Derivative-Based Clustering of Knee Kinematics During Weight-Bearing 4DCT Motion Acquisition

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Summary

4DCT and derivative-based functional data clustering were used to identify distinct patterns of tibiofemoral joint rotation. The approach employed a combination of first derivatives of the rotational motion, functional principal component analysis, and k-means clustering to classify rotational patterns. The method revealed meaningful kinematic variations in healthy knees by focusing on motion trends rather than amplitude. These findings provide a novel framework for assessing pathological deviations, offering potential improvements in diagnostic and therapeutic strategies.

Introduction

Dynamic computed tomography (4DCT) allows detailed investigation of knee kinematics under weight-bearing conditions. Understanding patterns of internal and external tibiofemoral rotation during flexion is critical for assessing knee function in both healthy and pathological knees. The screw-home mechanism—a critical feature of knee kinematics—describes the coupled motion of external tibial rotation near full extension, contributing to joint stability and efficient load distribution [1]. Analyses often focuses on the magnitude of this rotation [2], potentially overlooking subtle motion trends. This study aimed to identify distinct rotational patterns by applying functional data clustering (FDC) to the first derivatives of rotational motion, emphasizing dynamic trends over absolute values.

Methods

Forty-six healthy knees were analyzed using 4DCT imaging during weight-bearing flexion [3]. Internal reference frames for tibia and femur were reconstructed using bony landmarks to calculate the flexion-extension, internal-external rotation and abduction-adduction rotations angles across all time frames. Axial rotation data were interpolated and averaged for each degree of flexion, producing a continuous profile of internal and external rotation as a function of knee flexion.

To analyze motion trends, the first derivatives of the axial rotation were computed, and functional principal component analysis (FPCA) was used to reduce dimensionality. K-means clustering was applied to the FPCA scores.

Results and Discussion

Four distinct motion patterns were identified through clustering, each representing meaningful kinematic trends. These clusters revealed unique trajectories of internal and external rotation during weight-bearing knee flexion (Figure 1). By focusing on derivatives, the analysis shifted emphasis from magnitude of rotation to the pattern of change, improving differentiation between kinematic phenotypes. Derivative-based clustering identified motion patterns otherwise overlooked in a magnitude-based approach. As expected, it introduced greater overall dispersion, reflected in higher mean SD values (1.03 vs. 0.76). However, it also resulted in more stable variability, with a slightly lower mean coefficient of variation of SD (0.34 vs. 0.39). This suggests that while derivative-based clustering captures greater absolute variability, it does so in a structured manner, reducing random SD fluctuations and improving pattern stability. These findings highlight the variability of rotational dynamics in healthy knees and provide a novel framework for investigating kinematic patterns in pathological conditions.

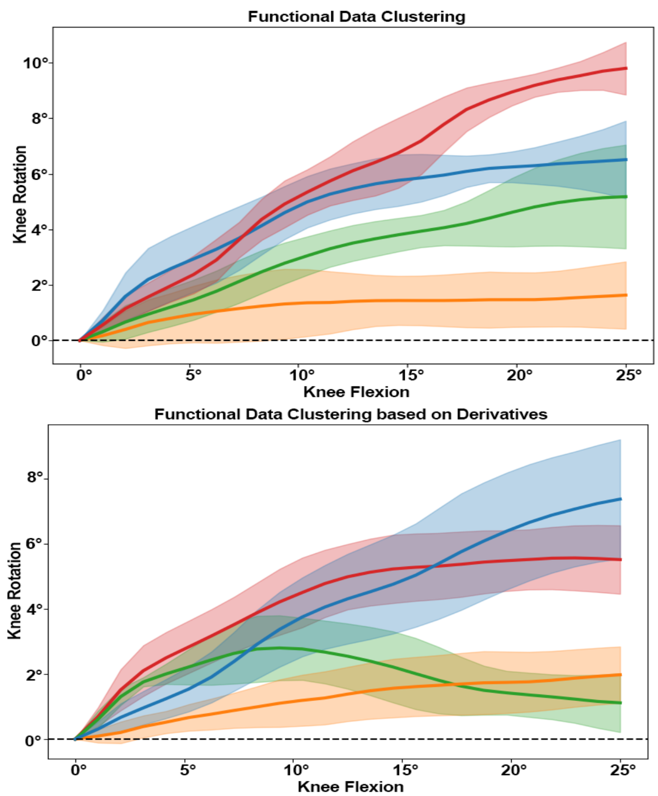

Figure 1: Functional data clustering of tibiofemoral rotation during knee flexion. Cluster means and standard deviations for four identified kinematic patterns. Top: Based on amplitude, Bottom: Based on first derivatives.

Conclusions

This study demonstrates derivative-based functional data clustering to distinguish patterns of internal and external tibio-femoral rotation during knee flexion. By prioritizing motion trends, this proof-of-concept method offers enhanced resolution in identifying kinematic phenotypes, paving the way for patient testing.

References

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