Medical Engineering and Physics 000 (2017) 1–10

Contents lists available at ScienceDirect

Medical Engineering and Physics

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

Concurrent prediction of ground reaction forces and moments and tibiofemoral contact forces during walking using musculoskeletal modelling

Yinghu Peng[a], Zhifeng Zhang[b], Yongchang Gao[c], Zhenxian Chen[c,*], Hua Xin[a], Qida Zhang[a], Xunjian Fan[a], Zhongmin Jin[a,d,e]

[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] Key Laboratory of Road Construction Technology and Equipment of MOE, Chang'an University, 710064, Xi'an, Shaanxi, China
[d] Institute of Medical and Biological Engineering, School of Mechanical Engineering, University of Leeds, Leeds LS2 9JT, UK
[e] Tribology Research Institute, School of Mechanical Engineering, Southwest Jiaotong University, 610031 Chengdu, Sichuan, China

ARTICLE INFO

Article history:
Received 30 April 2017
Revised 2 November 2017
Accepted 22 November 2017
Available online xxx

Keywords:
Ground reaction force and moment
Knee contact force
Subject-specific musculoskeletal model
Multibody dynamics
Total knee arthroplasty

ABSTRACT

Ground reaction forces and moments (GRFs and GRMs) measured from force plates in a gait laboratory are usually used as the input conditions to predict the knee joint forces and moments via musculoskeletal (MSK) multibody dynamics (MBD) model. However, the measurements of the GRFs and GRMs data rely on force plates and sometimes are limited by the difficulty in some patient's gait patterns (e.g. treadmill gait). In addition, the force plate calibration error may influence the prediction accuracy of the MSK model. In this study, a prediction method of the GRFs and GRMs based on elastic contact element was integrated into a subject-specific MSK MBD modelling framework of total knee arthroplasty (TKA), and the GRFs and GRMs and knee contact forces (KCFs) during walking were predicted simultaneously with reasonable accuracy. The ground reaction forces and moments were predicted with an average root mean square errors (*RMSEs*) of 0.021 body weight (*BW*), 0.014 *BW* and 0.089 *BW* in the antero–posterior, medio–lateral and vertical directions and 0.005 *BW*•body height (*BH*), 0.011 *BW*•*BH*, 0.004 *BW*•*BH* in the sagittal, frontal and transverse planes, respectively. Meanwhile, the medial, lateral and total tibiofemoral (TF) contact forces were predicted by the developed MSK model with *RMSEs* of 0.025–0.032 *BW*, 0.018–0.022 *BW*, and 0.089–0.132 *BW*, respectively. The accuracy of the predicted medial TF contact force was improved by 12% using the present method. The proposed method can extend the application of the MSK model of TKA and is valuable for understanding the *in vivo* knee biomechanics and tribological conditions without the force plate data.

© 2017 IPEM. Published by Elsevier Ltd. All rights reserved.

1. Introduction

Knowledge of the knee joint mechanics during daily activities is highly significant for refining implant design, evaluating the functional outcomes and understanding the mechanism of polyethylene wear in total knee arthroplasty (TKA) [1–3]. However, *in vivo* knee forces are difficult to measure with non-invasive method [4]. Although several studies [5–7] provided valuable information of the *in vivo* tibiofemoral (TF) forces after TKA using instrumented knee prostheses. These reported data were limited to a small number of subjects, implants and gait styles, and the generality of the measurement data was uncertain [8]. Nonetheless, the measured data by the instrumented knee prostheses provided opportunities for the computational prediction and evaluation of knee contact forces (KCFs) by the developed musculoskeletal (MSK) models of TKA.

Recently, a number of studies [4,9–12] have been performed to predict *in vivo* KCFs based on the available data of "Grand Challenge Competition to Predict *in Vivo* Knee Loads". Hast et al. [9] developed a dual-joint modelling method for knee joint to estimate the TF force based on a full-body MSK model in OpenSim [13]. Marra et al. [4] and Chen et al. [12] calculated the KCFs during walking using force-dependent kinematics (FDK) method based on a specific-specific MSK model of TKA. For all developed MSK model of TKA, the surface marker trajectory data and ground reaction forces and moments (GRF&Ms) data were utilized as the inputs to predict the subject-specific knee kinematics and kinetics during the entire gait cycle based on inverse dynamics method. However, the results of the inverse dynamic analysis are sensitive to inaccu-

* Corresponding author at: Key Laboratory of Road Construction Technology and Equipment of MOE, Chang'an University, Xi'an, Shaanxi, China.
E-mail address: zhenxian_chen@yeah.net (Z. Chen).

https://doi.org/10.1016/j.medengphy.2017.11.008
1350-4533/© 2017 IPEM. Published by Elsevier Ltd. All rights reserved.

Please cite this article as: Y. Peng et al., Concurrent prediction of ground reaction forces and moments and tibiofemoral contact forces during walking using musculoskeletal modelling, Medical Engineering and Physics (2017), https://doi.org/10.1016/j.medengphy.2017.11.008

racies in these input data [14,15]. The calibration error when the force plates (FPs) fixed to the ground may influence the prediction accuracy of the MSK model [16]. In addition, it is also difficult to measure the GRFs and GRMs during some gait patterns due to the inconvenience in equipment installation, such as treadmill gait. All these affect the prediction of KCFs using the MSK model of TKA.

Predictions of GRFs and GRMs have been studied recently for MSK multibody dynamics (MBD) modelling during daily activities [17–22]. Ren et al. [17] presented a MSK MBD model to predict GRFs and GRMs based on inverse dynamics by introducing a smooth transition assumption during double support phase. However, the smoothing functions were determined by empirical data and it was unknown whether this approach was still valid for other movements. Although Choi et al. [18] and Oh et al. [19] used an artificial neural network model to predict GRFs and GRMs, the method required a large number of training data, which was not always available. Most recently, a universal method based on force contact elements has been used to compute the GRFs and GRMs [20–22]. Fluit et al. [20] integrated a prediction method of GRFs and GRMs into a full-body MSK modelling to predict the GRFs and GRMs during normal walking with motion capture data only. The proposed method [20] introduced five artificial muscle-like actuators to 12 locations on each foot, and forces of actuators were computed using the muscle recruitment algorithm during the inverse dynamics analysis. Jung et al. [21] utilized distance- and velocity-dependent force models to predict GRFs during different walking speeds by attaching forty force elements to the sole of foot. Skals et al. [22] adopted the methods by Fluit et al. [20] to predict the joint reaction forces and GRFs and GRMs during sports-related movements by adding 18 contact points to each foot. However, the proposed methods were only used for the normal subject, and none of the GRFs and GRMs methods had ever been integrated into a MSK MBD model of TKA for predicting the KCFs. It is unclear that the effect of the predicted GRFs and GRMs on the prediction accuracy of KCFs. Furthermore, the previous models [20–22] did not consider subject-specific lower limb MSK architecture and the knee joint was modelled as a hinge joint, which omitted the effects of the GRFs and GRMs on the calculation of the TF medial, lateral and total contact forces.

In this study, a prediction model of the GRFs and GRMs based on elastic contact elements was integrated into a subject-specific MSK MBD modelling framework of TKA for predicting the GRFs and GRMs and KCFs simultaneously. The predicted KCFs and GRFs and GRMs were compared with the experimental results for model validation.

2. Materials and methods

2.1. Experimental data

The publicly experimental data [23] of a male subject (75 kg 75body weight (BW), 180 cm body height (BH)) with an instrumented prosthesis in the left knee were used in this study. The patient's comprehensive data were available in the SimTK website (https://simtk.org/projects/kneeloads/). This database included the pre- and postoperative computed tomography images of the knee, the geometry of the knee implant, the measured TF medial and lateral contact forces, marker trajectories data and FPs data. In this study, a static gait trial (staticfor2) and six normal walking gait trials (ss1, ss3, ss7, sss8, ss9 and ss11) were applied to evaluate the KCFs and GRF and GRMs.

2.2. Subject-specific musculoskeletal modelling

A subject-specific full-body MSK model of TKA was developed using Anybody modelling software (AnyBody Technology, Aalborg, Denmark, version 6.0) based on the generic MSK model extracted from the AnyBody Managed Model Repository (V1.6.2) [24]. The generic MSK model, which is based on the anthropometric database of the Twenty Lower Extremity Model (TLEM 1.1) [25]. It included head, two arms, trunk, pelvis, and two legs. Segments of the whole body are collected by meaning of various joints, including spherical joints at the glen humeral, hip joint, hinge joints at the neck, ankle, subtler, TF, and patella-femoral (PF) joints etc. The full-body model had more than 1000 muscle actuators and was defined by Hill-type muscle model with default properties in AnyBody [24]. For all muscles, the muscle strength of each muscle units was calculated as 27 N/cm^2 by multiplying the physiological cross-sectional area (PCSA). Further details can be found in the previous study reported by Damsgaard et al. [24].

As shown in Fig. 1, the generic MSK model was modified to establish the subject-specific MSK model of TKA. To obtain accurate subject-specific bone geometries, an advanced morphing method [26] was used to modify the original bones of the legs in the generic MSK model to the corresponding patient pre-operative bones, including femur, tibia, and talus. All related muscle attachment sites defined on the specific bones were scaled simultaneously. Since the CT images only included the left leg geometries, the right leg was scaled by a mirror operation, and the remaining bones of the MSK model were scaled utilizing the motion capture data. A static standing trial was used to obtain the remaining scaled segments in the inverse kinematic analysis proposed by Andersen et al. [27]. Parameter optimization was conducted to gain the model parameters and identify the locations of the model markers during the standing reference trial. Furthermore, the remaining segments were scaling according to the model markers. A Length–Mass–Fat scaling approach proposed by Rasmussen et al. [28] was employed to scale the muscle strength of generic MSK MBD model to the specific subject of interest. To represent the reduced strength of the flexion/extension muscles in subjects undergo TKA [29], a reduction of 35% of their nominal PCSAs was applied in the model, as reported by Marra et al. [4].

2.3. Knee model

After model scaling, the post-operative bones with the instrumented prosthesis of the left leg were used to create the subject-specific MSK model. A rigid-body registration technique based on the specific anatomical landmarks was used to keep the post-operative bones and prosthesis of the patient aligned with the pre-operative geometries. The knee joint implant was then modelled using a FDK approach [30], redefined with 11 degrees-of-freedoms (DOFs). Six DOFs were in the TF joint; the PF joint only assigned five DOFs, due to the patellar tendon was assumed to be rigid. As for the tibial insert, it was divided into the medial and the lateral part. Three rigid-rigid STL-based contact pairs were defined in the knee model, one for the PF joint and the other two pairs for the medial and lateral sides on the TF joint. The forces in all contact pairs were calculating based on a linear force-penetration volume law with a *PressureModule* value of 1.24e11 N/m^3. More details on the knee model can be found in our previous study [12]. A total of 17 non-linear spring elements were modelled to represent the ligaments around PF and TF joint in the knee model, including the posterior cruciate ligament (PCL, three bundles), the medial collateral ligament (MCL, three bundles), the lateral collateral ligament (LCL, three bundles), the posteromedial capsule (PMC, two bundles), and the medial PF ligaments (MPFL, three bundles) and lateral PF ligaments (LPFL, three bundles). The material parameters for various ligaments can be found in the previous study reported by [31].

Download English Version:

https://daneshyari.com/en/article/7237472

Download Persian Version:

https://daneshyari.com/article/7237472

Daneshyari.com