Medical Engineering and Physics 38 (2016) 708–716

Contents lists available at ScienceDirect

Medical Engineering and Physics

journal homepage: www.elsevier.com/locate/medengphy

Evaluation of a subject-specific musculoskeletal modelling framework for load prediction in total knee arthroplasty

Zhenxian Chen[a], Zhifeng Zhang[b], Ling Wang[a,*], Dichen Li[a], Yuanzhi Zhang[c], Zhongmin Jin[a,d]

[a] State Key Laboratory for Manufacturing System Engineering, School of Mechanical Engineering, Xi'an Jiaotong University, 710054 Xi'an, Shaanxi, China
[b] Department of Arthroplasty Surgery, the Second Affiliated Hospital of Inner Mongolia Medical University, 010030 Hohhot, Inner Mongolia, China
[c] Department of Orthopedics, the Affiliated Hospital of Inner Mongolia Medical University, 010050 Hohhot, Inner Mongolia, China
[d] Institute of Medical and Biological Engineering, School of Mechanical Engineering, University of Leeds, Leeds LS2 9JT, UK

ARTICLE INFO

Article history:
Received 3 July 2015
Revised 22 March 2016
Accepted 11 April 2016

Keyword:
Subject-specific musculoskeletal modelling
Force-dependent kinematics
Total knee arthroplasty
Multibody dynamics
Contact force

ABSTRACT

Musculoskeletal (MSK) multibody dynamics (MBD) models have been used to predict in vivo biomechanics in total knee arthroplasty (TKA). However, a full lower limb MSK MBD modelling approach for TKA that combines subject-specific skeletal and prosthetic knee geometry has not yet been applied and evaluated over a range of patients. This study evaluated a subject-specific MSK MBD modelling framework for TKA using force-dependent kinematics (FDK) and applied it to predict knee contact forces during gait trials for three patients implanted with instrumented prosthetic knees. The prediction accuracy was quantified in terms of the mean absolute deviation (*MAD*), root mean square error (*RMSE*), Pearson correlation coefficient (ρ), and Sprague and Geers metrics of magnitude (M), phase (P) and combined error (C). Generally good agreements were found between the predictions and the experimental measurements from all patients for the medial contact forces (150 N < *MAD* < 178 N, 174 N < *RMSE* < 224 N, $0.87 < \rho < 0.95$, $-0.04 < M < 0.20$, $0.06 < P < 0.09$, $0.08 < C < 0.22$) and the lateral contact force (113 N < *MAD* < 195 N, 131 N < *RMSE* < 240 N, $0.41 < \rho < 0.82$, $-0.25 < M < 0.34$, $0.08 < P < 0.22$, $0.13 < C < 0.36$). The results suggest that the subject-specific MSK MBD modelling framework for TKA using FDK has potential as a powerful tool for investigating the functional outcomes of knee implants.

1. Introduction

Accurate quantification of knee contact loading during daily life activities is essential for pre-clinical investigation of new materials and designs, understanding implant failure mechanisms and improvement of functional outcomes in total knee arthroplasty (TKA). Knee contact loading is closely related to complex interactions among the forces of bones, muscles, ligaments and the surrounding environment, which are difficult to measure in vivo [1]. Although in vivo knee contact forces have been measured experimentally using instrumented knee prostheses during dynamic activities in a limited number of patients [2], implementation of these devices is invasive and expensive, and the results might not necessarily be transferable to other patients [3]. Furthermore, these instrumented knee prostheses are limited and might not be extended to study the effect of different implant designs or surgical mal-alignments on dynamic loading and motion [4]. Consequently, lower limb musculoskeletal (MSK) multibody dynamics (MBD) modelling has been proposed as a useful alternative to gain insight into muscle and joint forces during movement.

Nonetheless, validation of MSK MBD models by comparing model predictions with experimental measurements is required before computational models can be widely accepted for use in clinical settings. The Grand Challenge Competition to Predict In Vivo Knee Loads was initiated by Fregly et al. [2] to advance MSK modelling and allow investigators to thoroughly evaluate computational models against measured knee contact force data. Certain novel TKA modelling approaches for prediction of the medial and lateral contact forces were developed in the competitions held from 2010 to 2014. Lundberg et al. [5], winner of the 3rd Grand Challenge Competition, established a numerical model to obtain the knee joint contact forces based on equilibrium equations between internal and the external loads. However, this study did not consider the implant and the patient's bone geometry and omitted the effects of these geometry factors on the knee joint forces and kinematics. With notable developments in the modular modelling method based on elastic foundation theory [6], it has become possible to incorporate a deformable knee model into an MSK MBD modelling system. Thelen et al. [7], winner of the 4rd Grand

* Corresponding author. Tel.: +86 29 83395187.
E-mail address: menlwang@mail.xjtu.edu.cn (L. Wang).

http://dx.doi.org/10.1016/j.medengphy.2016.04.010
1350-4533/

Table 1
Subject information and the files used from the data available for the grand challenge competition at https://simtk.org/home/kneeloads.

	Subject SC	Subject JW	Subject PS
Subject information			
Height	167 cm	168 cm	180 cm
Weight	78.4 kg	66.7 kg	75 kg
Gender	Female	Male	Male
Instrumented knee side	Left	Right	Left
Implanted components	NK-II CR, Zimmer	PFC Sigma, DePuy	NK-II CR, Zimmer
Gait trails (.C3D files)	SC_staticfor_again1	JW_staticfor	PS_staticfor2
	SC_ngait_og5	JW_ngait_og1	PS_ngait_og_ss1
	SC_ngait_og6	JW_ngait_og2	PS_ngait_og_ss3
	SC_ngait_og7	JW_ngait_og3	PS_ngait_og_ss7
	SC_ngait_og8	JW_ngait_og4	PS_ngait_og_ss8
	SC_ngait_og9	JW_ngait_og5	PS_ngait_og_ss9
		JW_ngait_og7	PS_ngait_og_ss11

Challenge Competition, introduced a framework for co-simulation of neuromuscular dynamics and knee joint mechanics during gait that considered the compliant contact of the knee implant for prediction of the tibial-femoral (TF) contact forces. Nonetheless, this study did not consider the subject-specific lower limb MSK architecture, and the prediction accuracy for the medial and lateral contact forces was dependent on the implant alignment in the TKA modelling. Furthermore, Andersen and Rasmussen [8] developed a novel force-dependent kinematics (FDK) approach that made it easier to incorporate an elastic joint contact model such that the dynamics associated with the numerically stiff contact degrees of freedom (DOF) were eliminated. Marra et al. [1], winner of the 5rd Grand Challenge Competition, applied the FDK technique and an advanced morphing technique [9] to establish a subject-specific MSK modelling framework for TKA. These researchers considered the weakening of muscle strength that occurred in subjects following TKA [10] and obtained good predictions of in vivo TF contact forces. In each of the above studies, the computational model was tuned and adjusted with different parameters to match the experimental measurements. However, a general MSK modelling approach for TKA that is applicable to any patient has not been assessed.

The purpose of this study was to evaluate a subject-specific MSK MBD modelling framework for TKA using FDK to predict in vivo knee contact forces over multiple experimental gait trials collected from multiple subjects implanted with instrumented prosthetic knees.

2. Methods

2.1. Experimental dataset

Experimental data from three subjects implanted with an instrumented knee replacement were obtained from the SimTK website (https://simtk.org/home/kneeloads) and used in this study (Table 1). This information was available from public data made available by the “Grand Challenge Competition to Predict In Vivo Knee Loads” for the 3rd, 4rd and 5rd competitions (2012–2014) [2]. The database for each subject included the geometry of the knee implants (femoral component, patella button, tibial insert, tibial tray) and lower limb (femur, patellar, tibia, fibula) from computed tomography (CT) scans, and marker trajectories and ground reaction forces (GRFs) from motion capture experiments. The TF medial and lateral contact forces were measured using the customised instrumented knee prosthesis.

2.2. Generic musculoskeletal modelling

As previously described [1], a subject-specific full lower limb MSK MBD modelling framework for TKA using FDK was reproduced in the commercially available MSK MBD software AnyBody (version 6.0; AnyBody Technology, Aalborg, Denmark). The generic MSK model extracted from the AnyBody Managed Model Repository (V1.6.2), which is based on the Twente Lower Extremity Model (TLEM 1.1) [11] anthropometric database, was modified to develop the modelling framework. An overview of the subject-specific full lower limb MSK MBD modelling framework for TKA using FDK in AnyBody is shown in Fig. 1. Differences in each patient’s MSK architecture, implanted knee prosthesis, and gait patterns in the modelling framework are described in the section on subject-specific modelling in which the generic MSK model was scaled to obtain a subject-specific full lower limb MSK model of TKA according to the patient’s CT image and gait dataset. In this work, the generic modelling aspects of the modelling framework are presented first.

The original hinge joint definition was removed for the knee of the generic MSK model and was replaced with an 11 DOF knee contact model. The new knee model with consideration of knee implants with elastic articular contacts and ligaments was developed using the FDK method developed by Anderson and Rasmussen [8] and was implemented as a standard functionality in AnyBody. The patellar ligament was assumed to be rigid, and therefore, six DOFs in the TF joint and five DOFs in the patellofemoral (PF) joint were released.

The above mentioned secondary knee DOFs were free to equilibrate automatically under the effect of contact forces, muscle and ligament forces, and external loads in the FDK solver [1,8]. FDK is based on the assumption that the movements in the secondary knee DOFs are small, and the dynamic effects occurring in these DOFs are negligible [1,8]. The movements of the secondary knee DOFs were explicitly defined and denoted as $\boldsymbol{\alpha}^{(\mathrm{FDK})}$ and referred as the FDK DOFs. With this assumption, the FDK algorithm was run using an iterative scheme (Fig. 2), which is wrapped around the inverse dynamics that computes the positions in the FDK DOFs such that the forces acting along these DOFs are in static equilibrium for each time step during the simulation [1,8].

At each step in the FDK solution process, kinematic analysis was performed to compute the positions, velocities and accelerations of all involved segments with the current $\alpha_k^{(\mathrm{FDK})}$ and the assumptions that $\dot{\alpha}_k^{(\mathrm{FDK})}$ and $\ddot{\alpha}_k^{(\mathrm{FDK})}$ were zero [1,8]. The joints, kinematic drivers and relationships among the segment coordinates and the movements of secondary knee DOFs were described by a set of kinematical holonomic constraint equations [1,8]:

$$\begin{aligned}&\boldsymbol{\Phi}(\mathbf{q},t)=\mathbf{0}\\&\boldsymbol{\Phi}^{(\mathrm{FDK})}(\mathbf{q})-\boldsymbol{\alpha}^{(\mathrm{FDK})}=\mathbf{0}\end{aligned} \tag{1}$$

where $\boldsymbol{\Phi}(\mathbf{q},t)$ denotes the joints and kinematic drivers in the system, $\mathbf{q}$ is the assembled coordinate vector for all segments, and t is the explicit time [12]. The latter equations indicate that