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Prediction of in-vivo kinematics and contact track of total knee arthroplasty during walking

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Abstract

In vivo kinematics of total knee arthroplasty (TKA) are essential to investigate the articular surface wear of the knee implant. However, the prediction of in vivo knee kinematics and contact track during walking remains challenged. In this study, a previously developed subject-specific musculoskeletal multibody dynamics model was utilized to predict the in vivo kinematics of TKA during the straight gait and right-turn cycles, and the contact position as described by the center of pressure (COP). The predicted in vivo knee motions of the straight gait cycle were found with similar kinematic patterns and ranges of motion to clinical studies. The main internal-external rotations of the femoral component relative to the tibial insert occurred at the stance phase of the straight gait cycle with a lateral rotational pivot point; while the remaining changes in the contact positon mainly exhibited the anterior or posterior translation. For the right-turn cycle, the major changes in the contact positon were the internal-external rotations, and the rotational pivot points were mostly located at the medial compartment. These predictions further demonstrate that in vivo kinematics and contact track are gait pattern-dependent and are important considerations to further investigate the in vivo wear mechanisms of TKA bearings.

Keywords: Total knee arthroplasty; In vivo kinematics; Contact track; Center of pressure; Musculoskeletal model

1. Introduction

Total knee arthroplasty (TKA) is a successful treatment approach for knee joint diseases. Ultrahigh molecular weight polyethylene (UHMWPE) remains the most popular bearing material for TKA to replace the damaged cartilage and bone in the articulating surfaces. However, long-term performance of TKA is still restricted by wear and aseptic loosening, resulted from wear particles. The relative movement between contacting components is an important factor for the tribology of TKA and generation of UHMWPE wear particles [1]. In addition, in vivo kinematics of total knee arthroplasty are also key for the prosthesis design [2] and postoperative functional assessment [3]. More physiological knee movement patterns may be correlated with better postoperative knee function [4]. Thus, knowledge of in vivo kinematics of TKA is essential to understand the failure mechanisms and improve the prosthesis performance [5].

Fluoroscopic measurement, especially the dual fluoroscopic imaging system developed by Li et al. [6], is the main method to obtain the in vivo knee kinematics. In a previous study [7], changes between the pre–TKA and post–TKA kinematics were observed based on the fluoroscopy imaging analysis for the specific patients, and significant differences of in vivo knee kinematics between different patients were also observed. Although in vivo kinematics have been measured using the fluoroscopic measurement method in a limited number of patients, the measurement device is expensive and the results might not necessarily be transferable to other patients. Moreover, the knee kinematics are activity-dependent, and the results obtained from one activity cannot be generalized to interpret the motion patterns of other activities [8]. However, most reported fluoroscopy data [6,7,9] were captured during a non-weight-bearing or weight-bearing deep knee bend, or lunge, only a few studies were

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performed to investigate the in vivo kinematics of TKA during the straight gait. And the fluoroscopic measurements were difficult for different over-ground gait trails like the right-turn trial. With the development of computational simulation, subject-specific musculoskeletal (MSK) multibody dynamics (MBD) model is an attractive platform to obtain in vivo kinematics of TKA. The secondary knee kinematics of TKA from the unloaded leg-swing trial have been quantified with a reasonable accuracy by Marra et al. [10] using a subject-specific MSK modeling framework via a force-dependent kinematics (FDK) approach. However, to our knowledge, the prediction of in vivo knee kinematics during overground gait trails remains challenged, and the reports about the prediction of the secondary knee kinematics during walking are rare.

Recently, an increasing attention has been focused on the contact position between the femoral condyle and tibial plateau, which was used to describe the motion of the knee. The medial and lateral TF contact locations were identified in three ways. First, the geometric centers of the medial and lateral femoral condyles, projected onto the transverse plane of the tibial coordinate system, was used to define the anterior–posterior (AP) position of the lateral and medial femoral condyles [8,11,12]. Second, Nakamura et al. [13] reported that the lowest points of the medial and lateral femoral condyles almost represented the corresponding geometric centers, and those points had been adopted to define the AP translation and rotation of the femoral component relative to the tibial tray component [9]. Third, the center of the overlapping area of the femoral component surface with the polyethylene articular surface was used by Suggs et al. [4] to define the contact point, the locations of which were used to describe the TF articular contact kinematics. However, the geometric centers and the lowest points of the medial and lateral femoral condyles could not characterize the accurate contact position, and the center of the overlapping area could not consider the weight of the force vectors at each of the penetrating vertices. This would influence the correct understanding of the in vivo knee motions and contact track. The center of pressure (COP), which considers the contact area and the weight of the force vectors at each of the penetrating vertices, has been used to successfully quantify the in vivo contact position of the nonconforming total shoulder arthroplasty [14]. However, none of the recent reports have made an effort to investigate the in vivo contact positon and contact track of TKA during walking using the method of COP.

The studies [8,11,15,16] of the knee IE rotational pivot points have brought considerable controversy on the design of the medial pivot knee system. Majority of current studies reported that motion of the medial femoral condyle is less than the lateral femoral condyle in the transverse plane [11,15,16] during deep knee bend or lunge activities. However, the center of knee rotation in the transverse plane was located on the lateral side of the TF joint during treadmill gait according to the dual fluoroscopic analysis reported by Kozanek et al. [8]. These studies suggested that the knee IE rotational pivot point is changed, depending on motion patterns. While the IE rotational pivot points after TKA during walking have still been rarely reported.

In our previous study [17], a subject-specific MSK MBD model of TKA using FDK was developed and evaluated, and the predicted knee contact forces by the developed showed good agreement with experimental measurements. However, the predictive power of the developed MSK model for in vivo knee motions still needs further study. In this study, the in vivo kinematics of TKA during the straight gait and right-turn cycles were predicted by the developed subject-specific MSK model [17], and the accurate contact position was described by the position of the center of pressure (COP). We hypothesized that the in vivo kinematics and contact track were gait pattern-dependent.

2. Material and methods

A previous developed subject-specific MSK MBD model of TKA using FDK [17] was used in this study. Publically available data (https://simtk.org/home/kneeloads) [18] of an adult male implanted with an instrumented left knee replacement were adopted for the model development. The experimental data included the geometry of a Zimmer NKII cruciate-retaining prosthesis, the computed tomography (CT) scans of lower limb (femur, patellar, tibia, fibula), marker trajectories and ground reaction forces (GRFs) from motion capture experiments, and the measured TF medial and lateral contact forces using the instrumented knee prosthesis. According to the patient's surgical report, the knee prosthesis was implanted with a standard antero-medial approach. The tibial components were located perpendicular to the long axis in the coronal plane and without considering the tibial posterior slope. The femoral component was located with a 6° valgus to the anatomic axis of the femur and a 3° external rotation to the posterior surface of the posterior condyles.

The subject-specific MSK MBD model of TKA was developed in the commercially software AnyBody (version 6.0, Anybody Technology, Aalborg, Denmark). Based on a subject-specific musculoskeletal modeling framework of TKA [17], the generic MSK model of the AnyBody Managed Model Repository (V1.6.2) was scaled to obtain a subject-specific full lower limb MSK model according to the patient's CT image and motion capture data. A new knee contact model with 11 degrees of freedom (DOF) was developed using the FDK method, which was developed by Anderson and Rasmussen [19] and implemented as a standard functionality in AnyBody, to replace the original hinge knee joint of the generic MSK model. The TF joint has six DOFs and the patellofemoral (PF) joint has five DOFs because of the rigid patellar ligament. The relative movement of the TF joint was quantified according to the femoral and tibial reference coordinate system, and these DOFs were free to equilibrate automatically under the effect of TF contact forces, muscle forces, ligament forces, and external loads in the FDK solver [10]. For maintaining the stability of the knee during gait, ligaments surrounding the TF and PF joints were included. There were the medial and lateral collateral ligament, medial and lateral PF ligaments, postero-medial capsule, and posterior cruciate ligament. The ligament