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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, posteromedial capsule, and posterior cruciate ligament. The ligament forces exerted by these ligament bundles followed a nonlinear piecewise force–displacement relationship and the used material parameters of these ligaments from a previous study reported by Blankevoort et al. [20].

The tibial insert was divided into two compartments in order to compute the TF medial and lateral contact forces respectively. The contact surfaces of the knee implants were represented with the triangles of STL files in Anybody. The contact forces between contact pairs were calculated using a linear force-penetration volume law [17] with a contact pressure module known as *PressureModule* in N/m^3. The equations derived by Frelgy et al. [21], based on the elastic foundation theory, were used to calculate the *PressureModule* and a computed [5] average value of 1.24e11 N/m^3 was adopted in this study. For the calculation of the contact force, the penetration depth of a vertex d_i was computed as distance to the closest point on the opponent surface, and the contact F_i was computed by multiplying the *PressureModule* by the penetration volume, V_i, which approximated by multiplying the vertex penetration depth by the opponent triangle area, A_i [10]. The contact force between the surfaces was calculated as the sum of all vertex contact forces, and was a three-dimensional force vector located at the COP of the master surface on the slave surface. The COP was calculated based on the contact area as average of position vectors of penetrating vertices, which weighted by the force vectors at each of the penetrating vertices. The position of COP (Fig.1) was quantized under the global coordinate system (GCS) using the FDK solver in dynamics analysis. For a better investigation of contact track and position of COP, a developed Matlab code was used to achieve the coordinate transformation from the GCS to local coordinate system of tibial insert.

The subject-specific standing, straight gait and right-turn trials were used for the subject-specific modeling and simulation. The standing reference trial were used to determine the original marker locations of the lower limb model and scale the other remaining segments which bone CT images did not include in the dataset. A Length–Mass–Fat scaling law was adopted for optimizing the model parameters and local marker coordinates simultaneously. And then, the marker motion data of the straight gait and right-turn trials were used to calculate the pelvic, hip and foot spatial motions in an inverse kinematics analysis. Together with patient's experimental GRFs, the outputs of the inverse kinematics analyses were used as inputs for actuating the MSK model. More details about the development of the subject-specific MSK MBD model of TKA based on FDK method could be found in previous studies [5,10,17].

The knee contact forces and motion were predicted simultaneously with a cubic polynomial muscle recruitment criterion in inverse dynamics analysis. The ISO-14243-3 and the experimentally data reported by DesJardins JD et al. [22] were used to indirectly assess the predicted in vivo knee kinematics.

3. Results

The predicted knee flexion, tibial IE rotation and anterior–posterior (AP) motion of the straight gait cycle are indirectly compared with the ISO-14243-3 and the experimentally data reported by DesJardins JD et al. [22] in Fig. 2. In general, the predicted knee flexion was consistent with the flexion angle profiles of the ISO and the reported average value of the patient's experimental data. The similar magnitude and general trend were observed between the predicted and the reported [22] tibial IE rotation without considering an average 7° external rotational femoral component alignment with respect to the tibial component. Although a similar general trend was observed between the predicted and the reported [22] tibial AP motion, a larger magnitude was predicted and the peak value

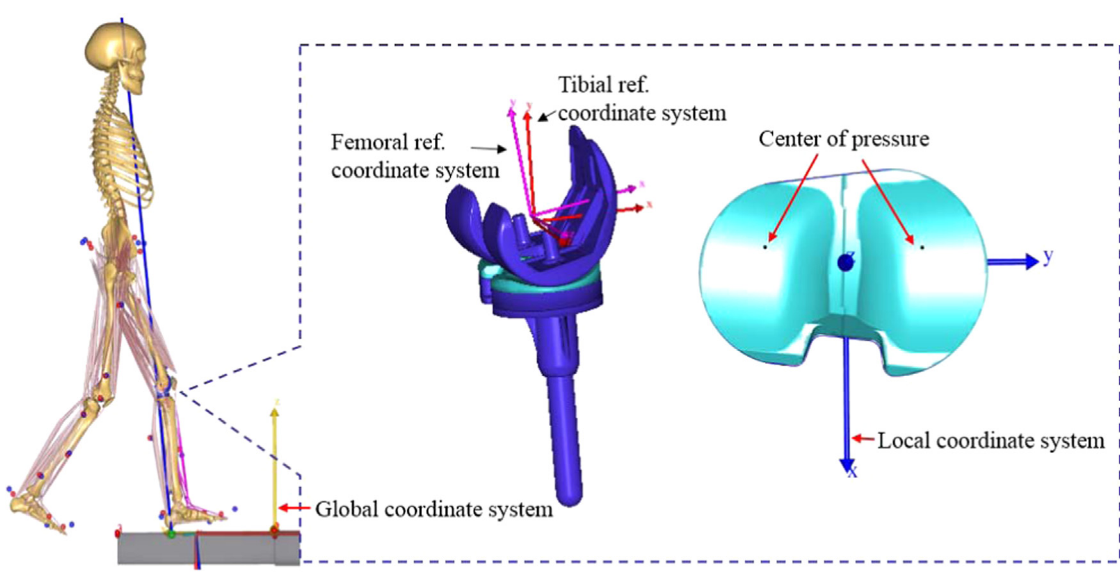

Fig. 1. Subject-specific musculoskeletal multibody dynamics model of total knee arthroplasty and the reference coordinate system and center of pressure of knee implants.

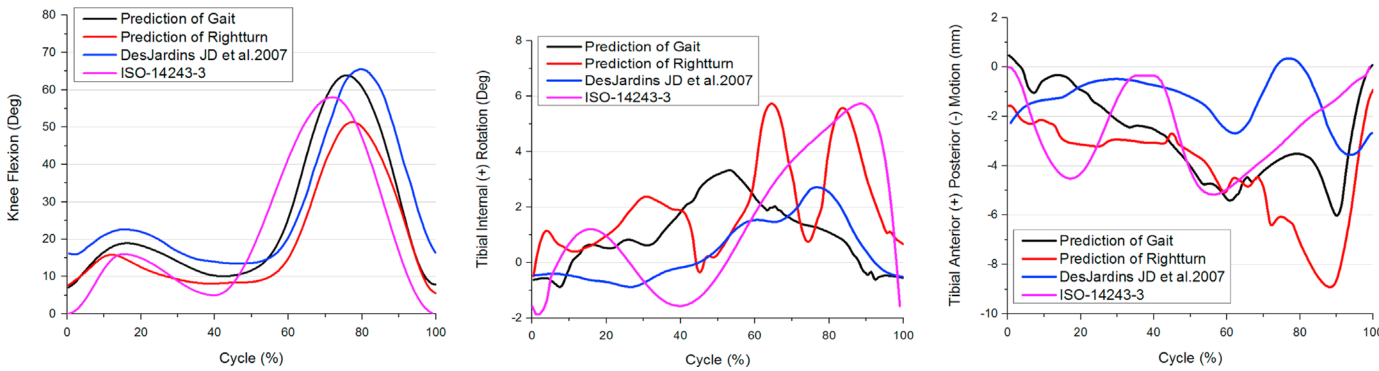

Fig. 2. Comparison of ISO-14243-3, the experimentally data reported by DesJardins JD et al. [21] and computationally estimated in vivo knee flexion, tibial internal–external rotation and tibial anterior–posterior motion.

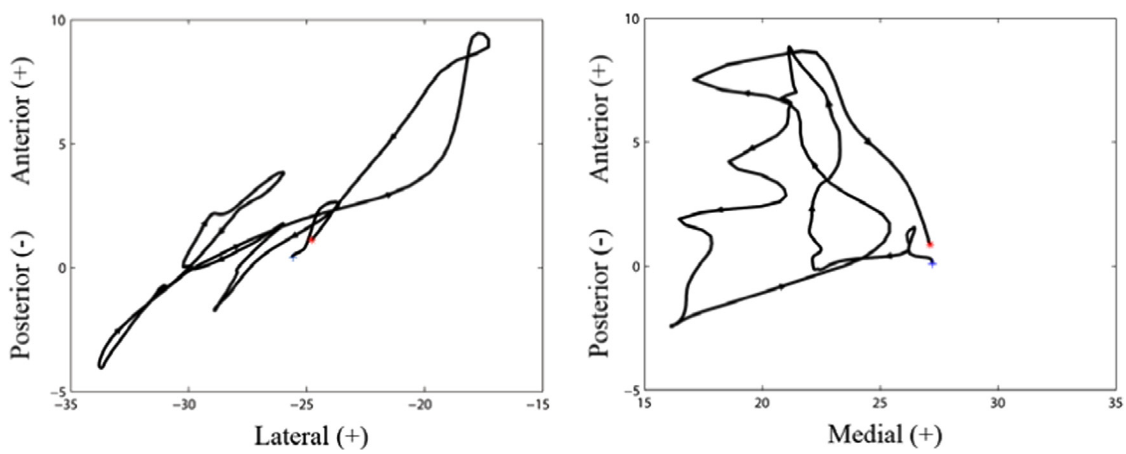

Fig. 3. The contact tracks of the medial (right) and lateral (left) COP of the Zimmer NKII TKR insert during the straight gait trial.

of the magnitude was closer to the ISO standard value. Meanwhile, the predicted knee motions of the right-turn cycle are also compared with the straight gait cycle (Fig. 2). A similar general trend was observed in the knee flexion-extension, but a smaller magnitude was predicted during the right-turn cycle than the straight gait cycle. The main trend differences were observed in IE rotation and AP translation during the swing phase, and a larger IE rotation and AP translation range were predicted during the right-turn cycle than the straight gait cycle.

Figs. 3 and 4 show the contact tracks of the medial and lateral COP of the TKA insert during the straight gait cycle and right-turn cycle. In general, a remarkable difference was observed between the medial COP track and the lateral COP track. The lateral COP track presented an approximately linear reciprocating movement, while the medial COP track showed an approximately circular movement. A marked difference in the contact tracks was observed between the straight gait cycle and right-turn cycle. Fig. 5 shows the COP positions at 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, 100% of the straight gait cycle and right-turn cycle. In addition to the changes in IE rotation and AP translation, the medial-lateral translation of the COP positions was also observed. Furthermore, the motion of the lateral femoral condyle in the transverse plane was smaller than that of the medial femoral condyle during the stance phase of the straight gait cycle. While the motion of the lateral femoral condyle in the transverse plane was larger than that of the medial femoral condyle during the stance phase of the right-turn cycle.

The changes in the COP position during the straight gait cycle are shown in Fig. 6. The changes in the COP position were mainly for the anterior translation during 0–7.5%, 15–30%, 45–53% and 75–90% of the straight gait cycle, and the changes in the COP position were mainly for the posterior translation during 7.5–15%, 60–75% and 90–100% of the straight gait cycle. The external and internal rotation of the femoral component relative to the tibial insert were observed during 30–45% and 53–60% of the straight gait cycle respectively, the IE rotational pivot points located predominantly on the lateral side of the TF joint during the stance phase of the straight gait cycle for this TKA design. The medial-lateral translation was observed during the swing phase of the straight gait cycle.

The changes in the COP position during the right-turn cycle are shown in Fig. 7. The changes in the COP position were mainly for the internal rotation during 0–6%, 11–37%, 48–66%, and 77–90% of the right-turn cycle, the changes in the COP position were mainly for the external rotation during 6–11%, 37–48%, 66–77% and 90–95% of the right-turn cycle. The IE rotational pivot points were located at the medial side

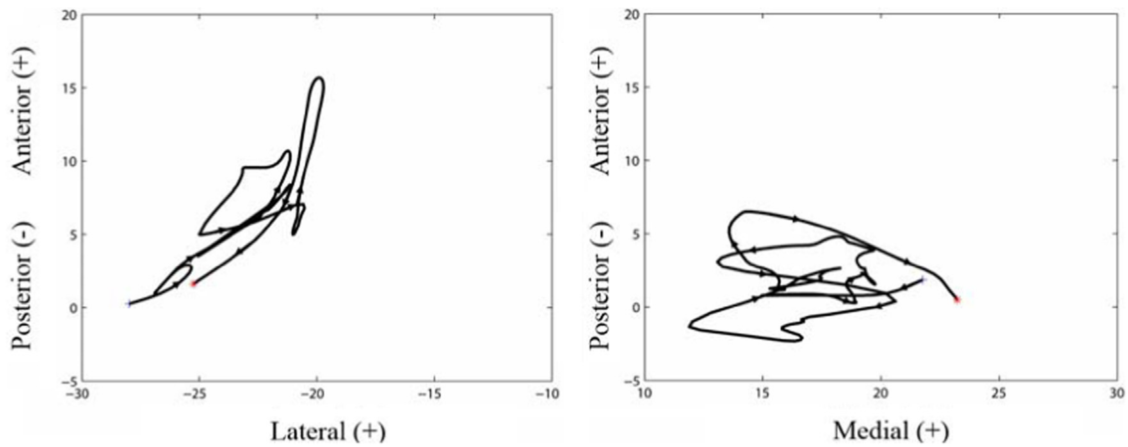

Fig. 4. The contact tracks of the medial (right) and lateral (left) COP of the Zimmer NKII TKR insert during the right-turn trail.

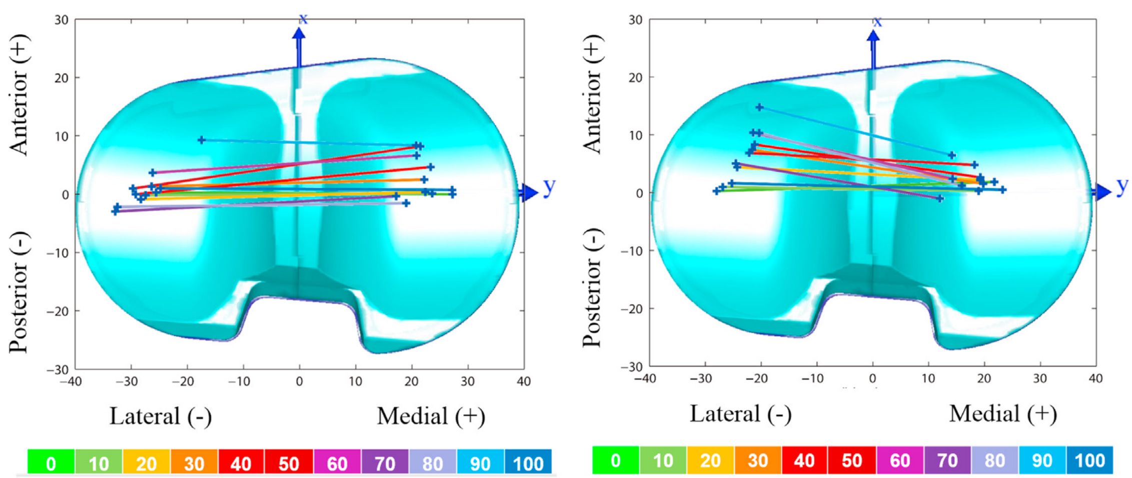

Fig. 5. The COP positions at 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, 100% of the straight gait trial (left) and right-turn trial (right). Different colored lines represented the corresponding contact position. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

of the TF joint during 0–58%, 66–69%, 77–84% and 90–95% of the right-turn cycle, while the IE rotation pivot points at the lateral side of the TF joint during 58–66%, 69–77% and 84–90% of the right-turn cycle. The posterior translation was mainly observed during 95–100% of the right-turn cycle.

4. Discussion

Accurate knowledge of in vivo knee kinetics and kinematics are important for the wear and function assessments, which can be further utilized to improve current lifetime of knee prostheses. A previous developed subject-specific MSK MBD model [17] provided a strong platform for predicting the in vivo knee kinetics and kinematics of TKA. The TF total, medial and lateral contact forces had been predicted in a previous study [17], and showed good agreement with the in vivo experimental measurements during the straight gait cycle. In this study, the in vivo kinematics during walking was predicted by a developed subject-specific MSK MBD model of TKA [17], and the positions of the center of pressure (COP) were adopted to describe the contact position of TKA.

The available in vivo contact forces from instrumented knee prostheses [18] offer a unique opportunity to evaluate the predictive power of the subject-specific MSK modeling approach for TKA. Unfortunately, the released patient's data did not include the fluoroscopic kinematic data. So the predicted in vivo kinematics of TKA were estimated by comparing with ISO-14243-3 and the fluoroscopic kinematic data reported by DesJardins et al. [22]. The measured data reported by DesJardins et al. [22] were obtained from patients with a Zimmer NKII right knee prosthesis, the 6–8° external rotational femoral component alignment with respect to the tibial component for the patient was not considered when compared with the predicted tibial IE rotation. Overall, the developed subject-specific MSK MBD model of TKA could predict in vivo kinematics with a reasonable level of accuracy. The phase difference of the tibial IE rotation and the magnitude difference of the tibial AP motion may be related to the ligament model. In this study, the properties assigned for the ligaments in the model were obtained from the literature [20], and each ligament origin and insertion point was adjusted manually to fit with the bone geometry of the patient knee

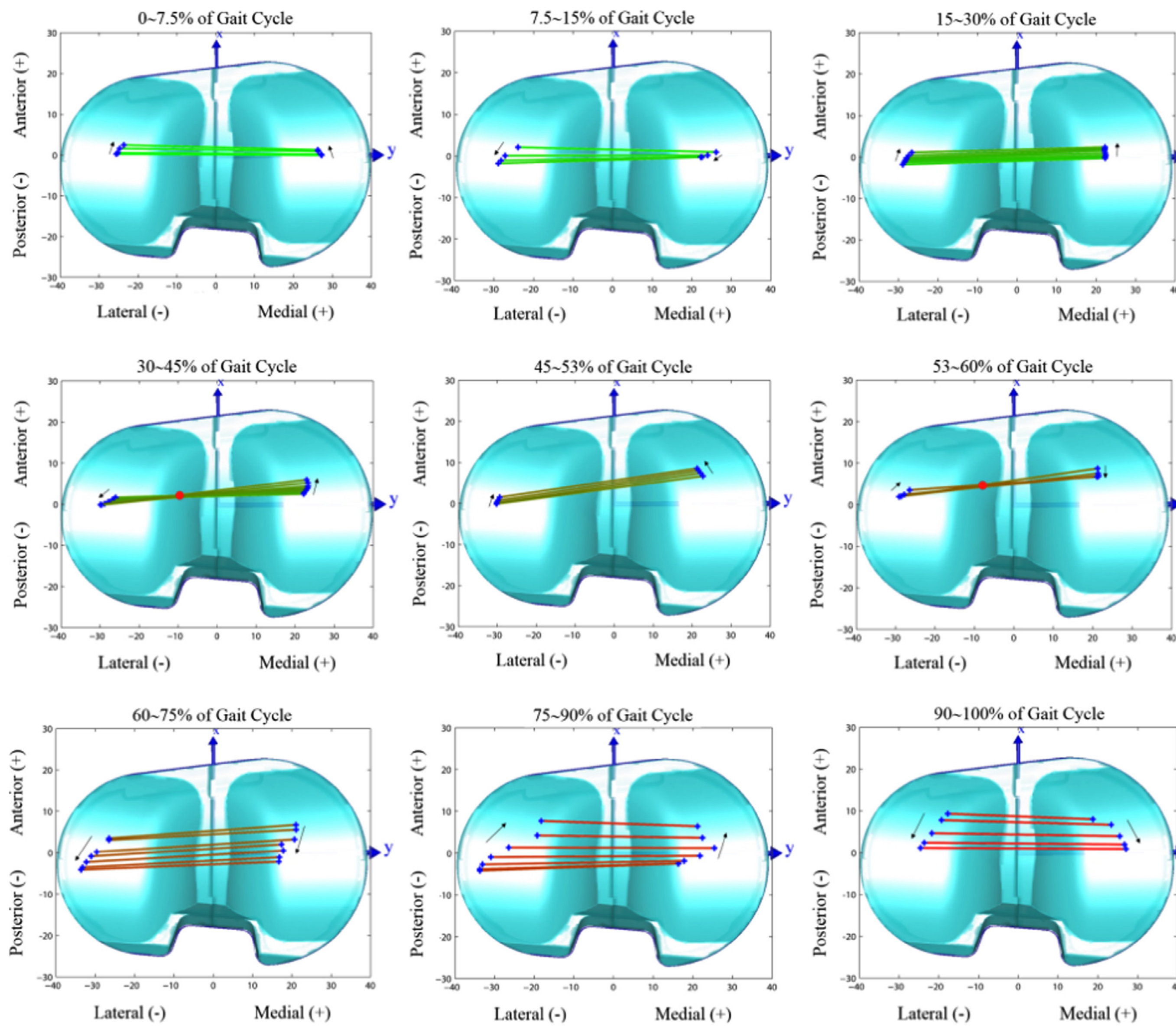

Fig. 6. The changes in the COP position during the straight gait trial.

model according to the anatomic descriptions. The prediction of in vivo kinematics may be affected by these approximations. More accurate ligament model and subject-specific fluoroscopic kinematic data should be adopted in the future prediction and estimation of in vivo knee kinematics.

The prediction confirmed that in vivo knee kinematics and contact track are gait pattern-dependent. Straight gait and turn to right or left gait represented the major gait character during walking. Compared with the straight gait cycle, the remarkable differences of the trend and amplitude in knee kinematics were predicted during the right-turn cycle. Moreover, the changes in the COP positions mainly showed as internal or external rotation during the right-turn cycle, and the rotational pivot point was located at the medial or lateral side of the TF joint, which were obviously different with the straight gait cycle. However, the right-turn or left-turn gait trial is rarely considered in the investigation of knee kinetics and kinematics, and articular surface wear of knee implants. The predicted results demonstrated that the in vivo knee loads and motions during the right-turn or left-turn gait trial should be considered in the understanding the wear mechanisms of TKA.

The prediction of the COP positions indicated that motion of the lateral femoral condyle in the transverse plane was smaller than that of the medial femoral condyle during the stance phase of the straight gait cycle. Our findings are consistent with the results reported by Kozanek et al. [8], which indicated that the medial femoral condyle made greater excursions than lateral femoral condyle during the stance phase of treadmill gait. Furthermore, the fluoroscopic experiments reported by DesJardins et al. [22], which obtained from several patients implanted with the Zimmer NKII right knee prosthesis design, exhibited IE rotation about a center-to-lateral condyle pivot point during the gait cycle. Our predictions also confirmed this point once again (Fig. 6), which the IE rotational pivot points

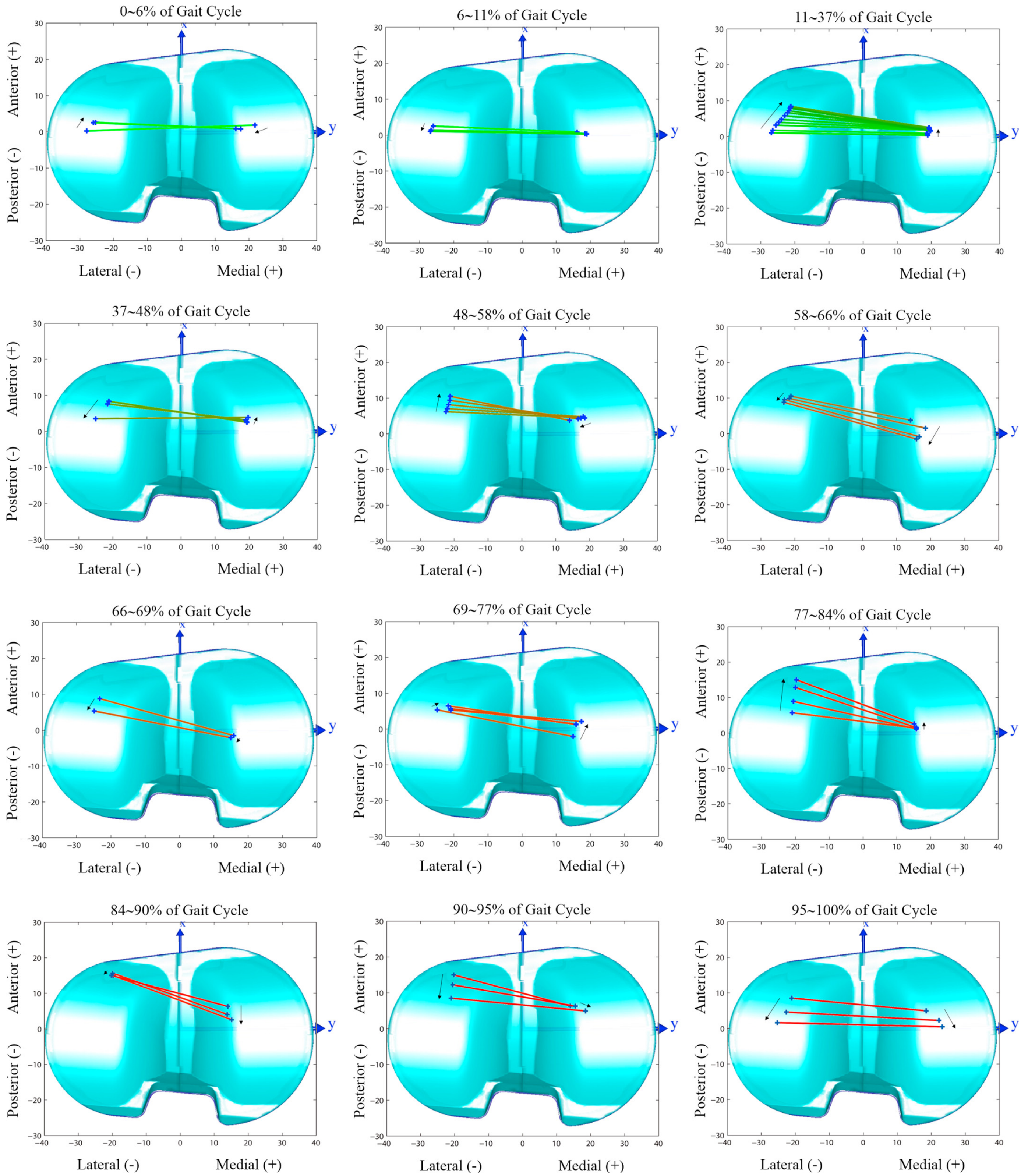

Fig. 7. The changes in the COP position during the right-turn trail.

were located predominantly on the lateral side of the TF joint during the stance phase of the straight gait cycle for this Zimmer NKII TKA design. Although some studies [11,16] reported that the medial femoral condyle was less mobile than the lateral femoral condyle, these studies were performed under the deep knee bend or lunge. Kozanek et al. [8] found that knee kinematics were activity-dependent and motion patterns of non-weight bearing flexion or lunge cannot be generalized to interpret a different one. The differences in the COP positions between the straight gait cycle and right-turn cycle from our study further confirmed this point.

The TF contact track is an important parameter for determining the knee joint forces and moments imposed by muscles about the knee-joint. In addition, it is significant to predict the TF contact track of TKA for understanding the effect of multidirectional motion on the UHMWPE wear of the tibial insert. Wear of TKA bearings is mainly dependent on kinematics at the articulating surfaces under the same design and material conditions. Motions which reproduced more cross-pathway sliding usually produced more wear [23]. The predicted contact tracks of the medial and lateral COP indicated that the multidimensionality and complexity of TF contact motion (Figs. 3 and 4). The difference between the medial and lateral contact tracks may be resulted from the asymmetric design of the Zimmer NKII tibial insert. This difference may influence the surface wear of the medial and lateral compartment because wear rate is dependent upon the wear path geometry [24]. Furthermore, the large medial-lateral translation was observed during the swing phase of the straight gait cycle, which resulted in a complex multidirectional motion and should not be ignored in wear studies for knee implant designs.

In vivo kinematics of TKA are very complex and depend on many factors. First, due to the individual differences in anatomical features and gait features, the changes in knee kinematics following TKA have been observed between different patients [7]. And the in vivo knee kinematics are activity-dependent [8], and all kinematics data of daily activities are required for understanding in vivo knee kinematics. In this study, knee kinematics function was only evaluated for one patient during the straight gait and right-turn cycle, more patients and more daily activities are needed. Second, TF kinematics were sensitive to the changes in different total knee arthroplasty designs [25]. For example, the tibial insert post and femoral cam designs have been used to achieve higher flexion [12], and different knee implant designs exhibit different IE rotational pivot points during high flexion [12]. The sensitivity of in vivo knee kinematics to the knee implant design should be investigated in future work.

5. Conclusions

In summary, this study successfully predicted the in vivo kinematics of TKA with a reasonable level of accuracy using a subject-specific MSK MBD model during walking simulation. The contact position and contact track of TKA during walking were quantified using the COP position. The changes in the COP position were mainly for the anterior or posterior translation during the straight gait cycle, the internal-external rotational pivot points were located predominantly on the lateral side of the TF joint during the stance phase of the straight gait cycle. While the major changes in the contact positon of COP were the internal-external rotations for right-turn cycle, and the rotational pivot points mostly were located on the medial compartment. The in vivo kinematics and contact track are complex and gait pattern-dependent.

Acknowledgments

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