博士論文（要約）

Integrated Computational Framework of Full Body Musculoskeletal Model and Ground Reaction Model for Postoperative Biomechanical Prediction
(術後のバイオメカニクス予測のための全身筋骨格モデルと床反力モデルを統合した計算フレームワーク)

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1. Background

Osteoarthritis and rheumatoid arthritis caused up to 44.7% of pain during daily activities. Poor alignment has been reported to be an important factor in the development and progression of knee arthritis. Because increased varus-valgus alignment may exacerbate the development and progression of knee arthritis, restoration of lower extremity alignment is an important goal of surgical intervention. However, a practical issue with knee surgery is postoperative satisfaction. Unsatisfactory surgical results have been reported in 11-19% of patients, with up to 6% requiring revision surgery due to surgical complications and implant failure.

One possible way to improve the performance of knee surgery is through treatment design. Computer models offer this possibility. Body kinematics and dynamics, contact mechanics, muscle forces, soft tissue stress, wear mechanics and many others can be studied and evaluated under a variety of dynamic loads and boundary conditions. Various inverse kinematics, inverse dynamics, and muscle-tendon force optimization calculations require whole-body musculoskeletal models. By scaling the generic model based on kinematic data, we can obtain a patient-specific whole-body musculoskeletal model. The scaled model includes body part size data, joint constraint data, and mass distribution data for specific topics closely related to human motion dynamics. Furthermore, inverse kinematics analysis can be performed using the scaled subject-specific model and corresponding kinematic data, resulting in a trajectory for any joint or any point on a particular body part. These data can be used to calculate the necessary inputs for the ground prediction stage. Considering the versatility and efficiency, we decided to build a whole-body musculoskeletal model in a finite element environment, which can cover most of the topics in current biomechanics-related research fields.

In addition, ideal therapy related to kinematic changes can help patients transition from pathological movement patterns to normal movement patterns. Therefore, the ground reaction changes with the movement pattern, which in turn brings about changes in the biomechanics of the whole body. To assess possible postoperative outcomes, we must predict ground reactions to new movements. Despite intensive research on this problem, there are still research gaps in prediction accuracy, method interpretability, implementation complexity, and computational speed. In response to these problems, our project is to propose a quadratic convex optimization method that follows four criteria: (1) satisfy the dynamic equilibrium condition, (2) construct the optimization as simple as possible while avoiding complex mappings or even black boxes relationship, (3) reduce the use of intermediate models, and (4) ensure system convergence.

Finally, ground reaction prediction cannot be predicted with the musculoskeletal model or the ground reaction prediction model alone. The terms of the dynamic equilibrium equation affected by kinematics should be derived from the whole body model, and then decoupled and optimized with the convex optimization-based ground reaction force prediction model. In addition, auxiliary data such as gait events should be predicted using the output of the whole-body model to provide the necessary input for the ground reaction prediction model. The kinetic changes between normal gait and mimic pathological gait were analyzed with the proposed model.

2. Full-body musculoskeletal modeling in finite element environment

A full-body musculoskeletal model was developed in a finite element environment. A model workflow consists of a main thread and sub-threads. The main line includes inverse kinematics, inverse dynamics, and tendon force optimization. It is similar to the normal rigid body musculoskeletal model workflow. An optional sub-thread can contain FEM tissue with detailed structural and material properties. Through the combination of the main thread and the sub-thread, the model can output detailed results of the target tissue, while reducing the computational cost to a relatively low level by setting other parts as rigid bodies.

It takes approximately 10 minutes to calculate 1 gait cycle in main thread mode. Models were evaluated by comparing the kinematic appearance and muscle-tendon force optimization results between predicted and experimental results. The generic model is successfully scaled to the initial position while satisfying all constraints. Movement of specific subjects was also successfully tracked. It should be noted that despite the seemingly simple scaling process, high-quality scaling and inverse kinematics are not achieved naturally due to interference between body segments and joint constraints. Neutral standing poses for zooming and well-chosen motion capture sensor placement for inverse kinematics are highly recommended. Further evaluation was performed by comparing the prediction of muscle activation of knee flexors/extensors with experimental EMG results. Although there are differences in magnitude and phase, the overall consistency of the predictions is acceptable. All muscle activations except the gastro lateralis muscle showed good agreement in trend with the experimental data. The prediction accuracy is comparable to the commercial software Anybody. However, significant rectus femoris and femoral phase differences were observed. Since the tendon force optimization performance depends on the performance of each previous step in the workflow, the model is considered feasible and efficient.

3. Ground Reaction Prediction Model based on convex optimization

"Ground reaction force" literally means the reaction force from the ground. It is the reaction of the ground to the relative movement of people and the ground. The ideal kinematic variant-related treatment can help patients transition from a pathological gait to a normal gait. Therefore, the ground reaction changes with the movement pattern, which in turn brings changes to the biomechanics of the whole body. To assess possible postoperative outcomes, we must predict ground reactions to new movements. This problem has been intensively studied over the past decade, and some methods have even found their way into commercial applications. However, there are still research gaps in prediction accuracy, methodological interpretability, implementation complexity, and computational speed. To address these issues, we propose a quadratic convex optimization method that follows four criteria: (1) the dynamic equilibrium condition is satisfied, (2) the optimization is constructed as simply as possible while avoiding complex mappings or even black boxes relationship, (3) reduce the use of intermediate models, and (4) ensure system convergence. The proposed method is evaluated using 5 different evaluation metrics. Excellent correlation and good accuracy are obtained in both magnitude and phase. The proposed method provides an accurate, interpretable, fast, and robust method for decoupling dynamic equations during the dual-support phase of human walking.

4. Integrated Computational Framework of the ground reaction prediction model and the full-body musculoskeletal model

A whole-body musculoskeletal model and a convex optimization-based ground reaction force prediction model are necessary components to predict ground reaction forces from kinematics alone. They are introduced in Chapters 2 and 3 and will be integrated into the computational framework in Chapter 4. In addition to the 2 models, a module had to be developed to process the data produced by the full-body musculoskeletal model. Inertial force, contact Jacobian and gait events are generated in the new module using trajectories obtained from inverse kinematics. The computing framework is considered to be a relatively complex system that needs to integrate all 3 self-developed modules. Data from different data sources should be accurately processed and calculated under different standards and logic, and must be delivered and received in an appropriate form. On a laptop (i7-8750H, 16 GB RAM, single thread due to python GIL), it takes about 2 minutes to perform 1 gait using the suggested method. Good correlation and accuracy were observed in both magnitude and phase. The proposed method provides an accurate, interpretable, and robust method for predicting ground reaction based on kinematics alone.

5. Dynamics variation between normal gaits and imitative pathological gaits

An integrated computational framework was used to analyze knee joint loads during normal, varus, and valgus gaits. The framework can only use motion input. Ground reaction forces and moments were successfully predicted and then used as input for further dynamic analysis. The prediction accuracy of tendon force optimization results is acceptable. Therefore, the accuracy of knee joint load prediction is guaranteed to a certain extent. It was found that varus and valgus gaits definitely introduce higher knee loads and muscle loads. Metabolic energy efficiency may also be affected due to the limited mobility of the knee joint.

6. Conclusions and future work

In this study, we have proposed an integrated computational framework for biomechanical analysis. The proposed workflow can only use motion input, which is considered a prerequisite for the prediction of post-processing results.