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In-vivo analysis of sliding distance and cross-shear in Bi-cruciate retaining total knee arthroplasty

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ABSTRACT

Polyethylene remains the most popular bearing material for total knee arthroplasty (TKA). Despite its widespread use, wear continue to be one of major factors implicated in revision surgery. Sliding distance, cross-shear, and contact stress are the major factors influencing polyethylene wear. As previous studies have either relied on wear simulations, computational modeling, or in vitro measurements to quantify sliding distance and cross-shear, in vivo subject-specific sliding distance and cross-shear after bi-cruciate retaining (BCR) TKA has not been previously reported. The objective of this study was to quantify the 6°-of-freedom (6DOF) in vivo kinematics, sliding distance, and cross-shear in BCR TKA patients during gait. Twenty-nine unilateral BCR TKA patients performed level walking on a treadmill under dual fluoroscopic imaging system (DFIS) surveillance. Cumulative normalized sliding distances between the lateral and medial compartments did not change significantly ($p > 0.05$) during the gait cycle. Although the total normalized sliding distance was similar between the lateral and medial compartments, the cross-shear at the lateral compartment differed significantly from that at the medial compartment ($p < 0.001$). Significant differences in the relative length positions of the peak sliding distance and cross-shear were found between the lateral and medial bearing components. The flexion-extension motion of the reconstructed knee was more associated with the linear displacements (anterior-posterior, $R^2 = 0.6$; lateral-medial, $R^2 = 0.8$, proximal-distal, $R^2 = 0.7$) than the angular displacement (varus-valgus, $R^2 = 0.18$; internal-external rotation, $R^2 = 0.28$). Despite some differences in peak sliding distance and cross-shear positons, our results suggest similar articular contact patterns between the lateral and medial compartments in BCR TKA patients during gait. The data could provide insights into understanding the potential wear patterns in BCR TKAs.

1. Introduction

Total knee arthroplasty (TKA) is a common surgical procedure for end stage osteoarthritis, and an increasing number of knee replacement operations are being carried out every year worldwide (Carr and Goswami, 2009). By 2030, the annual incidence of primary TKA is expected to be 3.5 million in the Unites States (Kurtz et al., 2007). Due to the fact that an increasing number of young patients require joint replacements, the expected life time of the prostheses is considerable increasing, and at the same time that more demanding activities are experienced, new materials and designs are introduced (Abdelgaied et al., 2011). Polyethylene remains the most popular bearing material for TKA. Despite its widespread use, wear and damage continue to be major factors implicated in revisions (Sharkey et al., 2014). Sliding distance, cross-shear, and contact stress are the major factors influencing polyethylene wear (Abdelgaied et al., 2011; D'Lima et al., 2008; Fregly et al., 2005; Knight et al., 2007; Mattei et al., 2013). Previous studies have either relied on wear simulations, computational modeling, or in vitro measurements to quantify sliding distance and cross-shear (Abdelgaied et al., 2011; Catani et al., 2010; D'Lima et al., 2008; Fregly et al., 2005). However, in vivo subject-specific sliding distance and cross-shear after bi-cruciate retaining (BCR) TKA remain unclear.

The ability to accurately measure in vivo knee-joint kinematics following TKA is important for determining joint-contact loading at the knee, predicting implant component wear, and evaluating the effects of implant design and surgical technique on TKA performance (Catani et al., 2010; D'Lima et al., 2008). In case of single-plane fluoroscopy, motion perpendicular to the image has at best and accuracy in range of 3.0–6.0 mm (Banks, 2005; Banks and Hodge, 1996; Catani et al., 2010). However, the dual fluoroscopic

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imaging system (DFIS) (Bingham and Li, 2006; Li et al., 2008) is a validated approach allowing for accurate measurement of in vivo kinematics of the knee joint. Despite this tool potential, little is known about the in vivo sliding distance and cross-shear following TKA during gait.

Bi-cruciate retaining total knee arthroplasty design preserves both anterior and posterior cruciate ligaments with the potential to restore normal posterior femoral rollback and joint kinematics. Abnormal knee kinematics and "paradoxical" anterior femoral translation in conventional TKA designs have been suggested as possible causes of patient dissatisfaction (Dennis et al., 1998; Schmidt et al., 2003). However, there is a paucity of in vivo data on sliding distance and cross-shear after BCR TKA. Since walking is a fundamental everyday functional activity allowing individuals for basic independent mobility, treadmill walking was used to assess the performance of the BCR TKA design. The purpose of this study was to quantify the six degree-of-freedom (6DOF) in vivo kinematics, sliding distance, and cross-shear in BCR TKA patients during gait using a validated non-invasive DFIS based tracking approach.

2. Methods

2.1. Participants

Twenty-nine well-functioning unilateral BCR TKA patients (14 males and 15 females) with no history of any surgical complication were included in this study with the institution's Internal Review Board approval. Patients underwent unilateral (16 left; 13 right) BCR TKA (Vanguard XP Total Knee System, Biomet, Warsaw, IN, USA) from May 2013 to June 2015. All BCR TKAs in this study had pre-operative varus deformity and implanted by a single surgeon using a standard medial parapatellar approach. Osteophytes were debrided and medial release was performed by elevation of medial tibial periosteum with knee in extension. Residual periosteum is dissected posteromedially to the level of the insertion of the semimembranosus. Space blocks were used to balance the flexion and extension gaps. The thickness of the lateral and medial polyethylene insert was selected to balance BCR TKA tibia-femoral conformity (Table1). The average age was 65.7 years (±7.7, range 47–76, Table 1). The average body weight and height were 89.2 kg (±15.9, range 57.7–120.3) and 172.7 cm (±9.2, range 154.9–185.4), with average BMI of 29.8 kg/m^2 (±4, range 21.8–38.1). The femoral and tibial component sizes were 66.8 mm (±5, range 60–42.5) and 75.3 mm (±4.5, range 67–83), respectively. The average follow-up time was 12.7 months (±5.1, range 3.9–21.3) from surgical data.

2.2. Experiment procedures

All unilateral BCR TKA patients performed level walking on a treadmill at self-selected speed under synchronized DFIS surveillance (BV Pulsera, Phillips Medical, USA) at 30 frames per second with an 8 ms pulse-width, 60–80 kV and 0.042–0.066 mA s (Bingham and Li, 2006; Kozanek et al., 2009). The approximate number of images per gait cycle was 40.

Table 1
Demographic data of bi-cruciate retaining total knee arthroplasty (TKA) patients.

N = 29	Average ± standard deviation (range)
Age (years)	65.7 ± 7.7 (47.0–76.0)
Gender	14 male, 15 female
Operated side	16 left, 13 right
Mass (kg)	89.2 ± 15.9 (57.7–120.3)
Height (cm)	172.7 ± 9.2 (154.9–185.4)
BMI (kg/m^2)	29.8 ± 4.0 (21.8–38.1)
Follow-up (month)	12.7 ± 5.1 (3.9–21.3)
Femoral component size (mm)	66.9 ± 5.0 (60.0–72.5)
Poly-thickness medial	9.7 ± 0.9 (9.0–12.0)
Poly-thickness lateral	9.7 ± 0.9 (9.0–12.0)
Tibia component size (mm)	75.3 ± 4.5 (67.0–83.0)

The two dimensional dynamic fluoroscopic images and the three-dimensional (3D) TKA Computer Aided Design (CAD) models were imported into a customized program in MATLAB (MathWorks®, Natick, MA, USA). A virtual DFIS environment was constructed in the customized program for determination of the TKA component positions. Furthermore, the position of each TKA component in 3D space was determined with a previously published protocol (Bingham and Li, 2006; Li et al., 2008) by performing optimal matching of TKA CAD model projections with the dynamic fluoroscopic TKA images. A cubic interpolation was performed to obtain continuous data during gait, and the average result of at least three complete gait cycles (120 images) was used for analysis. The coordinate systems were defined for the femoral and tibial components of a left BCR TKA (Fig. 1a). In addition, all twenty-nine patients received computer tomography (CT) scan (Sensation 64, Siemens, Germany, 140kVp, image resolution 512 $\times$ 512 pixels, voxel size 0.97 $\times$ 0.97 $\times$ 0.60 mm3) from the pelvis to the ankles for the creation of 3D surface models of both knees (BCR TKA and non-operated). For the non-operated knee, the femoral and tibial local coordinate systems were constructed using the anatomical bony landmarks (Qi et al., 2013). The transepicondylar axis (TEA) was defined as the medial-lateral axis and the mid-point of the axis as the femoral center. The cross product of the TEA and the long axis was the anterior-posterior axis (Fig. 1d). For the tibial coordinate system, two circles were created to fit the medial and lateral plateaus separately (Kozanek et al., 2009). The line connecting the centers of these two circles was defined as the medial-lateral axis and the mid-point as the tibial center. The cross product of the medial-lateral axis and the proximal tibial long axis was the anterior-posterior axis of the tibia (Fig. 1d). The anatomical coordinate systems of the operated knee were determined using a previously validated and published 3D mirroring technique (Tsai et al., 2014), allowing minimization of residual surface-to-surface registration errors between the remaining bone on the operated side and the mirrored non-operated one (Fig. 1d). In-vivo kinematics of the BCR TKA was then quantified in the anatomical coordinate system during the entire gait cycle.

2.3. Sliding distance, and cross-shear

The positions of the contact regions in the medial and lateral compartments were calculated for 101 time frames over the gait cycle. To approximate the position of the contact region, the overlapping region between the femoral and tibial component on the tibia bearing tray was used (Lundberg et al., 2014; Yin et al., 2017). The sliding distance was defined as the distance (tangentially projected on the tibia insert bearing surface) traveled by points on the femoral component past points on the bearing surface during contact accumulated over the gait cycle (Maxian et al., 1996) (Fig. 1b and c). Briefly, the changes in the angular and linear displacements of the femoral component between successive instants were used to determine the average instantaneous vector displacement of the contact points. Then, the vector, tangentially projected on the tibia insert bearing surface, was used to determine the instantaneous sliding distance of the contact points. Rolling motions were assumed when the instantaneous sliding distance was equal to zero. An average size tibial component was used to normalize the sliding distance of each patient accordingly (Fig. 1c). The relative position of the peak sliding distance was calculated as a percentage of the width and length of the lateral and medial bearing components (Fig. 1c).

The cross-shear was defined as the ratio between the frictional work released perpendicularly to the principal molecular