Femur and Tibia Segmentation, Expansion, and Anatomical Landmark Extraction from 3D CT Images

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Abstract

This report presents a comprehensive pipeline for the segmentation, morphological expansion, and anatomical landmark extraction of femur and tibia from 3D computed tomography (CT) images. The methodology leverages advanced image processing techniques to extract binary masks, apply fixed and randomized dilation, and identify critical tibial landmarks. The pipeline ensures anatomical fidelity by preserving voxel spacing and is designed for applications in orthopedic surgical planning, biomechanical modeling, and osteoarthritis progression assessment. Results demonstrate accurate segmentation, realistic mask expansion, and precise landmark identification, with all outputs saved in reproducible formats for further clinical and computational analysis.

1 Introduction

Accurate segmentation and morphological analysis of the femur and tibia from 3D computed tomography (CT) images are pivotal for clinical and research applications, including orthopedic surgical planning, biomechanical modeling, and osteoarthritis progression assessment. This project develops a robust image processing pipeline to address these needs through the following objectives:

- Extract femur and tibia masks from labeled CT volumes.
- Perform morphological expansion of masks using fixed and randomized dilation approaches.
- Identify key anatomical landmarks, specifically the medial and lateral lowest surface points of the tibia.

2 Materials and Methods

2.1 Dataset and Image Acquisition

The dataset comprises 3D CT volumes accompanied by a combined bone label mask, where each label corresponds to a specific bone structure:

- Femur: Label 1
- Tibia: Label 2

All image processing tasks were performed using the SimpleITK library, ensuring voxel spacing preservation for real-world spatial accuracy.

2.2 Mask Extraction

The combined mask volume was thresholded to generate separate binary masks for the femur and tibia, enabling independent morphological processing of each structure.

2.3 Mask Expansion

To simulate adjacent soft tissue regions and support advanced morphological analysis, both fixed and randomized expansion techniques were implemented.

2.3.1 Morphological Preprocessing

A series of preprocessing steps were applied to ensure mask integrity:

- Initial dilation using a $3 \times 3 \times 3$ structuring element to improve continuity.
- 2D hole-filling across axial, sagittal, and coronal planes to restore mask integrity.
- Final dilation using a $5 \times 5 \times 5$ kernel.
- Overlap removal between femur and tibia masks to ensure anatomical separation.

2.3.2 Fixed Expansion

Fixed expansion was performed as follows:

- Isotropic dilation at 2 mm and 4 mm distances.
- Structuring elements scaled anisotropically according to voxel spacing.

- Implemented using scipy.ndimage.binary$_{d}ilation$.

2.3.3 Randomized Expansion

Randomized expansion was achieved through:

- Computation of precise distance maps using SimpleITK's SignedMaurerDistanceMap.
- Application of stochastic thresholding to simulate biological variation.
- Controlled irregularity in resulting masks to mimic realistic expansion behavior.

2.4 Anatomical Landmark Extraction

The pipeline extracted the medial and lateral lowest surface points of the tibia, critical for biomechanical modeling and surgical planning:

- Analysis of the tibia surface in the axial direction.
- Midline division to separate medial and lateral compartments.
- Identification and storage of the lowest point from each compartment as an anatomical landmark.

3 Implementation Details

The pipeline was implemented using:

- Programming Language: Python
- Libraries and Tools:
  - SimpleITK: Image reading, writing, and distance map computation.
  - NumPy & SciPy: Binary mask operations and morphological filters.
- Voxel Spacing Handling: Applied in all spatial operations to ensure anatomical fidelity.

4 Results

The pipeline achieved the following outcomes:

- Successful extraction of binary masks for femur and tibia.
- Fixed dilation produced smooth, anatomically accurate boundaries.
- Randomized expansion yielded realistic, irregular patterns simulating soft tissue variation.
- Accurate identification and storage of medial and lateral lowest surface points of the tibia.
- All results saved in reproducible formats compatible with further clinical or computational analysis.

4.1 Anatomical Landmark Coordinates

The following table presents the extracted medial and lateral lowest tibial surface points for the original and expanded masks in both voxel and world coordinates (mm).

Table 1: Anatomical Landmark Coordinates: Medial and Lateral Lowest Tibial Surface Points

Mask Type	Medial Lowest Point (Voxel, World mm)	Lateral Lowest Point (Voxel, World mm)
Original Segmented	(366, 285, 109.5), (-95.61, -25.21, -681.50)	(374, 275, 109.5), (-102.56, -16.51, -681.50)
Fixed Expansion (2 mm)	(366, 285, 110.5), (-95.61, -25.21, -679.50)	(371, 277, 110.5), (-99.95, -18.25, -679.50)
Fixed Expansion (4 mm)	(366, 285, 111.5), (-95.61, -25.21, -677.50)	(371, 277, 111.5), (-99.95, -18.25, -677.50)
Randomized Expansion (2 mm)	(366, 283, 109.5), (-95.61, -23.47, -681.50)	(372, 275, 109.5), (-100.82, -16.51, -681.50)
Randomized Expansion (4 mm)	(365, 282, 110.5), (-94.74, -22.60, -679.50)	(371, 279, 110.5), (-99.95, -19.99, -679.50)

5 Discussion

The integration of fixed and randomized expansion methods enhances the pipeline's versatility and biological realism. By incorporating voxel spacing, all spatial transformations reflect real-world anatomical dimensions, ensuring clinical relevance. The successful extraction of anatomical landmarks provides valuable data for clinical interpretation, prosthetic design, and computational modeling. The modular design of the pipeline promotes reusability and adaptability across various bone structures and imaging modalities, making it a robust tool for orthopedic and biomechanical applications.

6 Conclusion

This project successfully developed a reproducible and anatomically accurate image processing pipeline for:

- Segmentation of femur and tibia from 3D CT images.
- Morphological mask expansion using fixed and randomized strategies.
- Extraction of critical anatomical landmarks from the tibial surface.

The methodology is adaptable for broader clinical and research applications, particularly in orthopedics and biomechanics, offering a foundation for advanced computational and clinical workflows.

7 Acknowledgment of AI Assistance

OpenAI's ChatGPT and xAI's Grok were used as supplementary tools to:

- Learn about processing tools and processes in medical imaging.
- Process 3D medical images and explore relevant Python libraries such as SimpleITK and SciPy.
- Apply morphological operations to fill holes and create masks.
- Extract anatomical landmark points for biomechanical analysis.

8 References

References

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