combine method effectively preserves global intensity patterns across CT reconstructions, notable local discrepancies exist. If unaccounted for, these differences could significantly impact subsequent material modeling and finite element analyses, where accurate mapping of material properties from CT data is critical for reliable simulation outcomes. Future work will focus on addressing these discrepancies to further improve simulation fidelity.

4 Conclusion

This study presents a resample-combine pipeline that enhances the spatial resolution of clinical CT images through multi-planar reconstruction. By integrating standard imaging protocols with voxel-wise mean intensity fusion across three planes, the method preserves global intensity distributions and

Tab. 1: Quartile statistics of intensity differences between reconstruction planes for selected femoral heads.

Femoral Head	Planes	25th Pctl.	50th Pctl.	75th Pctl.
1	coronal-axial	-0.022	-0.008	0.014
1	sagittal-axial	-0.031	-0.010	0.013
1	coronal-sagittal	-0.005	0.007	0.019
2	coronal-axial	-0.052	-0.002	0.049
2	sagittal-axial	-0.053	-0.002	0.049
2	coronal-sagittal	-0.030	0.000	0.029

reveals critical local discrepancies in reconstructed bone geometries.

These findings underscore a key limitation in current simulation workflows: routine clinical imaging protocols may not provide reliable baseline data for patient-specific finite element simulations. Our results demonstrate that even subtle differences-such as the choice of reconstruction plane-can significantly affect the representation of anatomical structures, with downstream consequences for material mapping and stress-strain analysis.

The preserved samples will serve as a foundation for future investigations, including high-resolution micro-focus CT imaging and the development of stratified transfer functions, ultimately aiming to bridge the gap between low-resolution clinical data and the inhomogeneous, anisotropic material models required for accurate, patient-specific simulations.

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Author Statement

The study was approved by the Ethics Committee of the State Medical Chamber of Baden-Württemberg under application F-2020-118.

Author Contributions

Benjamin Schnabel: Conceptualization, Methodology, Software, Writing - Original Draft, Visualization. **Johannes Gebert:** Data Curation, Writing - Review & Editing. **Ralf Schneider:** Methodology, Supervision. **Peter Helwig:** Resources.

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