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Knee kinematics in bi-cruciate stabilized total knee arthroplasty during squatting and stair-climbing activities

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ABSTRACT

This study aimed to evaluate clinical outcomes and in vivo kinematics of bi-cruciate stabilized (BCS) total knee arthroplasty (TKA), using image-matching techniques. We analyzed tibiofemoral anteroposterior translation, axial rotation, and anterior/posterior cam-post contact for 22 BCS TKAs during squatting and stair-climbing. The functional activities on the 2011 Knee Society Score were significantly improved from 36 to 71. The tibiofemoral translation and axial rotation during squatting/stair-climbing were 16.1 mm/7.1 mm and 2.5° external/1.1° internal, respectively. Anterior/posterior cam-post contacts were observed during squatting (14%/96%) and stair-climbing (27%/96%). In conclusion, BCS TKA produced physiological sagittal plane kinematics during activities with favorable clinical outcomes.

1. Introduction

The most important aims of total knee arthroplasty (TKA) are to achieve pain relief with improved function in patients with late-stage knee osteoarthritis. Over the last two decades, the proportion of younger and more physically active patients undergoing TKA has increased. Despite innovations in prosthesis design and surgical techniques, TKA has not completely restored normal knee kinematics and some daily activities could be limited compared to healthy knees; 52% of patients after TKA reported some degree of limitation in performing functional activities.[1] A report showed that only 72% of patients were satisfied with the pain relief and the ability to climb and descend stairs.[2] Moreover, patients after TKA are reported as feeling "artificial" when loaded in flexion during activities.[3]

There have been several reports on unphysiological kinematics after TKA, including decreased/paradoxical anteroposterior (AP) translation, and limited/reverse axial rotation of the femur with respect to the tibia with flexion.[4,5] The reasons for abnormal kinematics were thought to be related to a symmetric articular configuration and deficiency of the anterior cruciate ligament (ACL), regardless of cruciate-retaining and posterior-stabilized (PS) prostheses.[6] In addition, other cited causes of abnormal kinetics included the impingement of the anterior post, inappropriate tension of the posterior cruciate ligament (PCL), and dysfunction of the cam-post mechanism.[4] Native knee motion is guided by the collateral and cruciate ligaments and the surface geometry of the concave medial and convex lateral tibial plateau, the asymmetric femoral condyles,[7] as well as external forces. Meanwhile, knee motion after TKA is guided by the collateral ligaments, the surface geometry and, occasionally, by retained PCL or cam-post mechanisms,[7,8] depending on the posture.[7]

Kinematic analysis is important for understanding normal and pathologic joint function and could have a direct effect on patients' functional outcome and satisfaction. This study aimed to analyze the dynamic kinematics of the knee joint and the anterior/posterior cam-post mechanism during squatting and stair-climbing in bi-cruciate stabilized (BCS) TKA, measured using radiographic-based image-matching techniques.

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2. Methods

2.1. Patients

The study protocol was approved by our Institutional Review Board (IRB number 24–166). This prospective cohort study involved 20 patients with 22 varus knees. The patients had undergone BCS fixed-bearing TKA (JOURNEY II, Smith & Nephew, Memphis, TN, USA), with more than 12-months of follow-up, were prospectively recruited for the study, and provided their consent to participate. Patients with a history of neuromuscular disease, fractures around the knee joint, previous arthroplasty and osteotomy, and severe extra-articular deformity were excluded.

BCS TKA has asymmetrical anatomical femoral condyles, a tibial baseplate with concave medial and convex lateral polyethylene articular surfaces, and anterior and posterior cam-post mechanisms.[9] A 3° medial inclination of the articular surfaces, relative to the tibial baseplate, was implemented by including a 2.5-mm difference in the thickness of the medial and lateral compartments.[9] This knee system is designed to function with an anterior cam-post mechanism below 20° of knee flexion to limit anterior tibial translation and, therefore, partially replicate the function of the ACL. The posterior cam-post mechanism engages from 60° to 70° knee flexion and promotes physiological femoral rollback.

2.2. Surgical technique

Between November 2013 and June 2015, all TKAs were performed by a single experienced surgeon (KO), using a similar standardized technique based on the mechanical alignment and medial parapatellar approach. Using a measured resection technique, the femoral and tibial components were aligned perpendicular to the mechanical axes in the coronal plane by cutting the distal femoral and proximal tibial bone at 90° to their respective mechanical axes with intramedullary and extramedullary instruments, respectively. In the sagittal plane, the femoral component was aligned perpendicular to the distal anatomical axis of the knee and resection of the proximal tibia was planned to obtain a 3° posterior tilting using extramedullary guides according to the manufacturer's recommendation. In the axial plane, the femoral component was aligned along the surgical epicondylar axis, with the rotational alignment of the tibial component adjusted to the AP axis of the tibia. Additionally, the rotational alignment of the tibial component was also confirmed using the range of motion (ROM) technique as a reference. Soft tissue balancing was performed to achieve near-normal medial stability in knee extension and flexion and lateral extension laxity was acceptable.[10,11]

2.3. Patient-reported outcomes

Pre- and postoperative patient-reported outcomes were assessed using the 2011 Knee Society Score (KSS 2011). The subjective component of KSS 2011 evaluates the following: symptoms, satisfaction, and functional activities (walking and standing, standard activities, advanced activities, and discretionary activities). The maximum possible score for each component of the KSS 2011 is as follows: 25 for 'symptoms'; 40 for 'patient satisfaction'; 100 for 'functional activities'; 5 for 'squatting'; and 5 for 'climbing up or down a flight of stairs'.

2.4. Berg balance scale (BBS)

BBS was developed as a performance-oriented measure of balance in elderly individuals. BBS is a common tool for balance assessment and can be considered a reference standard for clinically assessing balance in patients with TKA, with good reliability and validity.[12] The utility includes grading different patients' balance abilities, monitoring functional balance over time, and evaluating patients' responses to treatment. BBS is a test of 14 items; it is performance based and has a scale of 0–4 for each item (higher score for independent performance), with a maximum score of 56.

2.5. Radiographic measurements

Pre- and postoperative whole-leg radiographs were taken with the patella facing a forward position, with the feet straight and at shoulder width. The hip-knee-ankle (HKA) angle was defined as the coronal angle between the mechanical axes of the femur and the tibia. Positive and negative values were expressed as varus and valgus, respectively. The coronal femoral component angle was defined as the medial angle formed by the mechanical axis of the femur and the horizontal axis of the medial and lateral femoral condyles calibrated by subtracting the 3° lateral incline of the articular surfaces of the femoral condyles. The coronal tibial angle was defined as the medial angle between the mechanical axis of the tibia and the horizontal axis of the tibial component. The sagittal femoral angle was defined as the angle between the anatomical axis of the distal femur and a line that was drawn perpendicular to the distal point of the femoral component. The tibial posterior slope was defined as the angle between a line that was perpendicular to the anatomical axis of the proximal tibia and a line that was drawn across the tibial tray.

2.6. Kinematic analyses

Periodic sagittal radiographs were obtained during two dynamic movements under radiographic surveillance, using a flat-panel detector (FPD: Ultimax-I, Toshiba, Tochigi, Japan) operating at 10 frames per second, with an image area size 420 (horizontal) × 420 (vertical) mm, and 0.274 × 0.274 mm/pixel resolution.[13,14] For squatting, subjects crouched downward from a standing position to where the knees were maximally flexed. For stair-climbing, subjects were assessed using a reciprocal stepping pattern, for a step height of 20 cm. The manufacture provided three-dimensional (3D) computer-aided design (CAD) models of the femoral and tibial components that were projected and superimposed onto the serial two-dimensional radiographic images acquired using the FPD.[11] Using image-matching techniques with a 3D CAD model to analyze the surfaces of the femoral and tibial components, we evaluated the dynamic in vivo kinematic parameters: tibiofemoral implant flexion angle, AP translation, and axial rotation. The positive or negative value of tibiofemoral flexion was defined as flexion or extension of the femoral component relative to the tibial component, respectively. The positive or negative value of AP tibiofemoral position was defined as anterior or posterior to the midline of the tibial tray, respectively. The positive or negative value of axial rotation was defined as the internal or external rotation of the femoral component relative to the tibial component, respectively. Simultaneously, the occurrences of contact between the anterior/posterior cam and the post were determined by the intersection of the femoral component and the tibial post, while assessing the configuration of the articular surfaces of the polyethylene insert.[4,13] A previous study estimated the root mean square errors for the femoral component relative to the tibial component to be 0.25 mm for in-plane translation, 0.28 mm for out-of-plane translation, and 0.27° for rotation.[14]

2.7. Statistical analyses

Statistical analysis was performed using JMP Software (Version 11.0; SAS Institute Inc., Cary, NC, USA). All values are expressed as the mean ± standard deviation. Welch's *t*-test and chi-squared tests were used to evaluate differences in demographic and radiographic data between pre- and postoperative TKAs. A repeated-measures analysis of variance and post hoc tests (Student's *t*-test) were used to analyze the kinematics, including the total amount of AP translation and axial rotation, and the flexion angle and AP position for the contact between