The Journal of Arthroplasty 30 (2015) 1237–1242

Contents lists available at ScienceDirect

The Journal of Arthroplasty

journal homepage: www.arthroplastyjournal.org

Analysis of the Flexion Gap on In Vivo Knee Kinematics Using Fluoroscopy

Shinichiro Nakamura, M.D., Ph.D. [a,b], Hiromu Ito, M.D., Ph.D. [a], Hiroyuki Yoshitomi, M.D., Ph.D. [a], Shinichi Kuriyama, M.D. [a], Richard D. Komistek, Ph.D. [b], Shuichi Matsuda, M.D., Ph.D. [a]

[a] Department of Orthopedic Surgery, Kyoto University, Graduate School of Medicine, Kyoto, Japan
[b] Center for Musculoskeletal Research, University of Tennessee, Knoxville, TN

ARTICLE INFO

Article history:
Received 9 November 2014
Accepted 29 January 2015

Keywords:
Total knee arthroplasty
Kinematics
Flexion gap
Ligament balance
Medial collateral ligament
Fluoroscopy

ABSTRACT

There is a paucity of information on the relationships between postoperative knee laxity and in vivo knee kinematics. The correlations were analyzed in 22 knees with axial radiographs and fluoroscopy based 3D model fitting approach after a tri-condylar total knee arthroplasty. During deep knee bend activities, the medial flexion gap had significant correlations with the medial contact point ($r = 0.529$, $P = 0.011$) and axial rotation at full extension. During kneeling activities, a greater medial flexion gap caused larger anterior translation at complete contact ($r = 0.568$, $P = 0.011$). Meanwhile, the lateral flexion gap had less effect. In conclusion, laxity of the medial collateral ligament should be avoided because the magnitude of medial flexion stability was crucial for postoperative knee kinematics.

Total knee arthroplasty (TKA) is a successful procedure with predictable long-term outcomes including pain relief and knee function restoration. Obtaining satisfactory stability in the coronal plane is critical for the long-term success of TKA. Precision of rotational alignment and proper ligament balance are required for excellent results of the surgery. Malrotation of the femoral component and flexion gap asymmetry have been associated with numerous undesirable conditions including patellofemoral and tibiofemoral instability, arthrofibrosis, knee pain, and abnormal knee kinematics [1–7]. Therefore, soft-tissue balance is considered an important factor in]the clinical success of TKA [8,9].

Previously, in vivo knee laxity was analyzed in normal knees to determine how much laxity could be tolerated by total knee prosthesis. The flexion gap in a normal knee is not rectangular, and the lateral joint gap is wider than the medial joint gap in knee flexion as well as in extension [10,11]. After resection of the anterior and posterior cruciate ligament, the lateral compartment could be stretched further than the medial compartment, and the corresponding flexion gap values were significantly larger [12,13]. In normal knee kinematics, the femur rotates externally with knee flexion during deep bend knee activities, called the medial pivot movement. It is suggested that medial tightness and lateral laxity contribute to this phenomenon [14]. Controversy exists regarding the most favorable joint gaps in implanted knees. Some favor a measured resection technique to tolerate lateral laxity, while others recommend a gap-balancing technique to obtain a parallel flexion gap.

Numerous in vivo kinematic analyses have been previously conducted for normal knees and implanted knees. They determined that posterior-stabilized (PS) designs are characterized by a posterior femoral rollback and a more normal axial rotation [15–18]. Thus far, it has been reported that either surgical technique or intraoperative soft-tissue balancing has some effects on postoperative knee kinematics [4,9]. However, there is a paucity of information on the relationship between postoperative knee laxity and in vivo knee kinematics. Moreover, the effect of ligament balance and how it enables normal knee kinematics postoperatively still remain unknown.

Recent kinematic study has shown that medial pivot kinematic patterns result in significantly better patient reported outcome and larger flexion angles [19]. To represent normal knee kinematics after TKA might be an important factor to improve clinical results. In the current study, it was hypothesized that medial tightness for implanted knees might induce more similar knee kinematics to normal knees. The purpose of this study was to analyze the relationships between postoperative coronal balance and in vivo knee kinematics while providing the proper ligament balance necessary to represent normal knee kinematics after TKA.

One or more of the authors of this paper have disclosed potential or pertinent conflicts of interest, which may include receipt of payment, either direct or indirect, institutional support, or association with an entity in the biomedical field which may be perceived to have potential conflict of interest with this work. For full disclosure statements refer to http://dx.doi.org/10.1016/j.arth.2015.01.046.

Reprint requests: Shinichiro Nakamura, M.D., Ph.D., Department of Orthopedic Surgery, Kyoto University, Graduate School of Medicine, 54 Shogoin-kawaharacho, Sakyo-ku, Kyoto, Japan.

http://dx.doi.org/10.1016/j.arth.2015.01.046
0883-5403/

Table 1
Demographic data for participants (average ± SD).

Patient age (years)	74.7 ± 9.8
Sex (female/male)	16/6
Weight (kg)	57.5 ± 8.7
Height (cm)	153.1 ± 6.2
Body mass index (kg/m^2)	24.5 ± 3.4
Diagnosis	OA: 16, RA: 4, ON: 2
Time after surgery (months)	25.3 ± 19.1
Preoperative Knee Society Score	40.0 ± 11.3
Preoperative Functional Score	42.0 ± 11.4
Postoperative Knee Society Score	98.7 ± 2.3
Postoperative Functional Score	78.6 ± 14.5
Preoperative femoro-tibial angle (degrees)	180.5 ± 12.0
Postoperative femoro-tibial angle (degrees)	173.1 ± 1.9

OA: osteoarthritis, RA: rheumatoid arthritis, ON: osteonecrosis.

Materials and Methods

In vivo knee kinematics were assessed in 22 knees (18 patients) implanted with a tri-condylar TKA. Patient demographics are shown in Table 1. There were no significant correlations between diagnosis and in vivo knee kinematics. The femorotibial angle was defined as the angle subtended by the axes of femoral shaft and tibial shaft as measured on the lateral side. A single surgical team performed each surgery while following the same procedure. The posterior cruciate ligament was sacrificed, and bony resection with a measured resection technique was carried out for all knees while aiming for equal flexion-extension gaps and medial-lateral laxity. Approval from the Institutional Review Board was obtained prior to the start of the study. All of the subjects were required to sign a written informed consent before participating in this study.

The tri-condylar implant used and analyzed in the current study is the Bi-Surface Knee System developed by Kyocera Medical (Osaka, Japan) (Fig. 1). This implant has a ball-and-socket joint in the midposterior portion to induce femoral rollback [20–22]. This ball-and-socket joint has been proven to work as a post-cam mechanism in vivo in previous biomechanical studies [23–26]. However, anterior displacement was observed sometimes during kneeling activities when shear forces were applied on the anterior aspect of the knee [24].

Under fluoroscopic surveillance, each patient was asked to perform weight bearing deep knee bend and kneeling activities, respectively. During the deep knee bend activity, the patients started squatting with their feet at hip-width distance, and their hips and feet had turned out slightly with a natural feeling. Fluoroscopic video was dynamically recorded at 30 frames per second from full extension to maximum flexion. Individual video frames were digitized at full extension as well as at 30°, 60°, 90° (if obtained), 120° (if obtained), and maximum knee flexion, respectively (Fig. 2-A). During the kneeling activity, a box with a height of 30 cm was placed on a table. Each patient was asked to place his or her tibial tuberosity just above the box (avoiding contact with box) and begin a kneeling activity from a non-weight-bearing stance to eliminate the effect of the posterior force to the anterior tibia (before contact). Subjects were then asked to place their tibial tuberosity on the box completely and load their weight as fully as possible onto the anterior tibia (complete contact). After loading their weight, subjects were asked to flex their knees as much as they could. Three subjects could not perform the kneeling activity. Thus, only 19 subjects were included in the analysis of the kneeling activity. Individual video frames were digitized before contact and at complete contact as well as at 105°,120°,135°,150° (if obtained) and at maximum knee flexion, respectively (Fig. 2-B). During deep knee bend and kneeling activities, 13.9 seconds (Standard Deviation (SD) = 4.1) and 12.4 seconds (SD = 4.7) were required for the entire process, respectively.

Fig. 1. Posterolateral views of a tri-condylar implant.

Using a previously reported 3-dimensional (3D) model fitting approach, the relative pose of the knee implants was determined in 3D from a single-perspective fluoroscopic image by manipulating a computer-aided design model in 3D space [16–18,27]. An error analysis of this process for TKA components was previously conducted, documenting a translational error of less than 0.5 mm for anteroposterior and proximal-distal directions and a rotational error of less than 0.5° for all axes [27]. Once the 3D kinematic pattern was recreated, the anterior/posterior contact positions for medial and lateral condyles and femorotibial axial rotation were determined. Medial and lateral contact points were measured in the coordinate system of the tibial component, and the anterior direction was denoted as positive. Axial rotation was determined using the Grood and Suntay method [28]. The polyethylene surface was placed on the tibial component for each patient because the polyethylene insert was fixed on the tibial component. Condylar lift-off was analyzed in the medial and lateral condyles based on the minimum distance between the femoral component and the polyethylene surface.

In order to evaluate a flexion gap and flexion alignment, axial radiographs of the distal femur were obtained using the technique reported by Kanekasu and Tokuhara [29,30]. Subjects sat on a table with their lower legs hanging down at neutral rotation. The X-ray beam was directed approximately at a 10° upward angle parallel to the tibial tray, and radiographs were taken without and with a 1.5-kg weight fastened at the ankle, respectively. Patients were instructed to relax their leg muscles, especially the quadriceps. Flexion alignment was measured as the angle between the surgical epicondylar axis (SEA) and the posterior condylar axis (PCA). The flexion alignment angle was denoted as positive if the PCA was externally rotated relative to the SEA. The asymmetry of the flexion gap was expressed as the angle between the PCA and tibial tray. The flexion gap angle was denoted as positive if the lateral laxity was greater than the medial laxity. To determine the medial and lateral flexion gaps, the distance between the bottom of tibial tray and the femoral condyle was measured first, and the thickness of polyethylene surface, including that on the tibial tray, was subtracted from this value (Fig. 3).

All analyses were performed using JMP Pro software version 11 (SAS Institute Inc., Cary, NC). Pearson correlation coefficients were calculated to determine the correlations between the data from axial radiographs and kinematic factors. Comparisons between the two axial radiographs with and without weight were conducted using a paired *t*-test. However, since the data were not normally distributed, the non-parametric Wilcoxon rank-sum test was used to detect differences between the radiographs. The level of significance was defined as $P < 0.05$.

Results

In axial radiographs, flexion alignment without and with a 1.5-kg weight were similar (Table 2). Femoral components were implanted within 3° of axial rotation from SEA in 19 out of 22 (86.4%) subjects