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On the effect of measurement uncertainties on estimated knee ligament properties from laxity measurements

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Summary

We investigate how noise during laxity trials affect optimisation-based estimations of knee ligament properties. One subject-specific knee model with known ligament properties was created. Four sets of laxity trials, with an increasing number of load cases, were simulated and uniform noise ([-0.5, 0.5] (mm and degrees)) were added to the resulting kinematics. Stiffness and reference strain for ACL, PCL, MCL, and LCL were estimated from 20 samples of noisy kinematics. Stiffness error ranges of 6 kN, 8 kN, 9 kN, and 4 kN; reference strain error ranges of 3 %, 3 %, 2 %, and 2 % for ACL, PCL, MCL, and LCL, respectively, were found for the three sets of laxity tests (7, 13, and 22 load cases). The laxity test with 60 load cases resulted in stiffness and reference strain error ranges below 500 N and 1 %.

Introduction

Joint stability is important for a healthy joint and instability can lead to pain, joint degradation, decreased mobility, and an overall reduced quality-of-life [1]. Knee joint stability is primarily ensured by the ligaments in combination with the condyle geometry, menisci, and muscles. Despite the importance ligaments have on joint stability, existing investigations have primarily used in vitro methods [2] as these tissues are typically very difficult to assess in vivo.

Laxity measurements can be employed to assess the overall joint stability. Such measurements have recently been introduced to estimate ligament properties by utilizing optimization-based techniques [3]. However, laxity measurements are exposed to noise and how this affects the estimated ligament properties is currently unknown. Therefore, the purpose of this study was to investigate how kinematic measurement noise during laxity trials affect estimated ligament properties.

Methods

A subject-specific knee model was developed in the AnyBody Modeling System; including the anterior cruciate (ACL), posterior cruciate (PCL), medial collateral (MCL), and lateral collateral (LCL) ligaments, with material properties obtained from the literature [4].

The employed workflow to assess the effect of noise on the estimated ligament properties is shown in Figure 1. Four sets of laxity tests were performed on the model, each capturing translational (anterior, posterior) and rotational (varus, valgus, internal, external) load cases at varying knee flexion angles (0° or 30°) and load magnitudes, including seven (Set 1), 13 (Set 2), 22 (Set 3) and 60 (Set 4) load cases. For each set, 20 samples with uniform noise ([-0.5, 0.5] (mm and degrees)) were obtained and the ligament properties estimated from each noisy sample and compared to the known ligament properties.

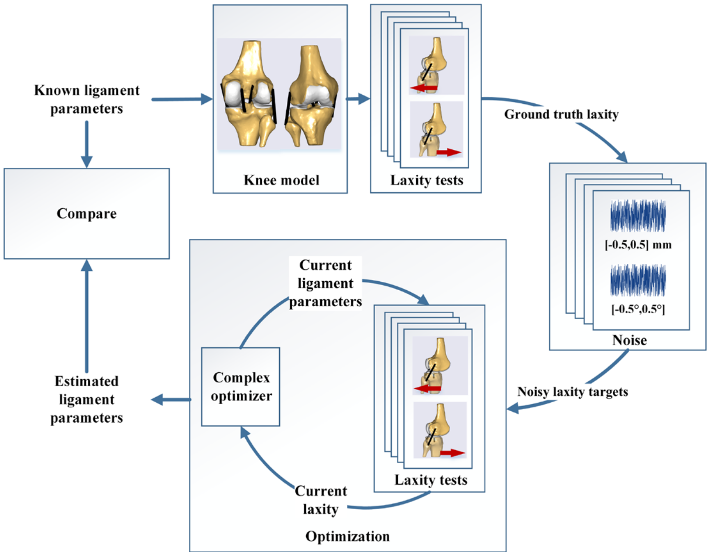

Figure 1: Assessment of noise on ligament property estimation.

Results and Discussion

We found a large range of estimated ligament properties (stiffness error ranges of 6 kN, 8 kN, 9 kN, and 4 kN; reference strain error ranges of 3%, 3%, 2%, and 2% for ACL, PCL, MCL, and LCL, respectively) for the three sets of laxity tests with fewest loads (7, 13, and 22 load cases). The laxity test with 60 load cases was able to keep the stiffness and reference strain error ranges below 500 N and 1 %, respectively.

Conclusions

Measurement noise, on the order of magnitude expected during bone pin marker-based motion capture or bi-planar x-rays of bone poses, have a large impact on estimated ligament properties. Therefore, we recommend that future studies assess and report both the estimated ligament properties and the associated uncertainties that arise from measurement noise.

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