Lessons Learned from the KneeHub Project - Harmonizing Knee Simulation Results Across Five Independent Teams

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INTRODUCTION: Modeling and simulation (M&S) continues to play an increasingly important role in the development and use of joint replacements, where virtual prototyping has influenced implant design and informed surgical and rehabilitation approaches [1,2]. The knee biomechanics community has taken significant strides to share modeling data [3], deliver software to build individualized knees [4], and understand the influence of modeling decisions [5]. Historically, however, M&S activities are performed by individual research teams using source data that is proprietary or inaccessible to the wider research community. Further, a challenge arises if the validity is based on comparisons with experimental results from the literature and prior M&S efforts. Addressing this challenge is a prerequisite for establishing credibility. Recent initiatives have emphasized verification and validation (ASME VVUQ40) and broadly applicable credible modeling practices (NIH IMAG/MSM Ten Simple Rules). Yet, a foundational concern emerges due to deviations in modeling and simulation of the same knee for the same purpose, i.e., the "art" of the modeler, or even deviations of a workflow when it is implemented again by the same modeler or by others, i.e., reproducibility. The absence of reproducibility, as dictated by the "context of use", is a significant barrier for adoption of simulation. An underappreciated concept is how independent modeling workflows contribute to discrepancies that may be encountered when comparing prediction results. Our NIH-sponsored "KneeHub" project evaluated the impact of independent modeling workflows and showed that even when target simulation scenarios and the source data to build models remained the same, variations in modeler's choices introduced uncertainties that influenced predictions [5] (Fig. 1.a and 1.b). This concept is taken a step further in the current study, where we aim to assess the steps needed to ensure that comparative analysis of kinematics across the KneeHub modeling teams was based on consistent coordinate frame placements and descriptions of motion.

METHODS: Previous activities included the delivery and documentation of modeling processes, working models, and outputs for five independent teams across four phases: Development, Calibration, Benchmarking, and Reuse. We focus here on the post-calibration phase results for the two freely-available experimental datasets (DU02 & OKS003) used in this project, where each team predicted passive flexion kinematics for both knees. The team-specific post-calibration deliverables were compiled to compare kinematic predictions, which required an evaluation of potential differences in the placement of the anatomical coordinate frames and the prescribed Grood and Suntay description of motion [6] (Fig 1.b). For all models, the team-specific kinematic predictions were also resampled in one-degree increments. After evaluation and updates to the team-specific predicted kinematics, anterior-posterior (AP), internal-external (IE), and varus-valgus (VrVl) versus knee flexion angle of each team for both models (uncalibrated and calibrated) were compared against the experimental data [5].

RESULTS: Evaluation of each team's models revealed variability in the orientation of the femoral and tibial coordinate frames (Fig 1.b). To enable comparisons between teams, each team's kinematic outputs were transformed to the same coordinate system as the original experimental data. Teams differed in the conventions used to describe the kinematics for each model (DU02 & OKS003) and the delivered results were transformed to the experimental data description of motion, which allowed direct comparison between the models and experiments (Fig 1.c). For the DU02 model, the experimental coordinate system is absolute clinical Grood and Suntay joint coordinate system (GS) rotations and translations [6]. In contrast, the OKS003 experimental coordinate system is cylindrical GS joint rotations and translations relative to a neutral full-extension experimental pose [6].

DISCUSSION: Despite utilization of the same source data, variability in the respective workflows of the modeling teams resulted in inconsistent coordinate frame placements and kinematic descriptions of motion. In spite of published standards [6,7], the lack of consistency resulted in the need to transform each team's predictions into a consistent interpretation of the description of motion (Fig 1.c), highlighting a lack of consensus in the reporting of simulation results across the group of established knee modelers. The need to perform these transformations was not initially captured in the team-specific reporting of workflow; this underscores the importance of access to the raw modeling products and data, and the need for dissemination of M&S assets. Further, community-established norms and standards for reporting coordinate systems and motions, e.g. 4x4 transformation, can facilitate results comparisons, model sharing, and evaluations of reproducibility.

SIGNIFICANCE/CLINICAL RELEVANCE: This study serves as a reminder that the comparison of competing M&S results is nontrivial and requires careful accounting of model coordinate frames and conventions. While the Grood and Suntay kinematic description of motion has emerged as the de facto standard in reporting of knee simulation results, team-specific interpretation impacted the validity of comparisons across the groups. This study highlights the need for detailed consensus modeling workflows, inclusive of the descriptions of motion and their reporting.

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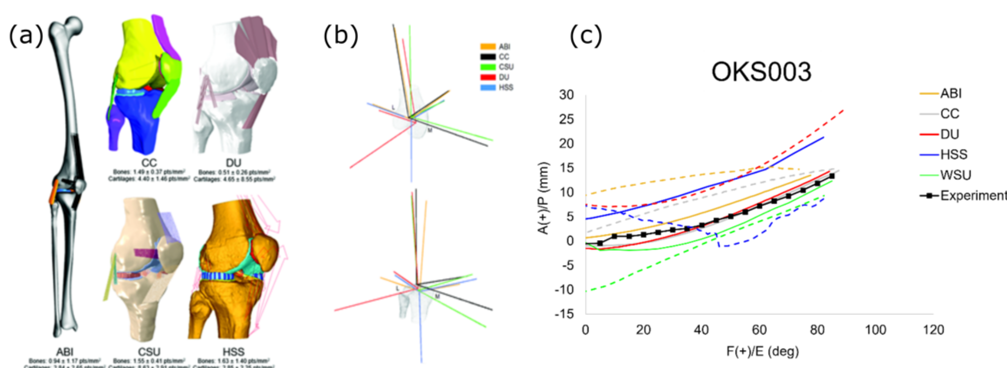

Figure 1. (a) Example knee models from the KneeHub project. (b) Femur and tibia coordinate frames from each modeling team before updating to consistent placement/orientation for one of two specimens. (c) Pre- and post-calibration predicted anterior-posterior displacement as a function of flexion angle for the OKS003 models after updating the coordinate frames and descriptions of motion. Pre-calibration results are the dashed lines and post-calibration are solid.