Framework For Building Finite Element Musculoskeletal Simulations Directly From Motion Data

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Introduction

- Orthopaedic diseases and injuries often **affect tissues at the microstructural scale** and small-scale pathology **impacts biomechanics at larger scales**, leading to whole-body movement compensations and further injury.
- A **multiscale approach** is needed in musculoskeletal simulation to elucidate the etiology of diseases, mechanisms of adaptation, and best treatment strategies.
- Advances in computational efficiency are making sophisticated musculoskeletal finite element (MSFE) models more practical [1,2]. **Yet, the formulation of subject-specific MSFE simulations remains a challenging problem**.

The goal of this work was to develop a software for building multiscale MSFE simulations directly from data collected in a standard motion laboratory.

Methods

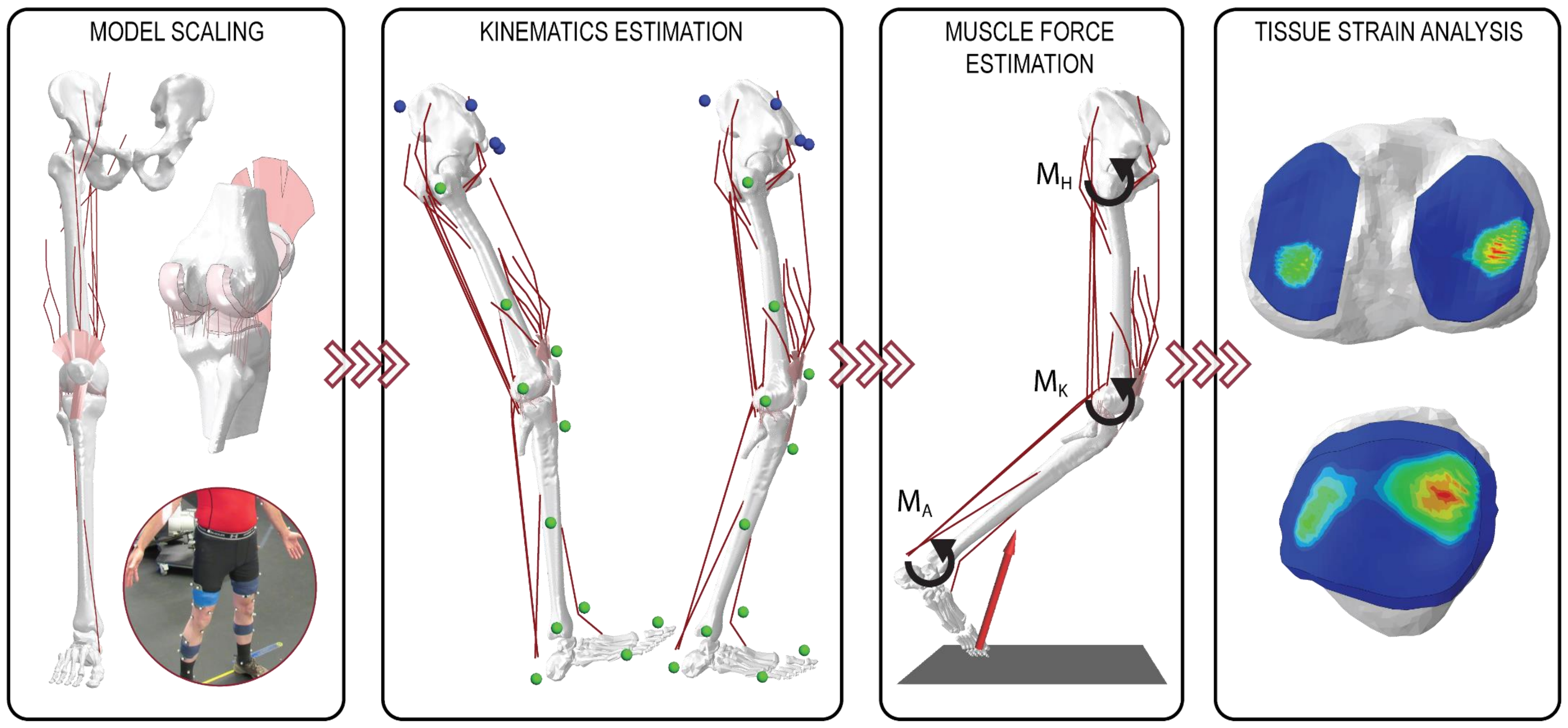

Figure 1: *ReadySim* is a software for preparing subject-specific multiscale finite element models for use in simulations of activity.

- We developed a user-friendly software, *ReadySim*, to build and run simulations that scale the size of a template MSFE model [1] and efficiently estimate joint kinematics and muscle forces from human motion data collected in a typical gait laboratory.
- *ReadySim* uses marker data to scale model segment lengths and estimate joint kinematics.
- Concurrent muscle force and tissue strain estimations are performed based on the estimated kinematics and ground reaction forces.
- *ReadySim* and a template model are made freely available on SimTK on the ReadySim project page to increase transparency in modeling and simulation.

Results

- *ReadySim* was used to scale the size of the multi-scale MSFE model to match subject marker data.
- Pelvis, femur, tibia, and foot were scaled in the ML (SF=1.09), SI (SF=0.97), SI (SF=0.96), and AP (SF=1.14) axes, respectively.
- Joint kinematics were estimated for the stance phase of gait and chair rising (3.5mm < RMSE < 11mm).
- Concurrent muscle force and tissue strain estimations were performed with resulting joint contact forces similar to patients with instrumented knee implants [3].
- *ReadySim* software managed parallel process control while performing kinematics and muscle force estimation on 13 time points concurrently for gait and chair rising, requiring 100 hours of computational time.

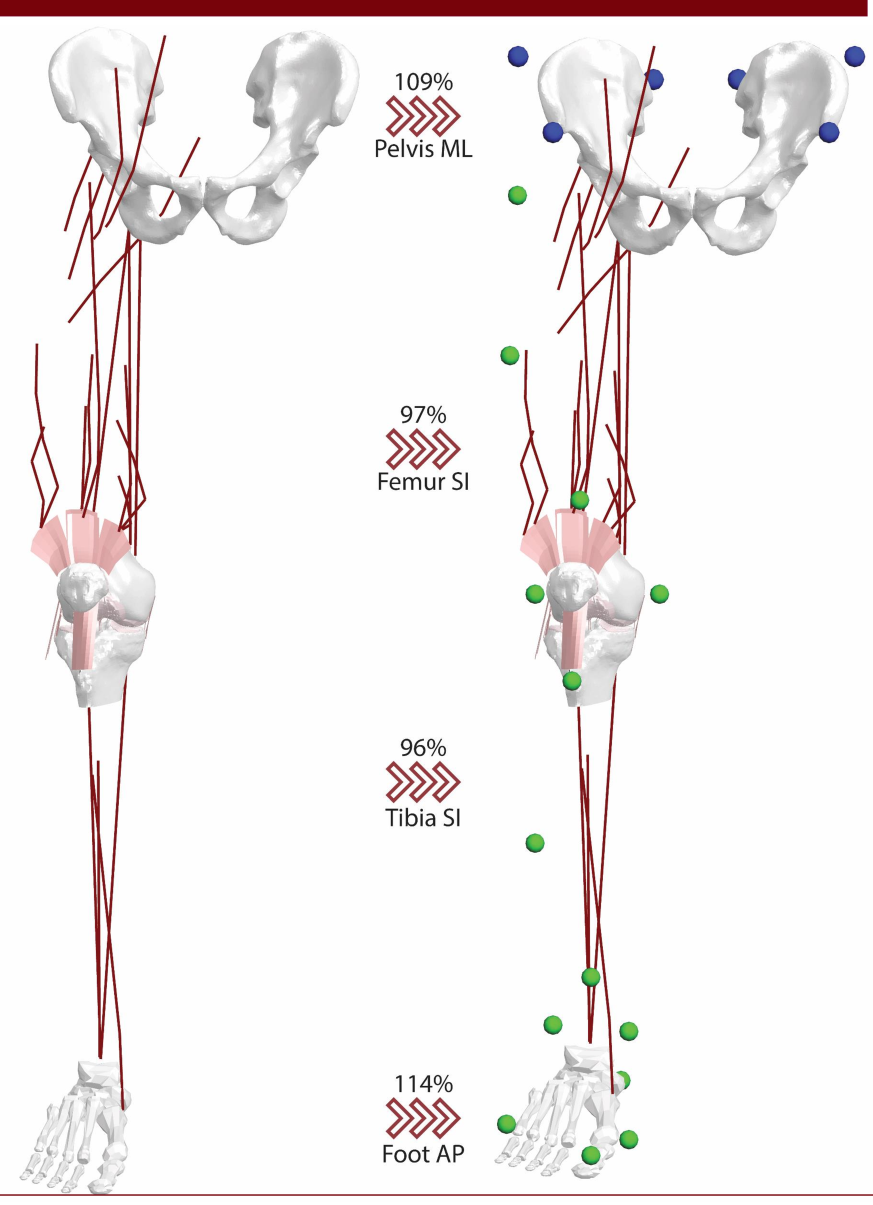

Figure 2: Template musculoskeletal finite element model (left) and model scaled to subject (right).

Discussion

- *ReadySim* provides a platform for researchers to perform multi-scale musculoskeletal simulations from data collected in the motion laboratory.
- This allows for single framework muscle force, joint force, and tissue strain estimation.

Significance: A software for developing multiscale MSFE simulations from laboratory data promotes 1) rapid development of complex models and simulations and 2) allows researchers to consider the coupled interaction of joint and whole body mechanics.

Limitation 1: Muscle requires a deformable 3D volumetric representation to understand the multiscale interaction between muscle and joint mechanics.
Limitation 2: Despite subject-specific model scaling, the template model incorporates a specimen-specific knee with calibrated soft tissue response convoluting model results.

Future Direction

The long-term goal is to develop high-fidelity subject-specific neuromusculoskeletal models which couple full body motion with joint and tissue mechanics to better understand pathology and response to treatment.

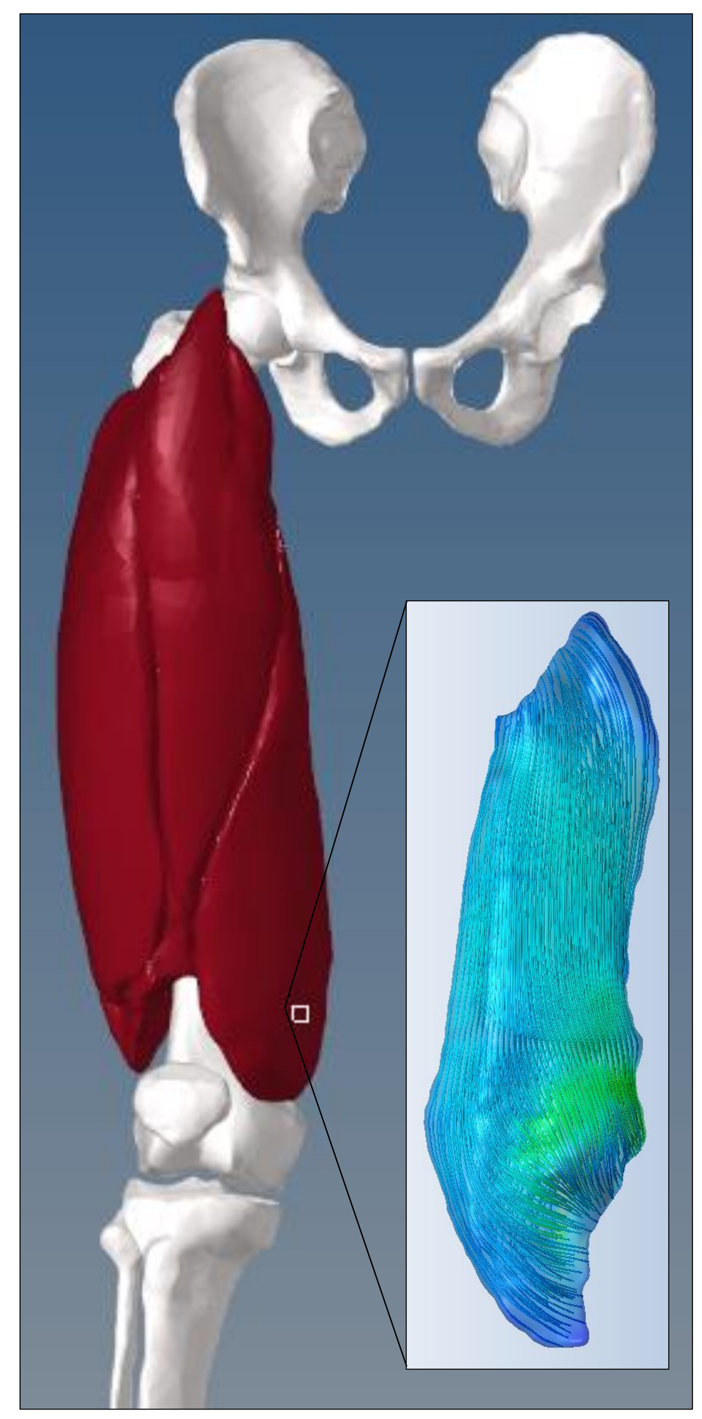

Figure 3: Validation of new apparatus for *in vivo* knee laxity testing (left) to *in vitro* measurements (middle) in cadaveric specimens. Deformable 3D visco-hyperelastic muscle model with active fiber orientation informed by CFD analyses (right).

- **Greater subject specificity:** the growing prevalence of computational modeling in biomechanics is limited by the data used to calibrate the underlying models.
- <u>Objective</u>: Develop the techniques to accurately measure laxity in vivo for the calibration of subject-specific knee models.
- We designed and evaluated an apparatus for making laxity assessments with accuracy similar to in vitro experiments.
- **Realistic 3D representation of muscles:** the intra- and extra-muscular interactions on the joints and musculoskeletal system can only be described by an actively contracting deformable 3D muscle representation.
- <u>Objective</u>: Evolve the current point-to-point muscle representation to allow for contact between muscles and segments.
- We are building complete musculoskeletal geometries from the Visible Human Male and Female project for open sharing.
- Using a previously presented visco-hyperelastic muscle model [4], we are piloting anatomically informed CFD to prescribe muscle fiber orientation [5] in 3D deformable muscle models.

References

[1] Hume et al., J Biomech, 2019. [2] Navacchia et al., J Biomech, 2019. [3] Bergmann et al., PLoS ONE, 2014. [4] Lu et al., J Biomech, 2010. [5] Inouye et al., SummerSim, 2015.

Funding

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