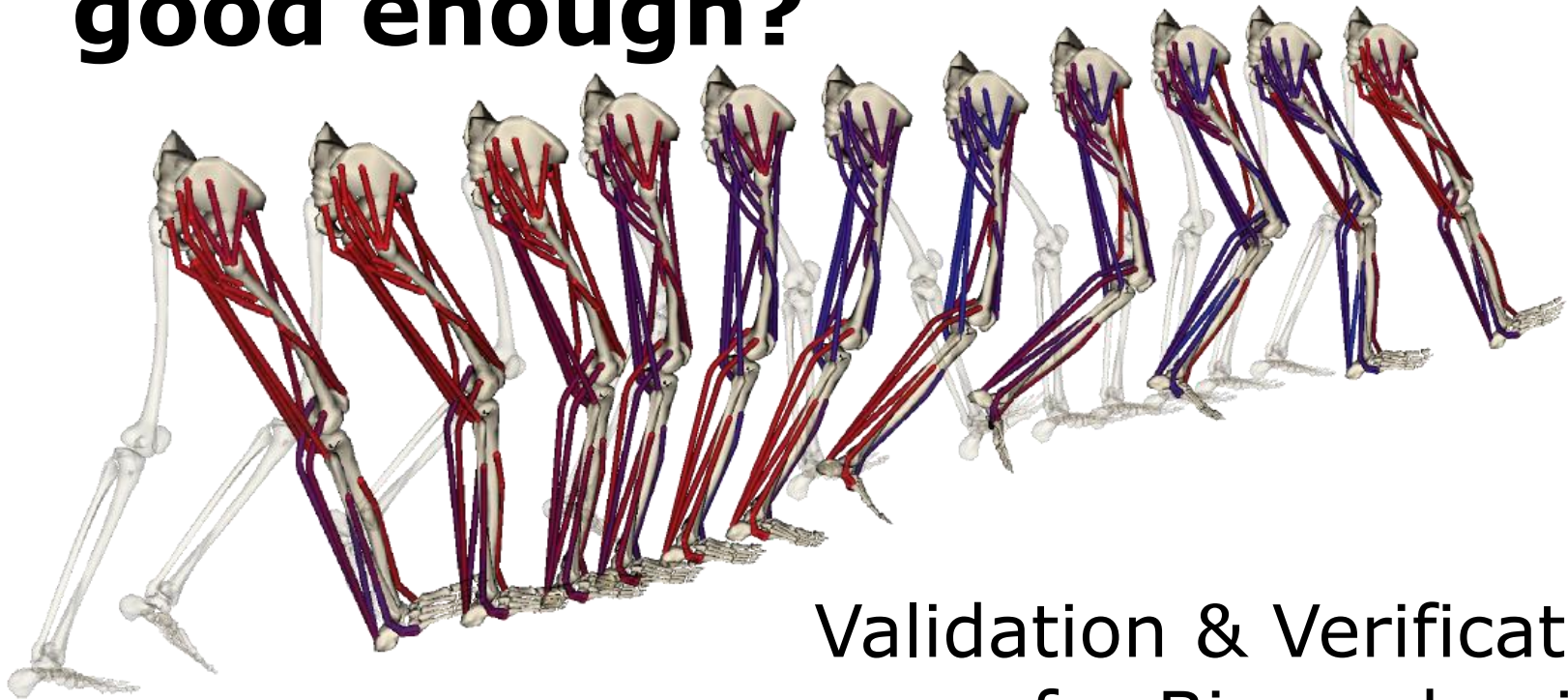


Is my simulation good enough?



Validation & Verification
for Biomechanical
Modeling and Simulation



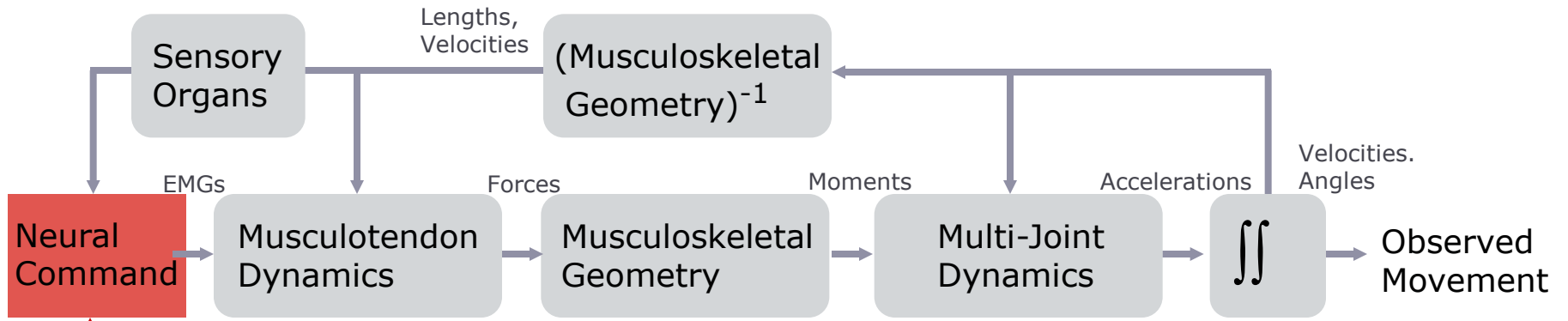
Why simulation?



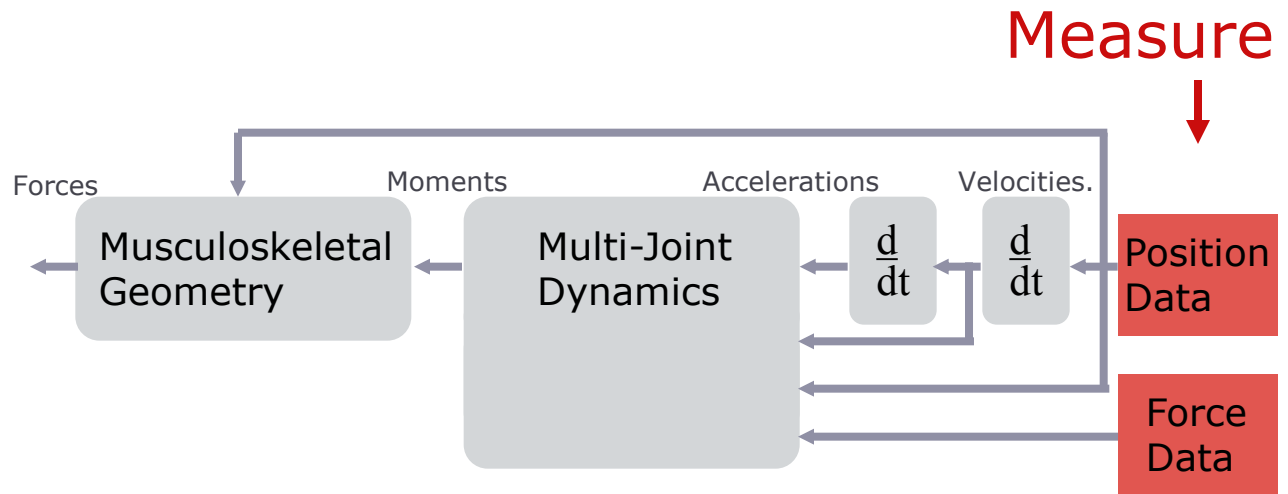
Huge impact in many fields

Better than trial and error!

What is biomechanical modeling and simulation?



↑
Measure or Estimate



Definitions: Validation and Verification

Verification

The process of determining that a computational model accurately represents the underlying mathematical model and its solution.

“solving the equations right”

Validation

The process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model.

“solving the right equations”

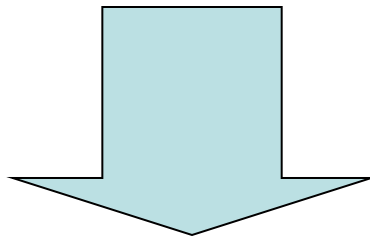
Validation is challenging, particularly in biomechanics

- *Biologists and Clinicians*: Randomized controlled trials are not possible.
- *Engineers*: There are many things that we can't measure precisely.

Importance of Verification and Validation

Musculoskeletal models and simulations of movements

Gap between growth of applications and clinical practice!



Accuracy and Reliability

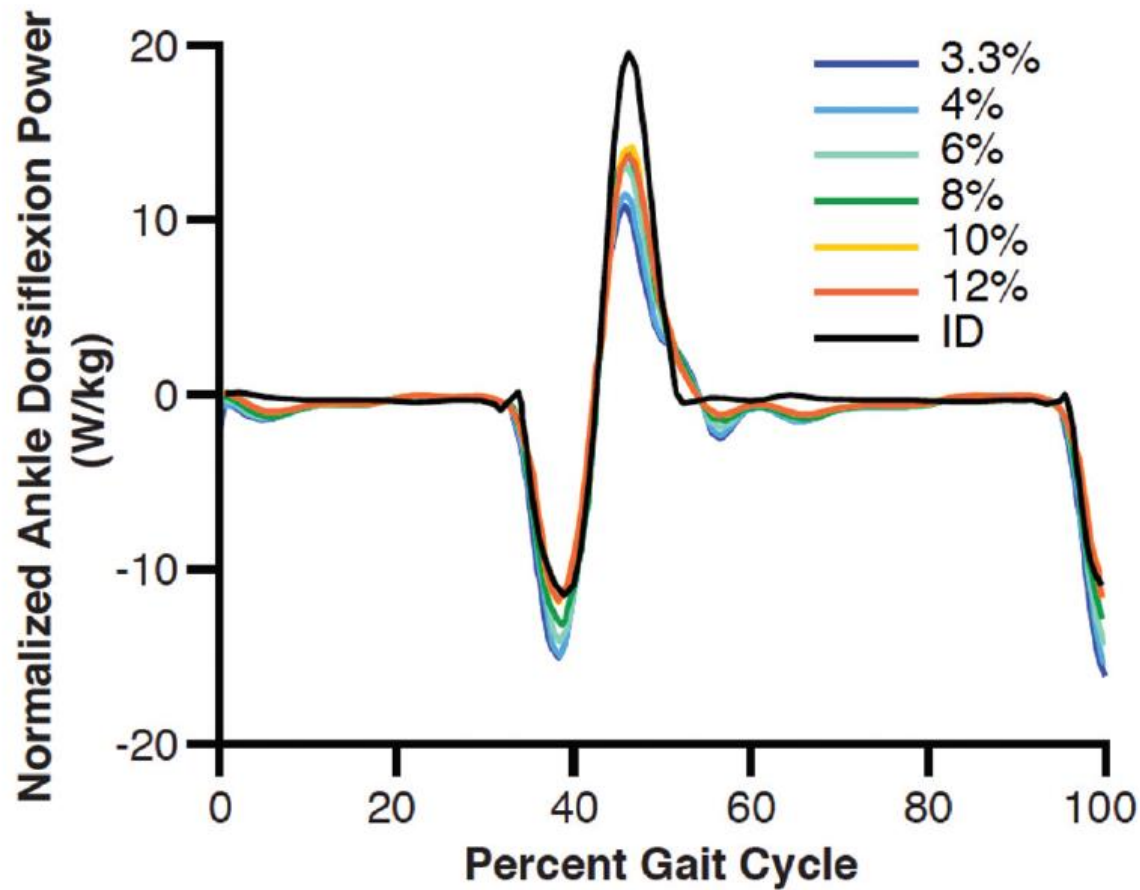
Why are verification & validation important?

1. It's good science.
2. It will help you make an impact by convincing modelers and non-modelers alike to trust and apply your research.
3. It helps prevent major and minor disasters.

Key Principles for Validation and Verification

1. Define a research question that a model can answer.
2. Understand and evaluate your methods.
3. Verify your software.
4. Test robustness by assessing sensitivity.

Ankle Power



Arnold et al., 2013

Key Principles for Validation and Verification

1. Define a research question that a model can answer.
2. Understand and evaluate your methods.
3. Verify your software.
4. Test robustness by assessing sensitivity.
5. Compare to experiments and other models.
6. Make real-world predictions and hypotheses.

Validation Challenges for the Field

- Create more gold standard datasets
- Share models and simulations so others can reproduce and extend
- Develop tools to help automate validation and sensitivity testing
- Learn and teach others what is inside the “black box”
- Hit more home runs with biomechanical modeling and simulation

Rules of good practise - Scaling

- Rely on **anatomical landmarks** and functional joint centers (FJC)
- Scaling is an iterative process. "**preview static pose**" option in the GUI.
- Check **marker errors**:
 - maximum marker errors for bony landmarks should be less than 2 cm.
 - RMS error should typically be less than 1 cm.
 - Pay close attention to errors in the bony landmark and FJC markers when assessing the quality of your scaling results.
- Visualize model and verify model fit.
- **Adjust** the virtual markers and marker weightings to improve your results (NOT anatomical and HJC)

Rules of good practise – IK/ID

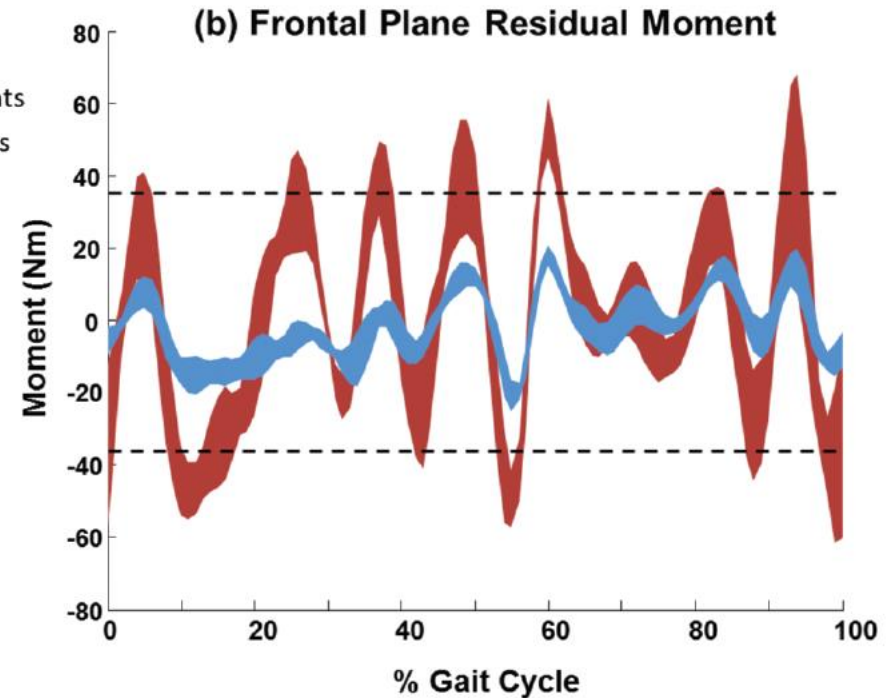
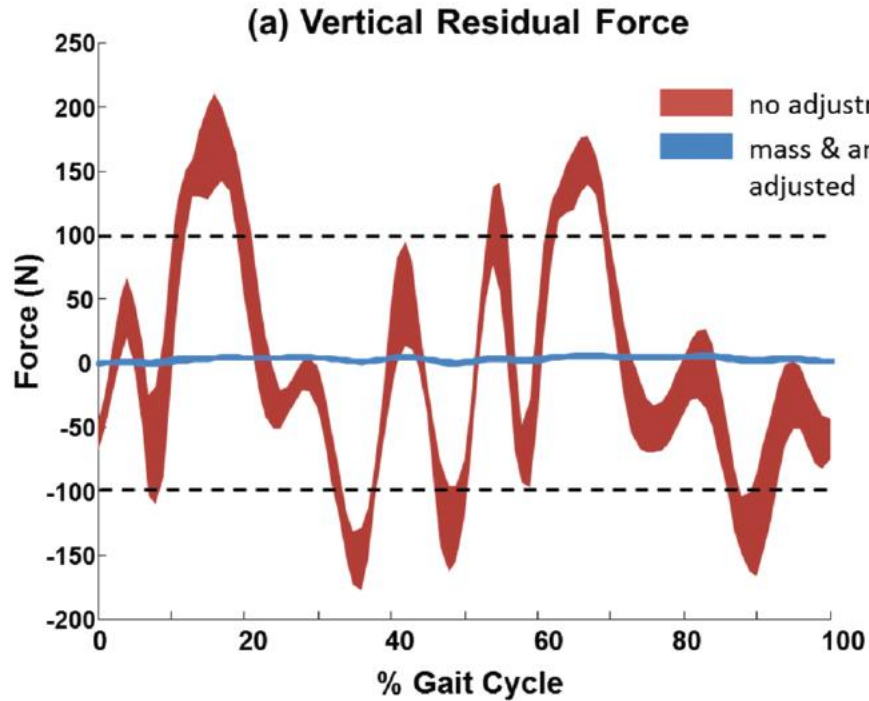
- Weight "**motion**" **segment markers** (technical markers) more heavily than anatomical markers
- **Relative marker weightings** are more important than their absolute values
- **Verify the marker error**
 - Maximum marker error should generally be less than 2-4 cm, and RMS under 2 cm is achievable.
- Check with other 3D Mocap Software
 - Do not expect absolute agreement
 - Cfr offset of pelvis coordinate system and hip angle.
 - Cfr ankle angle kinematics due to subtalar joint.

Rules of good practise - RRA

- All forces need to be known !
- **Trunk data** needed!
 - Keep **optimal forces** for residuals low (increase control bounds if necessary)
 - Verify magnitude of **mass adjustments**
 - Floating or Sinking models? -> check overall **model mass**.
 - Verify magnitude of **residual forces**
 - Verify changes in the kinematics

RRA example

Hamner et al. 2010

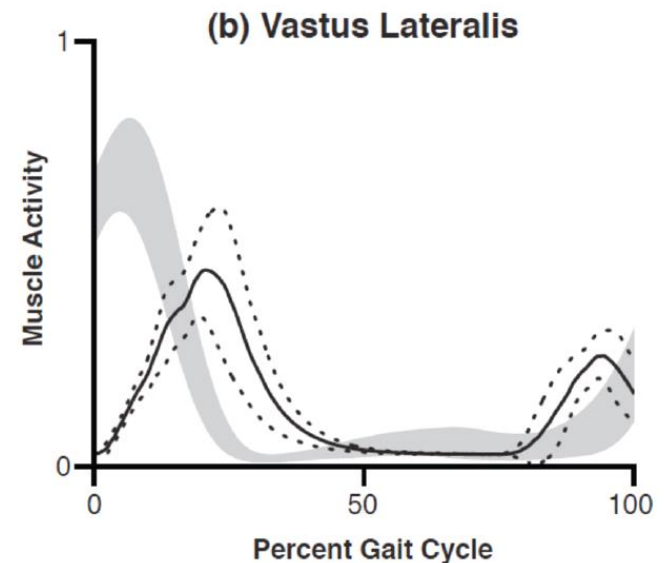
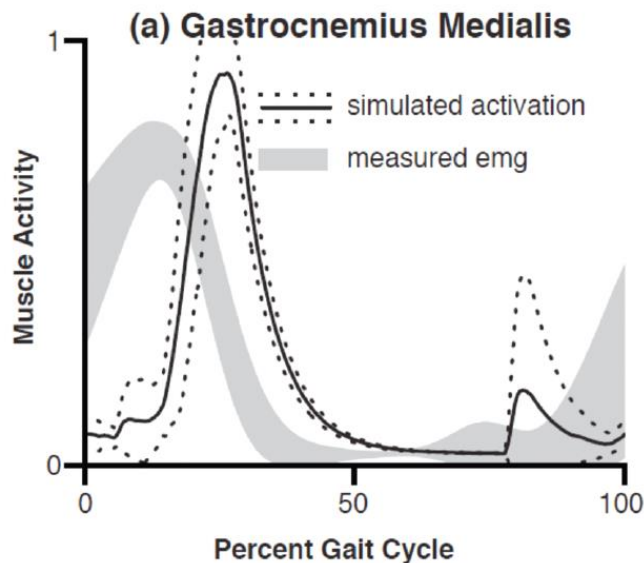


Rules of good practise - RRA

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 - Verify magnitude of **residual forces**
 - Verify changes in the kinematics
 - Adjust **application point of forces on the pelvis to adjusted pelvis COM** (Actuator file)
- Lower weight on kinematics that track closely or have low confidence in measurement
- Make mass adjustments and run RRA again - repeat until residuals no longer change

Rules of good practise – CMC/SO

- Verify the changes in kinematics (CMC)
- Compare muscle activation to **experimental EMG**
- Verify the level of involvement of the **reserve actuators**
- Verify maxing out of **muscle actuators**.
 - Explosive movements: Double/triple maximal isometric force (?)



Rules of good practise

- Joint Reaction Forces
 - Compare to experimental data from instrumented implants.
 - Cave!: reserve actuators do not contribute to reaction forces.
- Induced acceleration analysis
 - Verify superposition

1
2
3
4
5
6

Jennifer L. Hicks¹

Department of Bioengineering,
Stanford University,
Stanford, CA 94305
e-mail: jenhicks@stanford.edu

Thomas K. Uchida

Department of Bioengineering,
Stanford University,
Stanford, CA 94305

Ajay Seth

Department of Bioengineering,
Stanford University,
Stanford, CA 94305

Apoorva Rajagopal

Department of Mechanical Engineering,
Stanford University,
Stanford, CA 94305

Scott L. Delp

Department of Bioengineering and the
Department of Mechanical Engineering,
Stanford University,
Stanford, CA 94305

Is My Model Good Enough? Best Practices for Verification and Validation of Musculoskeletal Models and Simulations of Movement

Computational modeling and simulation of neuromusculoskeletal (NMS) systems enables researchers and clinicians to study the complex dynamics underlying human and animal movement. NMS models use equations derived from physical laws and biology to help solve challenging real world problems, from designing prosthetics that maximize running speed to developing exoskeletal devices that enable walking after a stroke. NMS modeling and simulation has proliferated in the biomechanics research community over the past 25 years, but the lack of verification and validation standards remains a major barrier to wider adoption and impact. The goal of this paper is to establish practical guidelines for verification and validation of NMS models and simulations that researchers, clinicians, reviewers, and others can adopt to evaluate the accuracy and credibility of modeling studies. In particular, we review a general process for verification and validation applied to NMS models and simulations, including careful formulation of a research question and methods, traditional verification and validation steps, and documentation and sharing of results for use and testing by other researchers. Modeling the NMS system and simulating its motion involves methods to represent neural control, musculoskeletal geometry, muscle tendon dynamics, contact forces, and multibody dynamics. For each of these components, we review modeling choices and software verification guidelines; discuss variability, errors, uncertainty, and sensitivity relationships; and provide recommendations for verification and validation by comparing experimental data and testing robustness. We present a series of case studies to illustrate key principles. In closing, we discuss challenges the community must overcome to ensure that modeling and simulation are successfully used to solve the broad spectrum of problems that limit human mobility.

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Hicks JL, Uchida TK, Seth A, Rajagopal A, Delp SL. Is my model good enough? Best practices for verification and validation of musculoskeletal models and simulations of movement. J Biomech Eng. 2015 Feb 1;137(2). doi: 10.1115/1.4029304. Epub 2015 Jan 26. PubMed PMID: 25474098.