Novel methodology for the estimation of subject-specific knee IHA using a dynamic 3D scanner

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Summary

This study introduces a method to estimate a **subject-specific knee Instantaneous Helical Axis (IHA)** using **dynamic 3D motion capture (MOVE4D)**. The novel iterative approach approximates the thigh and shank as rigid bodies, optimizing their local reference frames with PCA and SVD. A four-bar linkage models knee motion, refining IHA estimation for improved musculoskeletal model (MSM) personalization.

Introduction

The modeling of the knee joint in MSMs has been a longstanding challenge due to its biomechanical complexity. Simplifications are often required to approximate an IHA that accurately represents an individual's knee kinematics. This study presents a methodology for estimating a subject-specific IHA for a given movement using a dynamic 3D scanner.

Methods

The MOVE4D system (Instituto de Biomecánica (IBV), Universitat Politècnica de València, Valencia, Spain) was employed to capture three-dimensional motion of subjects performing a squat exercise. This dynamic scanner generates a surface mesh of the body, comprising thousands of points whose positions vary over time. A novel methodology was then applied to approximate the thigh and shank as rigid bodies through an iterative removal process, eliminating points with the highest displacement relative to a defined local centroidal reference frame.

At each iteration, the local xyz reference system for each segment was defined as the centroidal frame that best represented the central tendency of the corresponding points in space. This reference frame was computed using Principal Component Analysis (PCA) and Singular Value Decomposition (SVD). The z-axis was aligned with the eigenvector corresponding to the largest eigenvalue, while the x- and y-axes were determined through an optimization process that minimized the displacement of local coordinates. This process also optimized the rotational alignment for each time frame. Once the optimal orientation was established, points exhibiting maximum displacement relative to the reference system were removed. The iterative refinement continued until improvements were considered negligible.

Subsequently, the knee joint motion was modeled using a fitted four-bar linkage, which provided an optimal representation of the relative motion between the thigh and shank. The personalized IHA of the knee was then estimated based on this fitted mechanism.

Results and Discussion

An example of the iterative point removal process is illustrated in Figure 1 (left). In this example, 500 out of 5058 points were removed per iteration for the thigh segment. The average deviation from the centroidal mean for each retained point is presented in Table 1. Upon applying the same procedure to the shank, a four-bar linkage was fitted to describe the relative motion of the two segments, enabling the estimation of the subject-specific knee IHA (Figure 1, right).

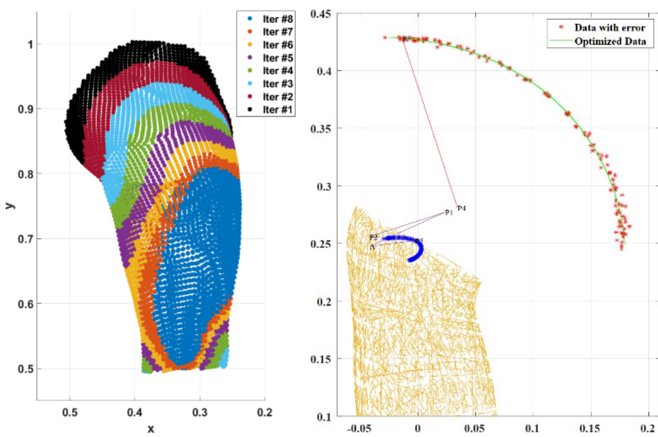

Figure 1: Points removed in each iteration for the thigh (left). Fitted four-bar linkage and personalized IHA estimation (right).

The application of a four-bar linkage mechanism allows for the estimation of the IHA within the sagittal plane, disregarding anteroposterior translation and axial rotation components of knee motion. While this assumption is likely valid for squat movements, the proposed iterative methodology could be adapted for alternative knee modeling approaches to further refine IHA computation.

Conclusions

A novel methodology was developed to estimate a personalized knee IHA for specific movements, enhancing MSM accuracy and individualization in biomechanical and clinical applications.

Table 1: Average deviation from the mean of each point of the thigh, for each iteration (summation of squared distances).

Iter. #	1	2	3	4	5	6	7	8
Dev. (mm)	18.81	18.07	10.58	7.007	5.315	4.316	3.185	2.128