Concurrent Prediction of Muscle Force and Cartilage Stress during Movement

Trent M. Guess
University of Missouri – Kansas City

The absence of detailed knowledge regarding mechanical loading on musculoskeletal tissues inhibits our understanding of joint degeneration and injury. Information on the interrelationships between muscle activations and tissue response is crucial to the development of tissue engineered cartilage and menisci, meniscus and ligament injury and repair, and our understanding of degenerative joint disease, specifically osteoarthritis. Personalized prediction of joint and tissue level loading during ambulation has the potential to significantly enhance orthopedic medicine. In addition to providing a greater understanding of knee biomechanics and tissue function, tools with this capability would enable subject specific intervention strategies aimed at modifying gait for targeted outcomes, such as reducing articular cartilage stress. Combining dynamic multibody musculoskeletal simulations with predictions of tibio-menisco-femoral contact mechanics would be a valuable tool for studying the relationships of muscle force and tissue loading.

The primary computational tools of musculoskeletal modeling include multi-body dynamics at the body level and continuum finite element methods at the joint and tissue level. The multibody method is computationally efficient, but lacks the complexity to accurately capture tissue behavior. In multibody musculoskeletal movement simulations the bones are considered rigid and are typically connected by idealized joints (e.g. representation of the knee as a simple hinge joint). Due to the muscle redundancy problem, musculoskeletal movement simulation involves optimization schemes that repeatedly solve the body level model. Finite element models can estimate tissue deformation, but they are computationally intensive and not used in body level musculoskeletal simulations. Predicted net joint loading and muscle forces from musculoskeletal movement simulations can provide inputs to finite element models that calculate tissue deformation. But in this scheme, the body level musculoskeletal model and the joint level model are not coupled. Joint level information is not fed back to the muscle level model and realistic joint motion and tissue level parameters are not included in the muscle force prediction. The interdependencies of the neuromusculoskeletal system require concurrent simulation at the body, joint, and tissue level.

Presented and discussed at the RPI-NSF Workshop on Multiscale Modeling of Complex Data was a method to combine muscle driven forward dynamics movement simulations with anatomical knee models. Several examples were shown for a muscle driven simulation of a dual limb squat. Demonstrated studies included prediction of cartilage contact pressure with and without the menisci, cartilage and meniscus contact pressure after partial and full transection of the anterior cruciate ligament, and contact pressure on patello-femoral cartilage for different quadriceps muscle distributions during the squat. The need for more detailed information at the tissue level was discussed and a method for developing neural network surrogates of cartilage tissue stress response was introduced. The neural networks learn from finite element and multibody solutions and predict cartilage von Mises stress based on rigid body bone-cartilage interface forces during movement simulation.
The synergy of experimental data and physics based modeling in musculoskeletal biomechanics was emphasized. Experimental data provides simulation inputs, validation, and parameters for computational models based on physical law. The computational models allow musculoskeletal researchers to predict what cannot be directly measured, in this case, mechanical loading on the cartilage and menisci during movement. Computational models also allow prediction of the interdependencies of system structures. They allow researchers to play “what if” scenarios, for example, what if the anterior cruciate ligament was compromised, how would the menisci be affected during walking? Experimental data for musculoskeletal movement simulation typically includes body level motion, ground reaction forces, muscle activations, and simple anthropometrics. In addition, dynamometry can measure torque-displacement relationships of individual joints. Joint level models use medical images, such as magnetic resonance images, to reconstruct subject morphology including bone, cartilage, and ligament geometries. At the body level, motion capture systems can measure the motion of markers attached to body segments, force plates can measure the reaction forces between the foot and ground during ambulation, and electromyography can measure the voltage associated with muscle activation. Mechanical properties of musculoskeletal tissue are typically measured on cadavers or animal models and are not subject specific. The variation of properties from individual to individual creates a challenge, and a need for large collections of data and statistical models to compliment the subject specific musculoskeletal models. It is possible that many subject specific material properties may be determined from medical images in the future.

My vision for musculoskeletal biomechanics includes clinical tools that combine body level measurements with medical images to build computational models that predict patient specific loading on joint structures and tissue. Such a tool could be used for physical therapy interventions to slow the progression of Osteoarthritis or to provide the basis for training strategies for athletes at risk of ligament injury. The tool could also be used for pre-surgical planning for ligament reconstruction or joint replacement and for the development of patient specific engineered tissues such as cartilage. To fully realize this vision, the biomechanics community would need access to tissue material property libraries that included statistical information based on age, gender, height, weight and other anthropometrics. The community would also require robust algorithms that map medical image data to geometries and, ideally, mapping of tissue properties from medical images. Computationally efficient models that accurately capture the variables of interest across multiple scales are also needed. The models would most likely come from combinations of physics based models (e.g. rigid body dynamics), phenomenological models (e.g. hill-type muscle models), and black-box surrogates (e.g. neural networks) that learn from experimental data or solutions from more complex models (e.g. finite element analysis). The development of computational resources, data reduction techniques, and system reduction methods demonstrated and discussed at the RPI-NSF Workshop on Multiscale Modeling of Complex Data are all fundamental to the realization of patient specific load prediction through musculoskeletal modeling.