論 文 の 内 容 の 要 旨

論文題目　　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

Up to 44.7% of the pain during daily activities is caused by osteoarthritis and rheumatoid arthritis. Malalignment is reported as one great factor in the development and progression of knee arthritis. As the increasing varus-valgus alignment might aggravate the development and progression of knee arthritis, the restoration of lower limb alignment is an important objective of surgical intervention. However, one practical problem of knee surgery is the postoperative satisfaction rate. 11–19% of the patients were reported dissatisfied with the surgical outcome, and up to 6% require revision surgery due to operative complications and implant failure.

One possible way to improve the performance of knee surgery is to perform treatment design. In-silico models provide such a possibility. The body kinematics and dynamics, contact mechanics, muscle force, soft tissue stress, wear mechanics and many other items can be investigated and evaluated under various dynamics loads and boundary conditions. A full-body musculoskeletal model is needed for all kinds of inverse kinematics, inverse dynamics, muscle-tendon force optimization calculations. By scaling the generic model based on kinematics data, we can obtain a patient-specific full-body musculoskeletal model. The scaled model includes subject-specific body segment dimension data, joint constraint data, and mass distribution data that are closely related to the dynamics of human movement. Furthermore, inverse kinematics analyses can be performed with the scaled subject-specific model and the corresponding kinematics data, yielding the trajectories of any joint or any point on a specific body segment. Those data can be used to calculate the necessary inputs for the ground prediction phase. Considering the versatility and efficiency, we decided to build a full-body musculoskeletal model in a finite element environment that can cover most of the topics in the current biomechanics-related research area.

Additionally, an ideal kinematics variation associated treatment helps patients shift from pathological movement patterns to normal movement patterns. Consequently, the ground reaction changes with the variation of the pattern of the motion, which will, in turn, bring changes to the biomechanics of the whole human body. To evaluate the possible postoperative results, we must predict the ground reaction of the new motion. Although the problem was intensively investigated, research gaps still exist in terms of prediction accuracy, methodology interpretability, implementation complexity, and computation speed. To address the problems, our project is to propose a quadratic form convex optimization method following four criteria: (1) to satisfy the dynamic equilibrium conditions, (2) to build the optimization as simple as possible, meanwhile avoid adopting complex mapping or even black box relations, (3) to reduce the use of the intermediate model, (4) to ensure systematic convergence.

Finally, the ground reaction prediction cannot be predicted with the musculoskeletal model or the proposed ground reaction prediction model alone. The terms of the dynamic equilibrium equations subjecting to the kinematics should be obtained from the full-body model, then the decoupling and optimization would be completed with the ground reaction force prediction model based on convex optimization. Besides, subsidiary data like the gait event should also be predicted with the output from the full-body model to provide necessary inputs to the ground reaction prediction model. Dynamics variation between normal gaits and imitative pathological gaits 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. The model workflow consists of the main thread and the sub-thread. The main thread comprises inverse kinematics, inverse dynamics, and muscle-tendon force optimization. It resembles the normal rigid body musculoskeletal model workflow. The optional sub-thread can incorporate FEM tissues with detailed structure and material properties. Through the combination of the main and sub-threads, the model can output results in full detail for the target tissue, while the computation cost is reduced to a relatively low level by setting the other segments as a rigid body.

The calculation for 1 gait cycle under main thread mode takes approximately 10 minutes. The model was evaluated through the comparison of kinematics appearance and the muscle-tendon force optimization results between the predictions and the experiment results. The generic model was successfully scaled to the initial position while meeting all the constraints. The subject-specific motion was also successfully tracked. It should be noted that although the scaling procedure seems quite simple, high-quality scaling and inverse kinematics are not naturally achievable because of the interference between the body segments and joint constraints. A neutral standing posture for scaling and carefully selected motion capture sensor placement for inverse kinematics are strongly recommended. Further evaluation was performed by comparing the muscle activation predictions of the knee flexor/extensor muscles with the experimental electromyography results. While the discrepancy in magnitude and phase exists, the overall consistency of the predictions was acceptable. All the muscle activations except for the gastro lateralis showed good consistency on trend with the experiment data. The prediction accuracy was comparable to the commercial software Anybody. However, obvious phase differences on the rectus femoris and the vastus were observed. Since the muscle-tendon force optimization performance relies on the performance of every step before the workflow, the proposed model is considered to be feasible and effective.

3. Ground Reaction Prediction Model based on convex optimization

The 'ground reaction force' literally means the reaction force coming from the ground. It is the reaction from the ground on the relative motion between humans and the ground. An ideal kinematics variation associated treatment helps patients shift from pathological gait to normal gait. Consequently, the ground reaction changes with the variation of the pattern of the motion, which will, in turn, bring changes to the biomechanics of the whole human body. To evaluate the possible postoperative results, we must predict the ground reaction of the new motion. This problem was intensively investigated in the past decade, and some methods even entered commercial applications. However, research gaps still exist in terms of prediction accuracy, methodology interpretability, implementation complexity, and computation speed. To address the problems, we have proposed a quadratic form convex optimization method following four criteria: (1) to satisfy the dynamic equilibrium conditions, (2) to build the optimization as simple as possible, meanwhile avoid adopting complex mapping or even black box relations, (3) to reduce the use of the intermediate model, (4) to ensure systematic convergence. The proposed method was evaluated with 5 different evaluation metrics. Excellent correlations and good accuracy on both magnitude and phase were obtained. The proposed method provides an accurate, interpretable, fast, and robust way for decoupling the dynamic equations during the double support phase of human walking.

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

The full-body musculoskeletal model and the convex optimization-based ground reaction force prediction model are necessary ingredients for predicting ground reactions solely from kinematics. They were introduced in chapters 2 and 3 and will be integrated into a computational framework in chapter 4. Besides the 2 models, a module to process the data yielded by the full-body musculoskeletal model must be developed. The inertia forces, contact Jacobian, and the gait events were generated in the new module using trajectories obtained from the inverse kinematics. The computational framework is considered to be a relatively complex system with all the 3 self-developed modules to be integrated. Data from different data sources should be processed and calculated under different criteria and logic accurately and must be passed and received in proper form. The execution for 1 gait with the proposed method took approximately 2 minutes on a laptop computer (i7-8750H, 16 GB RAM, single thread due to python GIL). Good correlations and accuracy on both magnitude and phase were observed. The proposed method provides an accurate, interpretable, and robust way for predicting ground reactions solely based on kinematics.

5. Dynamics variation between normal gaits and imitative pathological gaits

The integrated computational framework was used to analyze the knee loading during the normal, varus, and valgus gaits. The framework can work with only motion inputs. The ground reaction forces and moments were successfully predicted and then used as input for further dynamics analysis. The prediction accuracy of the muscle-tendon force optimization results was acceptable. Consequently, the knee joint loading prediction accuracy is guaranteed on some level. It is found that the varus and valgus gait will surely introduce higher knee joint load and muscle load. The metabolic energy efficiency may also be influenced because of the restricted knee motion ability.

6. Conclusions and future work

The conclusions and the future work were explained.