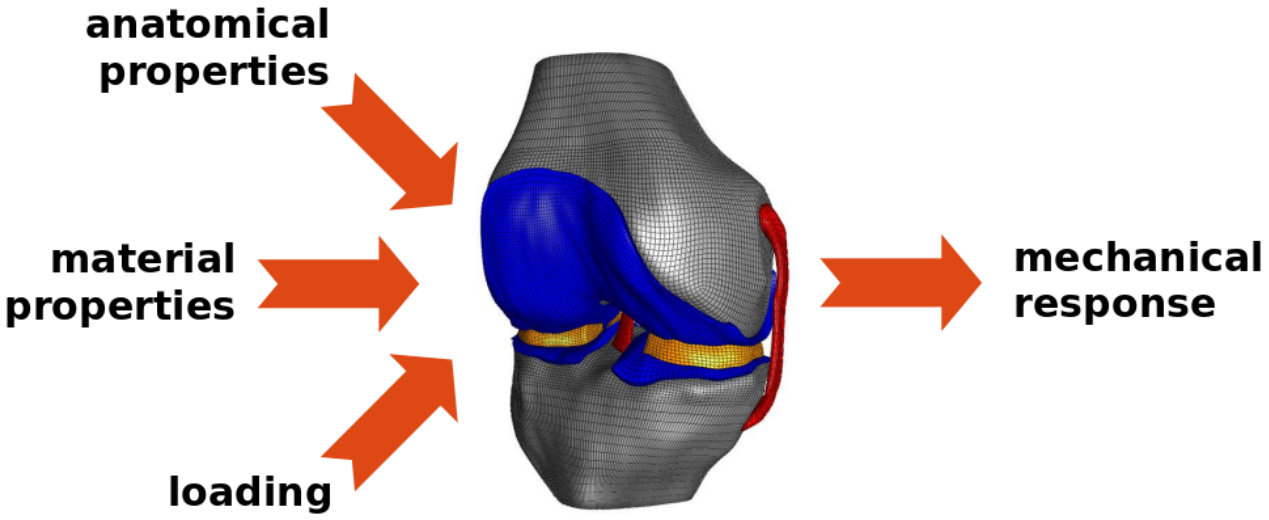
Before you start

Understand the Premise of FEA

Finite element analysis is a computational modeling & simulation strategy; specifically, a numerical procedure for solving field problems, e.g., stress, by dividing the problem domain into finite elements, i.e., a mesh. For biological structures, finite element analysis provides the platform for i) representation of anatomical properties, e.g., geometry of the knee and its tissue structures, ii) representation of physiological properties, e.g., tissue material properties such as Young's modulus, iii) prescription of loads (and boundary conditions) acting on the structures of interest, e.g., forces applied to the knee, and iv) simulations to explore the response of the system, e.g., mechanical response - for the case of the knee, tissue stresses and strains, and joint movement.



Define the problem and identify FEA as the favorable modeling & simulation strategy

The workflow for FEA assumes that this modeling & simulation strategy is indeed the favored tool to solve the problem. It is anticipated that this decision is made by following a broad, model agnostic workflow, where the problem is defined and conceptualizations were made to see how modeling & simulation can help and what type of modeling & simulation may be appropriate. Such a workflow is provided in Box 1 for guidance. The FEA specific workflow presented in the rest of the document will likely have some overlaps with such broader strategy independent workflows. Nonetheless, these steps provide opportunities for re-evaluation of the chosen path.

Before you start

Box 1. A broad modeling & simulation strategy agnostic workflow to define the problem, the utility of modeling & simulation and selection of a favorable modeling and simulation strategy (courtesy of C. Anthony Hunt. PhD).

1. Domain and Context
   - 1.1. Specify the biomedical research & development context, e.g., risk of cartilage degeneration in relation to its mechanics.
   - 1.2. Describe broad biomedical issues/questions/needs, e.g., is cartilage at increased risk of degeneration following anterior cruciate ligament deficiency?
   - 1.3. Identify referent experimental systems.
   - 1.4. From a very broadly computational modeling & simulation perspective: how is it envisioned that modeling & simulation approaches may contribute to 1.2? E.g., prediction of cartilage stresses for altered joint mechanics.
2. Objectives
   - 2.1. Spanning wet-lab and computational modeling & simulation perspective: state scientific objectives (immediate, near-term, longer-term)
   - 2.2. .From a broad modeling & simulation perspective: what model usage type might be needed to approach 1.4? E.g., predictive, analysis, heuristic, reproduce another lab's computational modeling & simulation work, challenge a hypothesis, etc.
   - 2.3. What criteria will be used to recognize outcomes (that progress is being made in achieving 2.1)? E.g., visualizations, validations, falsified hypotheses, iteration logging, etc.
3. Usage patterns (a pattern = similar use cases)
   - 3.1. Identify wet-lab experimental system usage patterns from 1.3.
   - 3.2. Detail planned & envisioned (immediate, near-term, longer-term) model usage patterns.
   - 3.3. Identify targeted attributes.
   - 3.4. How will 3.2 synergize with 3.1?
   - 3.5. Metrics: for a given usage pattern, how will model outputs and targeted attributes be mapped to outcome criteria?
   - 3.6. Design concrete verification cases for each usage pattern.
4. Survey
   - 4.1. What prior modeling approaches have been used for one or more usage pattern from (3)?
   - 4.2. Can an available (external or internal) model be repurposed?
   - 4.3. Given (2) & (3), are there standard formats and model structures? Should they be adopted?
5. Requirements
   - 5.1. Given 2–4, list immediate, near-term, and longer-term requirements.
6. Implementation
   - 6.1. Decide on modeling & simulation approaches and structures needed to actualize (3) & (5).

[1] Confirm suitability of FEA for the problem

Activities

If not done already as part of a broader workflow to identify modeling & simulation strategy, follow the activities listed below. If already done, review and detail with relevance to FEA.

1. Ask your question explicitly.
2. Identify specific domains,
    1. physiological, and
    2. mechanical.
3. Identify structure of interest.
4. Identify characteristics of modeled sample(s),
    1. demographics,
    2. state (in vivo, in vitro, in situ), and
    3. health condition.
5. Identify scales,
    1. spatial, and
    2. temporal scale.
6. Identify desired utility.
7. Identify expected outcomes.

[2] Confirm suitability of FEA for variables of interest

Activities

If not done already as part of a broader workflow to identify modeling & simulation strategy, follow the activities listed below. If already done, review and detail with relevance to FEA.

1. Identify variables to make decisions in relation to defined problem,
    1. which can be acquired directly from simulation results, or
    2. which require further processing of simulation results.
2. Identify variables to evaluate correspondence of simulation results to reality,
    1. which can be acquired directly from simulation results, or
    2. which require further processing of simulation results.

[3] Check availability of models & data relevant to FEA

Activities

If not done already as part of a broader workflow to identify modeling & simulation strategy, follow the activities listed below. If already done, review and detail with relevance to FEA.

1. Search for previous models developed to resolve similar problems, which can be reused for simulations relevant to the problem.
2. Search for previous models developed to resolve other problems, which can be repurposed and reused for simulations relevant to the problem.
3. Check access to information that can be used directly to assemble the model, e.g., derivative data presented in the form of geometries, meshes, material properties, loading conditions, etc.
4. Check access to raw data that can be processed and used to build the model, e.g., imaging of the structure of interest, raw physiological testing data.
5. Identify existing knowledge and data to evaluate correspondence of simulation results to reality.

[4] Acquire data

Activities

1. Collect data to inform anatomical properties of the model.
2. Collect data to inform physiological/material properties of the model.
3. Collect data to inform simulation scenarios of the model, e.g. loading.
4. Collect data to evaluate correspondence of simulation results to reality.
5. Use data management system to organize data and keep them under version control.

[5] Choose simulation software for FEA

Activities

1. Choose simulation software relevant to physiological and mechanical domains of interest.
2. Decide which version of the simulation software you will be using.
3. Choose solution strategy available within the simulation software relevant to domains of interest.
4. If default setting is not desirable, determine convergence criteria used for completion of a simulation.
5. Verify capabilities of the simulation software relevant to the components needed to solve the problem.
6. If licensing (cost) is an issue, identify alternative simulation software.
7. If necessary, integrate your own code into existing simulation software.
8. If necessary, rebuild simulation software based on available software libraries.

[6] Process data (pre-processing)

Activities

1. Process anatomical data to define the geometry of the model:
    1. imaging to geometry (segmentation),
    2. geometry to mesh (meshing), and
    3. set definitions on mesh, to define regions for prescription of properties, loading conditions, interactions, etc in model assembly.
2. Process physiological/material data to define physiological/material properties of the model, i.e., constitutive modeling to obtain material coefficients from stress-strain data.
3. Extract loading and boundary conditions from data relevant to simulation scenarios.
4. Extract biomechanical metrics, relevant to simulation output variables, from raw data collected to evaluate correspondence of simulation results to reality.
5. Use data management system to organize derivative data and keep them under version control.
6. Use version control system to organize and keep track of data analysis code and scripts.

[7] Assemble model

Activities

1. Assemble derivative data, e.g. meshes, physiological/material parameters (constitutive coefficients) to define subcomponents of the model, i.e. anatomical and physiological representation of biological structures.
2. Define interactions between subcomponents of the model, i.e. mechanical connections and data exchange pathways between subcomponents.
3. Prescribe simulation scenarios, i.e. loading and boundary conditions, relevant to the defined problem.
4. Use version control system to organize and keep track of different model assemblies.

[8] Conduct simulations

Activities

1. Conduct simulations to assess mesh convergence (a verification step).
2. Conduct simulations to evaluate correspondence of simulation results to reality (a validation step).
3. Conduct simulations to evaluate uncertainty of simulation results (a sensitivity analysis step).
4. Conduct simulations to make decisions in relation to the defined problem.
5. Use data management system to organize simulation results and keep them under version control.

[9] Process simulation results (post-processing)

Activities

1. Visualize and extract variables, which can be acquired directly from simulation results,
    1. relevant to mesh convergence,
    2. relevant to correspondence of simulation results to reality, and
    3. relevant to uncertainty in simulation predictions.
2. Process simulation results to calculate and store variables
    1. relevant to mesh convergence,
    2. relevant to correspondence of simulation results to reality, and
    3. relevant to uncertainty in simulation predictions.
3. Visualize and extract variables that can be acquired directly from simulation results, which can potentially be useful to make decisions in relation to the defined problem.
4. Process simulation results to calculate and store variables that can potentially be useful to make decisions in relation to the defined problem
5. Use data management system to organize processed simulation results and keep them under version control.
6. Use version control system to organize and keep track of code and scripts for analysis of simulation results.

[10] Interpret results

Activities

These activities can be a part of a broader workflow independent from the selected modeling & simulation workflow. When needed, specialized treatment due to the use of FEA may be necessary.

1. Confirm the association between variables used to evaluate correspondence of simulation results to reality to those used to make decisions in relation to defined problem.
2. Indicate the influence of the bounds of verification, validation, and sensitivity analysis results on potential errors in making decisions in relation to defined problem.
3. Indicate the practical implications of potential errors in making decisions in relation to defined problem.
4. Make decisions in relation to defined problem.

[11] Report

Activities

These activities can be a part of a broader workflow independent from the selected modeling & simulation workflow. When needed, specialized treatment due to the use of FEA may be necessary.

1. Document study indicating
    1. model identifiers & structure,
    2. simulation conditions, parameters, and solution settings,
    3. verification & validation, uncertainty estimation, sensitivity,
    4. assumptions and limitations, and
    5. availability.
2. Prepare a User's Guide describing the model in detail with sample use cases, e.g. simulation scenarios.
3. Publish implications of simulation results for scientific review of modeling workflow and conclusions of simulations.
4. Conform to available recommendations for reporting[1].

References

1. Erdemir A, Guess TM, Halloran J, Tadepalli SC, Morrison TM. Considerations for reporting finite element analysis studies in biomechanics. J Biomech. 2012 Feb 23;45(4):625-33.

[12] Share

Activities

These activities can be a part of a broader workflow independent from the selected modeling & simulation workflow. When needed, specialized treatment due to the use of FEA may be necessary.

1. Choose licensing for dissemination, e.g. public (at various levels) or private.
2. Disseminate raw data used for modeling, e.g., imaging, physiological/mechanical testing, ideally in human readable, openly accessible, or standardized formats .
3. Disseminate derivative data used for modeling, e.g., geometries, meshes, constitutive coefficients, ideally in human readable, openly accessible, or standardized formats.
4. Disseminate model(s), ideally in human readable, openly accessible, or standardized formats.
5. Disseminate workflows, i.e., specifications of building the model, conducting simulations, and evaluating and interpreting simulation results.
6. Provide access to data management and source code version control systems during development and/or afterwards.
7. Utilize sustainable repositories for long term dissemination of release versions of data, derivative data, scripts, model(s), etc.