Computational Model Verification and Validation: An Emerging Pathway for Orthopaedic Regulatory Submissions

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INTRODUCTION: Computational modeling and simulation is commonly used in orthopaedic device development to assist with the determination of device safety and device performance. Model validation is a critical element to ensure that the model adequately addresses the specific question of interest. A risk-informed credibility assessment framework is currently being developed by ASME V&V40 subcommittee to serve as a guide to both the medical device industry as well as regulatory bodies [1]. Its purpose is to provide a consistent framework for assessing the rigor of verification and validation (V&V) activities to justify the credibility of the model with respect to its Context of Use (COU). This paper describes a pathway for validating an example knee implant finite element analysis (FEA) model using this framework (Figure 1).

METHODS: An example FEA model is used to evaluate strength of locking mechanism in a posterior stabilized total knee arthroplasty by measuring tibial component lift-off from the tibial tray, subjected to posteriorly directed load on the tibial spine (Figure 2). This model can have multiple COUs based on the amount of available additional information (e.g. bench testing, predicate device). Two COUs were considered: COU1 where a predicate device and benchtop test data are not available, and COU2 where both are available. While the framework does not prescribe a grading system, for the purpose of this example, a 3-level classification system was utilized; low, medium and high, for the risk assessment and credibility factors (CF) for the subsequent V&V activities.

Specifically, the assessment of model risk and determination of model credibility were performed for the two specific COUs.

RESULTS: The Model Risk (the possibility of the model leading to incorrect decision) depends on the combination of the decision consequence (e.g. patient harm) and influence (contribution of the model to the decision relative to other available information). For both COUs, the worst patient harm could lead to revision surgery depending on the amount of component lift-off, resulting in high consequence. The influence is high for COU1 because the tibial component lift-off is exclusively determined by the model. Alternately, the influence is low for COU2 because additional data from predicate device and benchtop testing are available. As such, the model risk is high for COU1 and medium for COU2, which drives the required level of rigor for the V&V activities and the CF within each activity (Figure 3) for each COU.

If a commercial finite element analysis (FEA) code is used, model credibility is increased by leveraging Code Verification efforts documented by the software provider. While a mesh convergence study should be performed for both COUs for Solution Verification, the mesh convergence for COU1 should target areas of lift-off in both components to quantify the error, and the model should be peer reviewed for accuracy. Consequently, the overall Verification level for COU1 and COU2 could be established as high and medium, respectively. Computer Model Validation incorporates both model form and model input CF. Model Form CF considered how the selected poly material model impacts the predictions. A nonlinear stress-strain curve for the poly material could be used from the literature for COU2. For COU1, a validated material model may be created using stress-strain data on the proprietary poly material. Model Input CF considered the component sizes and the geometry of the locking mechanism. For COU1, two component sizes can be selected from the product line, where as a single size can be used for COU2. Sensitivity of material conditions (least and maximum) can be evaluated for both sizes of the tray and poly locking mechanism areas for COU1. Components can be modeled at nominal dimensions for COU2. Interference fit can be modeled between the tray and the poly to capture the residual effects in the poly for both COUs. Additionally, the process of inserting poly into tray could be modeled for COU1. For the purpose of this example, the Comparator Validation CF (bench-top test) can target credibility levels of high and medium for COU1 and COU2, respectively based on the rigor associated with test sample measurements and how well the test conditions were controlled. Validation Assessment considered the equivalency of input and output parameters for both the model and the comparator. For COU1, the force could be applied through a femur modeled as a flexible component, whereas the femur could be modeled as a rigid body for COU2. It is assumed that the output from the model will closely match with the benchtop test measurement within the error established by the mesh convergence study. For both COUs, the lift-off displacement could be measured in the model as well as in the benchtop test; however, for COU2, the standard deviation among test samples need not be quantified because the model risk is low. The overall Validation levels (Computer Model Validation, Comparator Validation, and Validation Assessment) for COU1 and COU2 could be established as high and medium. The Applicability CF could be determined as high for both COUs based on the relevance of the V&V activities to the quantity of interest (lift-off displacement) and to the respective COUs. Thus, the V&V activities described in this example could meet the required credibility goals of high and medium for COU1 and COU2, respectively for the model to be considered validated for the respective COUs.

DISCUSSION: This example demonstrates the application of an emerging V&V framework for validating a computational model for clearly defined contexts of use. The same model can be used for multiple COUs by establishing different levels of credibility goals for the individual V&V activities. In addition to the model, the appropriate level of rigor required for the comparator (e.g., validation experiment) should be noted, so that a careful V&V plan is established. Once the risk informed credibility requirement is established, users are encouraged to contact regulatory bodies to verify the planned strategy, if in doubt. Finally, the goal of the framework is to provide guidance to individual organizations for establishing their own strategies for its application. It is the responsibility of an analyst to properly articulate the decisions made based on the V&V activities, when submitting the data based on computational models.

SIGNIFICANCE/CLINICAL RELEVANCE: While regulatory bodies accept the evidence for medical design safety based on computational models, currently there is no standard for establishing credibility of the model. This creates ambiguity regarding the outcome of the submission utilizing data from computational models, and in many cases results in increased cost due to unnecessary benchtop testing as well as increased time to market. This framework provides a pathway for validating models based on its context of use by minimizing the uncertainty of its use in regulatory submissions. It not only helps to ensure that correct decisions are made based on models, but also minimizes the efforts, in some cases, if additional information is available. This framework aims to reduce the current ambiguity and uncertainty associated with modeling use in regulatory submissions and drive the CDRH goal of advancing the innovation process for medical device development.