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# A subject-specific finite element musculoskeletal framework for mechanics analysis of a total knee replacement

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ABSTRACT

Concurrent use of finite element (FE) and musculoskeletal (MS) modeling techniques is capable of considering the interactions between prosthetic mechanics and subject dynamics after a total knee replacement (TKR) surgery is performed. However, it still has not been performed in terms of favorable prediction accuracy and systematic experimental validation. In this study, we presented a methodology to develop a subject-specific FE-MS model of a human right lower extremity including the interactions among the subject-specific MS model, the knee joint model with ligament bundles, and the deformable FE prosthesis model. In order to evaluate its accuracy, the FE-MS model was compared with a traditional hinge-constraint MS model and experimentally verified over a gait cycle. Both models achieved good temporal agreement between the predicted muscle force and the electromyography results, though the magnitude on models is different. A higher predicted accuracy, quantified by the root-mean-square error (*RMSE*) and the squared Pearson correlation coefficient ($r^2$), was found in the FE-MS model ($RMSE = 177.2$ N, $r^2 = 0.90$) when compared with the MS model ($RMSE = 224.1$ N, $r^2 = 0.81$) on the total tibiofemoral contact force. The contact mechanics, including the contact area, pressure, and stress were synchronously simulated, and the maximum contact pressure, 22.06 MPa, occurred on the medial side of the tibial insert without exceeding the yield strength of the ultra-high-molecular-weight polyethylene, 24.79 MPa. The approach outlines an accurate knee joint biomechanics analysis and provides an effective method of applying individualized prosthesis design and verification in TKR.



## 1. Introduction

Total knee replacement (TKR) surgery is an effective procedure for relieving associated pains, correcting leg deformity, and enabling patients to resume normal daily activities. Since the first TKR surgery, which was performed in 1968, improvements in the surgical materials and techniques have greatly enhanced the effectiveness of this procedure (Jones, 1968). However, highly standardized geometric structure of the knee prosthesis has been one of the reasons for highly variable surgical outcomes due to different characteristics of patients (Khosravipour et al., 2018; Nagamine et al., 2000; Zeller et al., 2017). It has been reported that 11–19% of primary TKR patients are unsatisfied with the surgical outcome, while approximately 6% require revision surgery due to operative complications (Bourne et al., 2010; Pabinger et al., 2013; Von Keudell et al., 2014).

In order to improve the performance of the TKR, two types of computational biomechanics methodologies, finite element analysis (FEA) and musculoskeletal (MS) multibody dynamics, have been widely used in TKR design and evaluation. FEA is historically utilized for local mechanics prediction and optimization of the prosthesis (Abdelgaied et al., 2011; Baldwin et al., 2012; Clary et al., 2013; Halloran et al., 2005; Liau et al., 2002). Most of these previous FE models were developed based on a static or standard (ISO 14243) boundary condition, whereas the mechanics of the knee joint are known to vary with the specific subject. Moreover, the biomechanical properties of the knee joint are controlled by complex interactions between the muscles, ligaments, bone, and surrounding environment (Fitzpatrick et al., 2012; Madeti et al., 2015). The MS model, which is comprised of a skeleton consisting of rigid body segments (bones) connected by joints and muscle-tendon (MT) units, is able to consider the individual characteristics of the patients for biomechanical analysis and simulation (Delp

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et al., 2007, 1990; Erdemir et al., 2007; Nakamura et al., 2005; Pandy et al., 1997; Saraswat et al., 2010). However, the contribution of muscle forces and joint loads at the implant levels and the effects of prosthesis design on human movement cannot be studied using the MS model owing to the simplification of the joint and segments. Hence, a combination using FE and MS models would help to overcome the limitations of each modeling domain, while improving the quality of the analysis.

In the past decade, some studies have combined MS and FE models in an effort to consider their individual attributes, but the applications were generally non-concurrent in which implant deformations were analyzed by FE post-processing under a given MS loading boundary condition (Cronskär et al., 2015; Farrokhi et al., 2011; Navacchia et al., 2016b; Pizzolato et al., 2017; Scarton et al., 2016; Zhang et al., 2017). Guess et al. (2014) and Thelen et al. (2014) developed modeling frameworks for the concurrent simulation of MS dynamics and knee joint mechanics through the development of a knee model with rigid-body spring contact during gait cycle. Chen et al. (2016) systemically evaluated the predicted accuracy of the co-simulation model combining MS dynamics and knee joint mechanics based on Grand Challenge Competition. Regardless of the complexity of their frameworks, the contact mechanics and deformation analysis of the implant were performed based on a simplified rigid-body spring contact model, without accounting for viscoelasticity of material (Fregly et al., 2003). It also only provides predictive information on contact pressures without surface tensile stresses and sub-surface stresses which are important metrics to analyze the subsurface damage of implant (Sathasivam and Walker, 1998; Willing and Kim, 2011, 2009). Halloran et al. (2010) presented a concurrent 2D FE-MS model to alter computationally predicted neuromuscular control for optimizing the tissue strain given the desired kinematic and muscular behavior. However, the study focused on the sagittal plane of the lower limb, ideal hinges were used for modelling joints. Moreover, Adouni et al. (2012) presented a detailed FE-MS model with the entire 3-D intact knee joint that can simultaneously predict the muscle force and cartilage stress, but limited posts of gait cycle were discontinuously predicted and the experimental validation was not included.

The objective of this paper was to develop a concurrent subject-specific FE-MS model of a human right lower extremity with consideration of the interactions between the prosthetic mechanics and multibody dynamics after a TKR surgery. We hypothesize that FE-MS model can better predict the muscle, ligament, and contact forces than MS model alone. A systematic verification of the model was performed through comparison of the simulation results and the *in vivo* experimental knee-joint reaction force and muscle activation from the grand challenge competition dataset with a MS model developed as a comparison. The concurrent predicted contact pressure, contact area, and stress were achieved using the FE-MS model.

## 2. Materials and methods

### 2.1. Subject data

The patient data obtained from the grand challenge competition regarding the prediction of *in vivo* knee loads (Fregly et al., 2012) were used to verify the FE-MS lower extremity model. The experimental data were acquired from a male subject (JW: age 83 years, height 166 cm, and body weight (BW) 64.6 kg), who underwent an instrumented TKR procedure on his right knee. The referenced dataset included the prosthesis geometry, post-operative computed tomography (CT) scans, trajectories of the motion capture markers, ground reaction force (GRF), electromyography (EMG), and the medial and lateral tibiofemoral (TF) contact forces.

### 2.2. Subject-specific FE-MS model

#### 2.2.1. FE-based generic MS model

The FE-based generic MS model was developed on Abaqus CAE v6.14, as shown in Fig. 1 (Saraswat et al., 2013). The center of mass (COM), muscle parameters, and muscle origin, insertion and via-point coordinates were obtained from Biomechanical Data Resource (Delp and Loan, 1995). The hip, ankle, and hindfoot joints were defined as spherical joints with three degrees of freedom (DOF). The TF joint was firstly defined as a hinge joint (flexion-extension) in the MS model due to the inaccuracies in the estimation of knee joint internal motion from marker data by soft tissue artifacts (Benoit et al., 2006). Then it was modified to a 6 DOF joint with ligament constraints in the FE-MS model. A detailed description will be presented in FE TKR session. What's more, the comparison between simple hinge joint and 6 DOF joint was used to understand the influence of TF joint internal motion on predicted accuracy of joint contact force. Details of the MS model are in the supplementary materials section.

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.jbiomech.2018.07.008.

#### 2.2.2. Model scaling and positioning

The subject-specific MS models were developed by scaling and positioning the generic MS model based on the first frame of the marker position in the motion capture data. The objective function was to minimize the least square error of the marker coordinates on each segment with the joint constraints. An optimization of the marker offsets was implemented within −15 and 15 mm because the video cameras recorded the centroid of the spherical marker on the skin rather than on the anatomical location on the bone. The coordinate of each muscle attachment point and that of the center of mass were scaled and positioned with the segments. The mass and moment of inertia were also scaled to match the target subject. The optimization problem was solved by a non-linear program derived from a quadratic Lagrangian algorithm in the Isight optimization module (Schittkowski, 1982).

#### 2.2.3. FE TKR knee model

After scaling and positioning the generic MS model, the hinge joint for the TF joint was removed (Yao et al., 2014), and an anatomical right TF joint, including the implant, bone, and ligaments, was created. The deformable contact model was defined between the tibial insert and femoral component geometries, as shown in Fig. 2. Details of the FE TKR model are in the supplementary materials section.

### 2.3. Implementation of subject-specific FE-MS model

The subject-specific FE-MS modeling implementation was mainly composed of inverse kinematics analysis, inverse dynamics analysis, MT force optimization, and joint reaction computation. The detailed workflow of the simulator is shown in Fig. 3. The models were developed and implemented using Abaqus (Dassault Systems Simulia Corp., Johnston, USA). Isight (Dassault Systems Simulia Corp., Johnston, USA) was used to process the automation and optimization. What's more, some Python scripts were coded to transfer the data between the analyses and update the models.

#### 2.3.1. Inverse kinematics and dynamics

Inverse kinematics was used to apply the marker trajectories and to obtain the time history of the lower extremity kinematics during the normal gait. The motion of the three or four markers on each leg segment was reduced to 6 DOFs per segment. The step