Deciphering the "Art" in Modeling and Simulation of the Knee Joint: Model Benchmarking and Evaluation

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Summary

The goal of the multicenter KneeHub effort is to determine how decisions in developing physics-based models of the knee influence predictions of knee mechanics. Our objective in this benchmarking phase was to compare estimates from five independent teams to data from controlled cadaveric experiments. The benchmarking data corresponded to clinically relevant conditions of ACL deficiency and multiplanar loads simulating a clinical exam and were not used for model calibration. Differences were most prominent in estimates of axial rotation of the tibia. Extrapolating model predictions to knee states or loading conditions beyond those used in model calibration should be done with caution.

Introduction

Reproducibility and credibility of estimates derived from physics-based modeling and simulation tools are crucial for their adoption in the research setting and ultimate translation to clinical care. The goal of the multicenter KneeHub effort is to determine how modeling decisions influence estimates of knee mechanics across five independent teams with expertise in modeling and simulation [1]. The research effort included four modeling phases: development, calibration, benchmarking, and reuse [1]. This study focuses on the outcomes of the benchmarking phase of the project. To this end, our study objective was to quantify the level of agreement of each team's model estimates to a controlled cadaveric experiment.

Methods

For model development, each of the five teams utilized their prospectively documented modeling protocols with two publicly available experimental data sets: Open Knee(s) and Natural Knee [1]. Model benchmarking utilized data that were not included in the calibration phase of the study. Natural Knee benchmarking focused on assessing models with a deficient ACL in response to two tests: 1) uniplanar laxity in the anterior-posterior (AP), internal-external (IE), and varus-valgus (VV) directions at two flexion angles (15º and 55º) and 2) passive flexion from 0º to 120º of flexion. Open Knee(s) benchmarking focused on application of combined internal rotation (5 Nm) and valgus (10 Nm) moments at four flexion angles (0º, 30º, 60º, 90º) simulating the pivot shift clinical exam. Regarding our study objective, RMS differences were calculated for each team and each loading condition and summarized via mean and standard deviation.

Results and Discussion

Regarding Natural Knee, all models estimated less AP translation and less external rotation than the corresponding experimental measurements. Across all tests, IE rotation showed the greatest variability among teams (Table 1). Regarding Open Knee(s), differnces between model estimates and experimental measurements under the multiplanar torques were larger in IE than in the VV and AP directions (Table 1).

Table 1: RMS errors (mean and standard deviation) for specified degrees of freedom during benchmarking comparisons. Shaded cells correspond to loaded degrees of freedom.

Model	Test	AP (mm)	IE (deg)	VV (deg)
Natural Knee No ACL	AP Laxity	6.6 ± 2.4	13.5 ± 12.9	3.7 ± 2.0
	IE Laxity	4.7 ± 3.0	8.8 ± 4.2	3.3 ± 1.7
	VV Laxity	5.0 ± 3.4	8.8 ± 7.4	5.3 ± 3.4
	Passive flexion	6.1 ± 5.3	7.4 ± 5.8	4.0 ± 1.9
Open Knee	Combined Loading	1.6 ± 0.8	7.3 ± 3.8	1.7 ± 0.9

Variation between groups in their agreement with corresponding experimental data may stem from using different calibration strategies [3]. Regarding Natural Knee, those models that excluded the menisci may overcompensate by overtightening the remaining soft tissues. Regarding Open Knee(s), calibration strategies may require further tuning of the medial and lateral collateral and capsular ligament, which restrain axial rotation under multiplanar loads.

Conclusions

Extrapolating model predictions to knee states or loading conditions beyond those used in model calibration should be done with caution. Altogether, the KneeHub project provides insight on model validity and reproducibility and lays the foundation for standardized knee modeling workflows.

Acknowledgments

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References

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