Enhancing Tibial Fracture Osteosynthesis with Synthetic Data: A Mathematical Approach

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INTRODUCTION

Traumatic tibial fractures are complex and require careful preoperative planning to ensure favorable clinical outcomes. However, current workflows are slow and rely heavily on manual effort. To address this, we introduce the **REPAIR** project [1], which aims to support clinicians by using Machine Learning (ML) to automate tasks such as fragment segmentation, fracture reduction and plating. These ML models require large labeled datasets, which are often scarce and expensive to produce. To overcome this, a parametric model is proposed that simulates fractures from intact bone segmentations, enabling automatic large-scale dataset generation without manual labeling. The synthetic data supports core clinical tasks and improves planning efficiency for tibia fracture osteosynthesis.

OBJECTIVES

The goal is to generate high-quality synthetic data of tibial fractures from intact bone segmentations to avoid tedious manual labeling. This data should cover a wide range of fracture types and is intended to train ML models for osteosynthesis tasks such as fragment segmentation, fracture reduction and plating. To automate and improve the precision of osteosynthesis planning tasks such as fracture reduction and plating, learning from a diverse set of fractures is required, and synthetically generated models enable to identify, classify, and predict optimal treatment strategies for real-world fracture cases without the need for extensive manual labeling.

MATERIAL AND METHODS

Pipeline Overview

The pipeline, shown in Figure 1, creates synthetic tibial fractures in seven steps:

1. **Healthy bone segmentation:** A healthy tibia is segmented from a computertomography (CT) scan using *TotalSegmentator* [2]. Manual correction is needed to ensure high segmentation quality. Anatomical landmarks should also be provided.
2. **Fracture generation:** A parametric model simulates a fracture in the segmentation. Fracture position and orientation, can be controlled.
3. **First CT adjustment:** The CT image is updated by assigning realistic Hounsfield Units (HU) values to fracture regions.
4. **Fragment displacement:** Fragment is displaced using rigid transformations (translation + rotation).
5. **Second CT adjustment:** CT is updated to reflect the new fragment position.
6. **Multifragmentation:** Large fragment is split (voxel clustering).
7. **Third CT adjustment:** CT is updated to reflect the multifragmentation step.

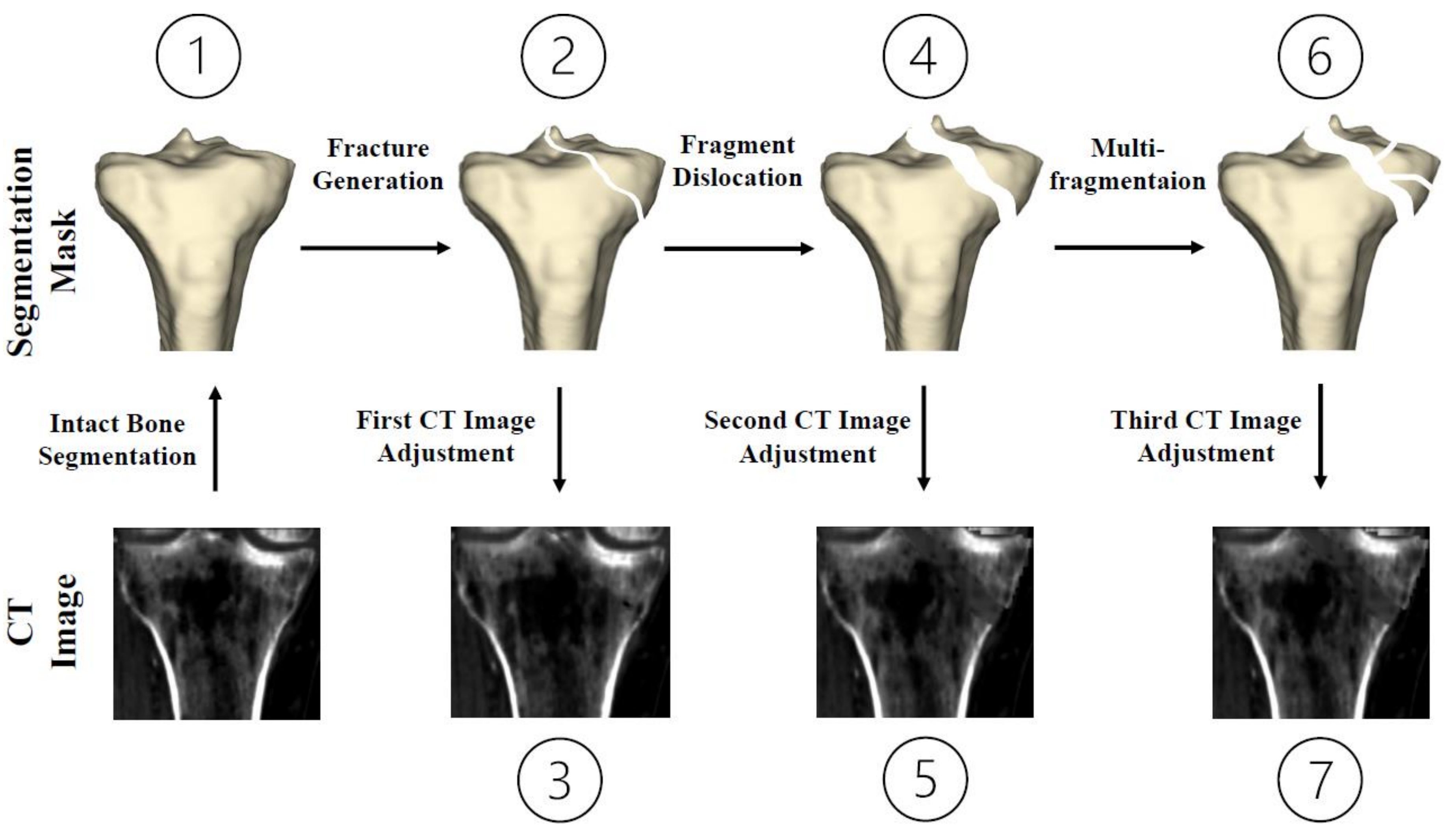

Figure 1. ***Overview of the synthetic fracture generation pipeline.***

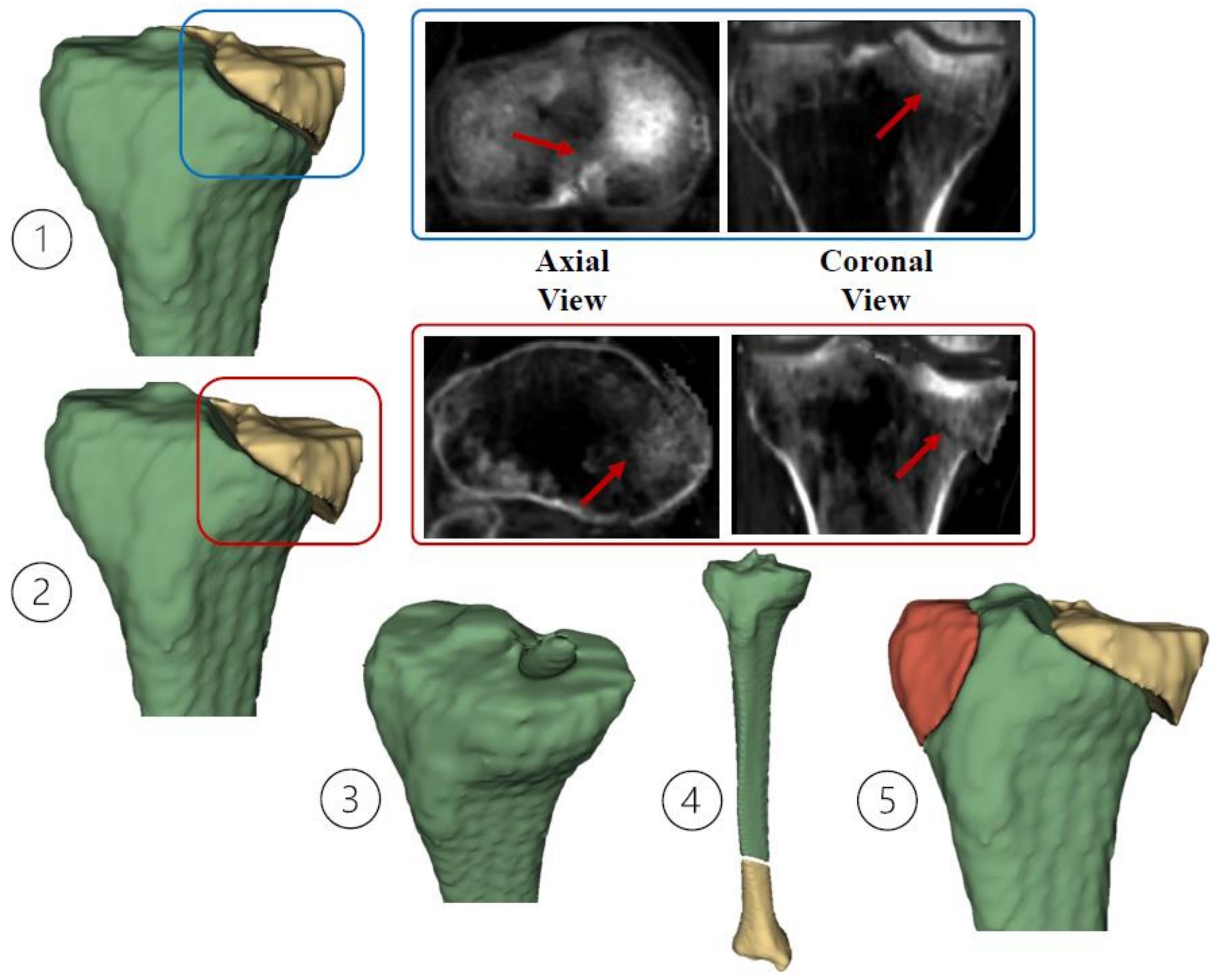

Figure 2. ***Fracture samples generated by our method. 1-2: Unicondylar fracture before and after fragment displacement. 3: Depression fracture. 4: Shaft fracture. 5: Bicondylar fracture (Schatzker V classification).***

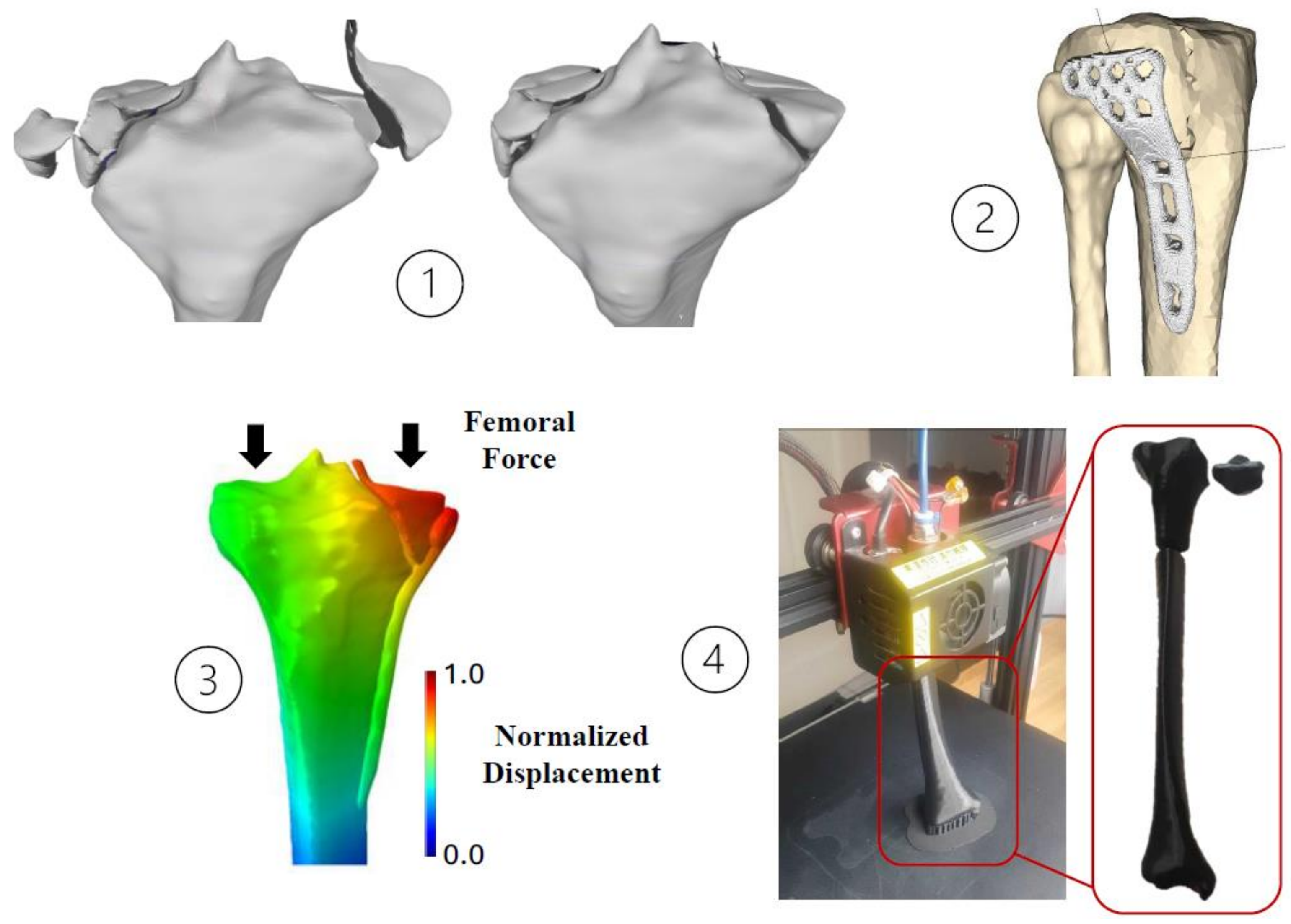

Figure 3. ***Some downstream applications enabled by our synthetic data. 1: Fracture reduction. 2: Virtual plating. 3: Biomechanical simulation. 4: 3D printing.***

RESULTS AND DISCUSSION

Covering a wide range of simple and complex types, 1000 synthetic tibial fracture cases were generated (Figure 2). Each case includes CT volumes, segmentation masks, and 3D surface models. Unlike most clinical datasets, the data is balanced across all fracture classes.

A clinician evaluated a subset of cases. The average quality score was 3.45/5, with high ratings for segmentation fidelity (3.89/5) and fracture location (3.77/5). Lower scores for multifragmentation behavior (3.2/5) and fragment displacement (2.89/5) indicate potential areas for improvement.

Preliminary results for key downstream tasks (Figure 3) demonstrate the applicability of the synthetic data to support fracture osteosynthesis planning. All tasks were performed using only the synthetic data, without any manual labeling.

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REFERENCES

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