Subject-Specific Predictive Dynamic Simulation of Sit-to-Stand Motion After Total Knee Arthroplasty

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EXTENDED ABSTRACT

1 Introduction

Total knee arthroplasty (TKA) is a common procedure for patients with advanced knee osteoarthritis. However, it has been reported that complications such as pain, instability, and altered knee kinematics leave approximately 20% of patients dissatisfied postoperatively [1]. Implant positioning has been shown to be a crucial factor in postoperative knee kinematics, ligament tension, and instability. However, due to the complex nature of the knee joint, the impact of the alignment parameters on the outcome of the TKA is yet not well understood. Patient-specific predictive dynamic simulations allow the study of the effect of implant positioning on joint dynamics following TKA [2]. However, the main drawback common in most previous simulation studies is that they are based on inverse dynamic analysis coupled with a static optimization. To investigate the effects of different implant positioning and alignment, predictive simulation models could be better alternatives. In this study, a high-fidelity subject-specific musculoskeletal model is created and the effect of different knee implant positioning on the medial and lateral contact forces and the kinematics of the knee joint during sit-to-stand motion is predicted.

2 Methodology

Musculoskeletal and knee implant model: The experimental dataset of the 4th Grand Challenge Competition [3] was used to create a subject-specific musculoskeletal model. The sit-to-stand motion was predicted for a male subject (age = 88 years, mass = 68 kg, and height = 1.66 m) who underwent TKA due to primary osteoarthritis and received an instrumented implant on the right knee. The data included the CAD model of the knee implant, post-operative CT scans, motion capture data, fluoroscopy data, and medial and lateral tibiofemoral contact forces that were calculated using the method given in [3]. A detailed description of this dataset can be found in [3]. The musculoskeletal model used in this research is shown in Fig. 1. The hip and knee joints are actuated by 36 Hill-type muscle models [3] and the rest of the joints are torque driven. A buttocks-seat contact model adapted from [4] was also included. The knee joint model consists of a pair of volumetric sphere-sphere contact models for lateral and medial condyles and another volumetric sphere-sphere contact model between the patella and femur. Furthermore, medial (MCL) and lateral (LCL) collateral ligaments, medial (MPFL) and lateral (LPFL) patellofemoral ligaments, and patellar ligament (PL) were modeled as described in [3]. Considering the sensitivity of the knee models to ligament properties and insertion locations, in this study, the knee ligament insertion locations were adjusted by minimizing the error between the magnitude of the computed and measured medial and lateral contact forces (two contact forces) during sit-to-stand motion.

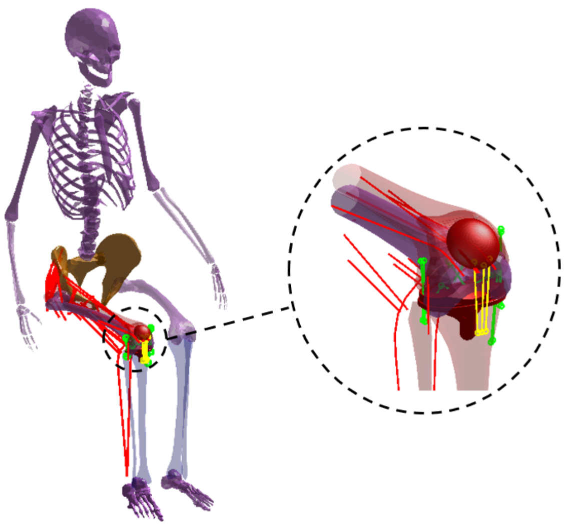

Figure 1: The musculoskeletal and knee model used in this study.

Predictive sit-to-stand motion: Assuming that the movement of humans is optimal with respect to some criterion has been shown to produce acceptable results for motion prediction. Minimization of squared muscle activations has been widely used for motion prediction to minimize muscle effort [5]. In this research, since the model is not fully actuated with muscles, the following cost function is used to predict sit-to-stand motion:

$$J = \int_0^{t_f} \left(\sum a_i(t)^2 + \sum \left(\frac{\tau_j(t)}{\tau_{j,\max}} \right)^2 \right) dt \qquad (1)$$

where $0 \le a_i \le 1$ is the activation of the *i*th muscle and τ_j and $\tau_{j,\max}$ are respectively the torque and maximum isometric torque of the *j*th joint. The cost function given in Eq. (1) was subjected to the musculoskeletal dynamic model, joint limits, and initial and final conditions, and the general-purpose optimal control MATLAB software (GPOPS-II) was used to solve the constrained optimization problem.

3 Results and Discussion

The value of the predicted medial and lateral contact forces and the knee kinematics are compared with the experimental data in Fig. 2. Since the ligament properties and insertion locations were adjusted to match the experimental knee contact loads, it is not a surprise that the predicted contact forces match the experimental data relatively well. However, as can be seen, the adjusted model also predicts the trend of knee kinematics. This indicates that this model can make good predictions for an adjusted subject-specific ligament property.

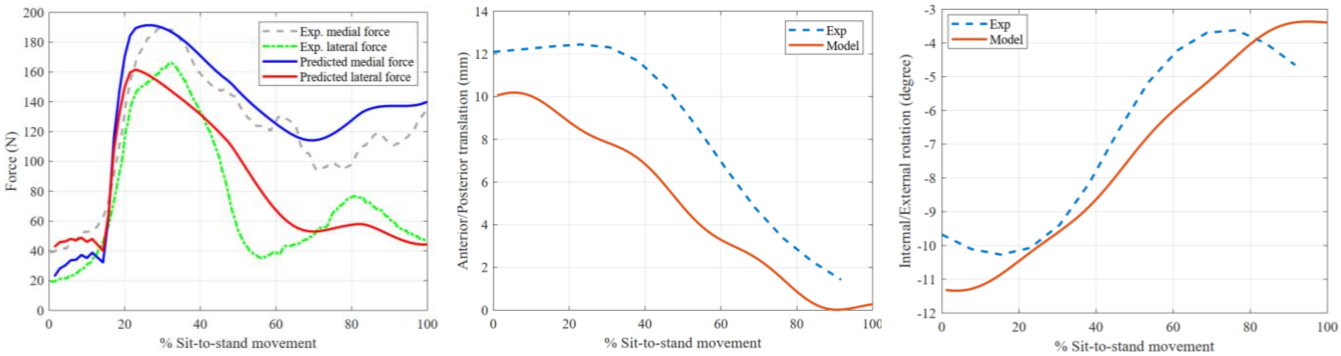

Figure 2. Predicted knee joint contact force (Magnitude) and kinematics versus experimental data for sit-to-stand motion.

4 Conclusion

This study presented a novel approach for predicting knee contact forces and kinematics during daily activities such as sit-to-stand. Unlike other simulation studies, this approach was not dependent on kinematic data and can be used to create “what-if” simulations for different knee implant positioning. Predictive simulations allow us to eliminate the need for kinematic data that is needed in inverse dynamic-based methods. The need for in vivo contact force data to adjust the ligament properties and insertion locations is one of the limitations of this study.

Acknowledgments

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