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Estimation of Musculoskeletal Features by Inferring Femur from Thigh Skin

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Abstract

Musculoskeletal disorders (MSDs) pose significant healthcare challenges. This study addresses diagnostic limitations by proposing a novel algorithm able to estimate key anatomical features of the femur from thigh skin. Leveraging a dataset of 50 angioscanner thigh-femur pairs, we pioneer a robust Statistical Shape Model (SSM) that captures correlations between the skin and the underlying femur. Femur inference from a known thigh uses a Bayesian approach and demonstrates promising results. Although the femur reconstruction error may seem high, it is important to note that the goal is MSK feature estimation rather than precise bone reconstruction. Preliminary results are promising, suggesting a potential application in non-invasive MSK diagnosis for surgery.

1 Introduction

This research tackles the complex challenge of inferring femur features from the surrounding thigh region by proposing a novel approach based on a Statistical Shape Model (SSM). Current diagnostic methods, including medical imaging and optical marker systems, have proven invaluable but suffer from notable drawbacks. Medical imaging techniques, while providing detailed anatomical data, are associated with high costs, radiation exposure, and cumbersome navigation requirements [1]. Similarly, optical marker-based motion analysis, although non-invasive, is hindered by high costs and dependency on sophisticated, often inaccessible, technologies, making their clinical use limited [2].

Existing approaches to estimate bone structure from external skin features are primarily aimed at animated applications, with limited clinical relevance [3, 4]. A clinically oriented method developed by Alireza et al. [5] estimates the femoral mechanical axis using virtual markers placed on the thigh skin. However, this method has its limitations, primarily due to the need for a highly controlled registration process.

Our research seeks to address these limitations by establishing a formalized correlation between the thigh and the underlying femur. The core objective is to predict the femur based

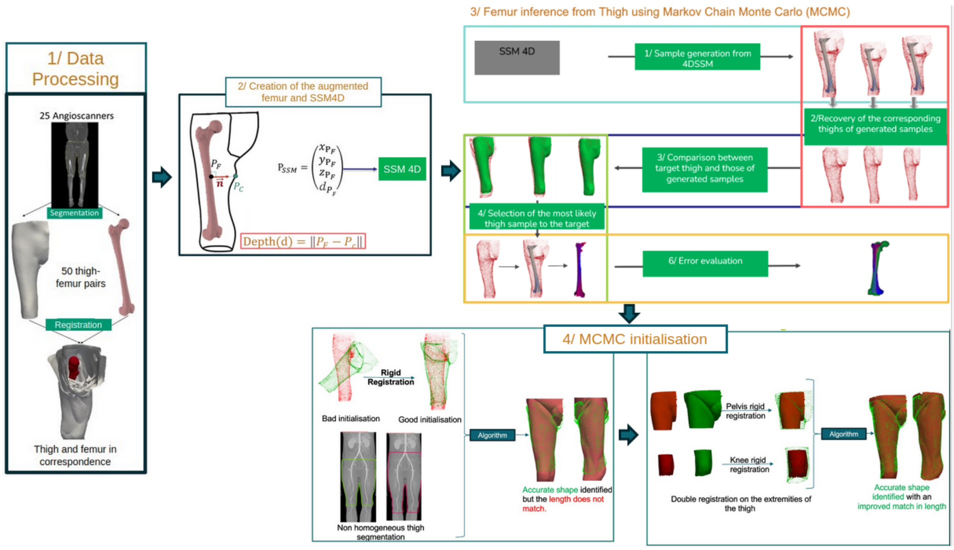

Figure 1: 4D-SSM building and femur inference

on the outer thigh surface and derive clinically significant anatomical features, such as the mechanical axis of the femur.

To achieve this, we develop an SSM that captures the relationships between the femur and thigh skin, employing the Markov Chain Monte Carlo (MCMC) method for femur inference.

2 Materials and Methods

2.1 Dataset and Preprocessing

We use a dataset of 50 femur-thigh pairs generated from angioscanner scans. A quadratic decimation was applied to reduce mesh complexity while preserving anatomical features. We introduced a novel variable, "Depth," representing the distance between the femur points and their corresponding points on the thigh, computed along the normal to the local femur surface (Figure 1-Part 1).

2.2 Statistical Shape Model Construction

The correlation between the femur and thigh is formalized through a 4D-SSM. A statistical model represents the variability of similar objects in a dataset by combining the mean object with key variations, such as length, curvature, and width [6]. The SSM learns the variations from the dataset and generates similar objects (Figure 1-Part 2).

Accurate statistical shape modeling relies on mesh alignment and correspondence. Using both rigid and non-rigid alignments, we created an augmented dataset of femurs with corresponding depths. Leveraging Gaussian Process Morphable Models (GPMMs) [7], within the Scalismo framework, we built a continuous model that captures shape variability. To our knowledge, this 4D-SSM is the first model to capture correlations between surface skin and the underlying bone.

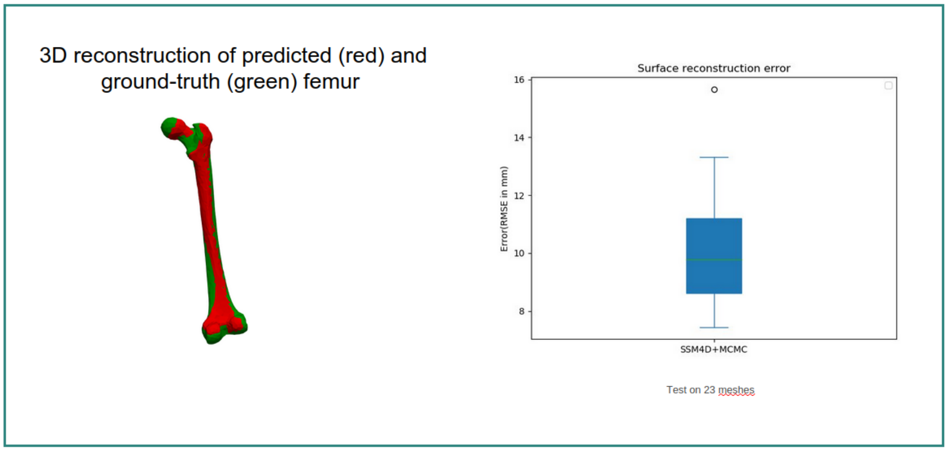

Figure 2: Femur inference errors

2.3 Femur Prediction

Given a known thigh, our algorithm predicts the associated femur using MCMC with the Metropolis-Hastings algorithm, a method for approximating posterior distributions. Figure 1-part 3 shows how we generate samples from the 4D-SSM, approximating femur shape based on the thigh. Likelihood is computed by assessing surface mean distance between the generated thigh samples and the target thigh. The best-aligned sample provides the predicted femur.

Proper initialization is crucial for convergence, achieved by registering the mean model thigh to the target thigh using the Iterative Closest Points (ICP) algorithm (see Figure 1-Part 4). However, non-homogeneous thigh segmentation poses challenges, which affects femur length during the MCMC evaluation. To address this, we introduce a double registration approach focusing on thigh extremities, improving femur length matching.

3 Results

From the dataset of 50 femur-thigh pairs, two were discarded. The 4D-SSM construction used 25 datasets, with 23 retained for evaluation. Figure 2 illustrates the femur inference errors.

Our method achieved a Root Mean Square Error (RMSE) between 7 mm and 14 mm for femur surface reconstruction, aligning with [5], which reported RMSE values between 7.5 mm and 10.5 mm using well-localized skin landmarks.

4 Discussion

Despite the non-homogeneous nature of the meshes and the absence of prior femur information, our model performed well. The femur reconstruction error might be high for direct femur estimation, but for MSK feature estimation, this error remains acceptable. The predicted femurs can be used to assess the mechanical axis, with results comparable to those of Asvadi et al. [5], who reported a mechanical axis angle deviation of less than 2°. The accuracy achieved suggests potential for clinical application, particularly in scenarios where non-invasive MSK feature estimation is needed.

Nevertheless, we acknowledge that the model's performance requires further improvements to reduce the Root Mean Square Error (RMSE) and address limitations in clinical scenarios. Managing cases where the patient's anatomy deviates significantly from the norm necessitates a more robust modeling approach. We are currently investigating strategies to improve the accuracy. Possible solutions may involve hybrid methods that combine machine learning techniques with classical shape modeling approaches.

5 Conclusion

We presented a novel algorithm that infers femur bone structure from thigh skin, outperforming existing methods. Despite the challenges of non-homogeneous meshes, our approach shows promising results. The accuracy of femur prediction suggests it can be used to estimate the mechanical axis, a crucial parameter in surgical planning. Future improvements may include addressing gender distinctions and incorporating additional factors such as body mass index (BMI) to improve the model prediction. Addressing the current limitations could lead to a more precise and adaptable method for estimating musculoskeletal features, particularly in challenging cases.

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