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Weight-bearing condyle motion of the knee before and after cruciate-retaining TKA: In-vivo surgical transepicondylar axis and geometric center axis analyses

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ABSTRACT

An equal knee joint height during flexion and extension is of critical importance in optimizing soft-tissue balancing following total knee arthroplasty (TKA). However, there is a paucity of data regarding the in-vivo knee joint height behavior. This study evaluated in-vivo heights and anterior–posterior (AP) translations of the medial and lateral femoral condyles before and after a cruciate-retaining (CR)-TKA using two flexion axes: surgical transepicondylar axis (sTEA) and geometric center axis (GCA). Eleven osteoarthritis (OA) knee patients were studied during a weight-bearing single leg lunge, using a validated dual fluoroscopic imaging system (DFIS) based tracking technique. Eight healthy subjects were recruited as controls. The results demonstrated that following TKA, the medial and lateral femoral condyle heights were not equal at mid-flexion (15–45°, medial condyle lower then lateral by 2.4 mm at least, $p < 0.01$), although the knees were well-balanced at 0° and 90°. While the femoral condyle heights increased from the pre-operative values (> 2 mm increase on average, $p < 0.05$), they were similar to the intact knees except that the medial sTEA was lower than the intact medial condyle between 0° and 90°. At deep flexion (> 90°), both condyles were significantly higher (> 2 mm, $p < 0.01$) than the healthy knees. Anterior femoral translation of the TKA knee was more pronounce at mid-flexion, whereas limited posterior translation was found at deep flexion. These data suggest that a well-balanced knee intra-operatively might not necessarily result in mid-flexion and deep flexion balance during functional weight-bearing motion, implying mid-flexion instability and deep flexion tightness of the knee.

1. Introduction

In total knee arthroplasty (TKA), soft tissue balancing is controlled by the alignment of bone cuts, the soft tissue envelope about the knee and the geometric design of the component (Ries et al., 2003). An equal knee joint height during flexion and extension is of critical importance in optimizing soft-tissue balancing following TKA (Laskin, 1995). Poor soft-tissue balancing after TKA is associated with pain, stiffness, limited range of motion and more detrimental long-term outcomes such as polyethylene wear, subluxation and aseptic loosening (Fehring et al., 2001; Insall et al., 1985). Although, many intra-operative methods have been developed to balance the soft tissue in flexion and extension, including spacer blocks and ligament tensioners (Hanada et al., 2007; Tanzer et al., 2002), an increasing body of evidence suggests that inadequate soft-tissue balancing may provoke mid-flexion instability, despite a well-balanced knee at full extension and 90° of knee flexion (Del Gaizo and Della Valle, 2011; Martin and Whiteside, 1990; McPherson et al., 2008). Therefore, a thorough investigation of the soft tissue balancing during in-vivo knee activities may provide a deep insight to the TKA function and optimize TKA components' alignment and design.

Relatively few studies have investigated the in-vivo soft tissue balancing, mainly due to technical limitations. Recently, in vitro (Nowakowski et al., 2012) and intra-operative devices were applied to measure knee joint gap following insertion of a femoral component (Hananouchi et al., 2012; Matsumoto et al., 2009) and polyethylene insert to investigate the soft tissue balancing after TKA operation (Minoda et al., 2014). Although, these studies contributed

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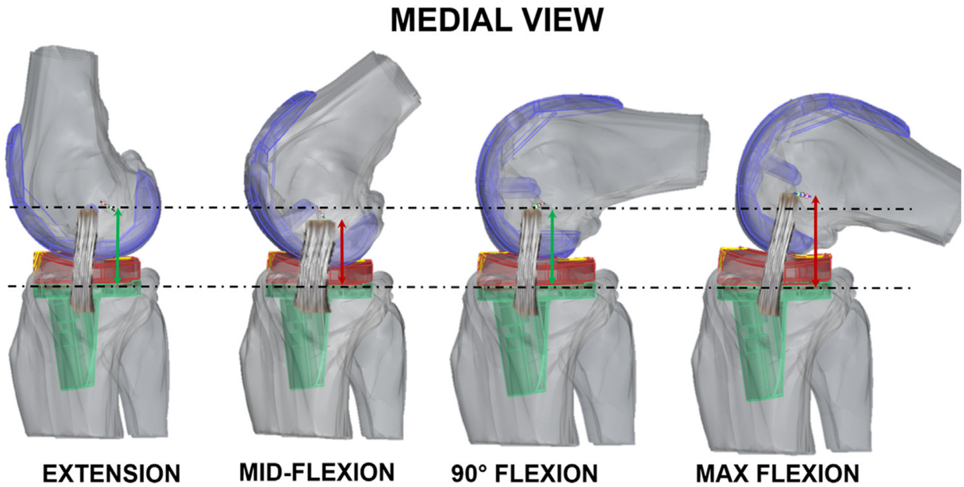

Fig. 1. Schematic representation of the medial femoral condyle heights with soft tissue balancing of the knee. Green arrow represents knee height at full extension and 90° of flexion, in a well-balanced knee. Red arrow represents medial condyle heights in mid-flexion and maximum Flexion. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

significantly to the understanding of the knee joint gap behavior, the soft issue balancing during in-vivo functional activities of the knee is still unclear due to the difficulty of measuring in-vivo soft tissue tensioning. Furthermore, knee balancing at 0° and 90° of flexion alone does not represent the overall anatomical changes of the soft tissue following TKA along in-vivo knee motion path.

From a biomechanical point of view, the medial and lateral femoral condyle heights relative to the tibia insert along the flexion path represent the cumulative effects of bone cuts, soft tissue releases, the space occupied by the components and the in-vivo joint loading conditions. An increased femoral condyle height could reflect a tight knee, while a decreased height could indicate a relatively loose knee joint for a specific range of motion (ROM) (Fig. 1). Therefore, measurement of femoral condyle heights could be a useful tool in the investigation of in-vivo knee balancing during actual post-operative conditions. The objective of this study was to evaluate the in-vivo heights and anterior–posterior (AP) translations of the medial and lateral femoral condyles before and after a CR-TKA using two popular flexion axes, surgical transepicondylar axis (sTEA) and geometric center axis (GCA) (Kitagawa et al., 2010b). The data were then compared with those of healthy control subjects.

2. Materials and methods

2.1. Patients

The study was approved by our Institutional Review Board and each patient provided written informed consent prior to participation. Eleven patients (7 males, 4 females) with advanced medial knee osteoarthritis (OA) (6 left, 5 right) scheduled for TKA were included in this study. Patients' average age at the time of surgery was 61 ± 4 years (range: 51 to 73 years), height 173.5 ± 9.9 cm (range: 154.9 to 185.4 cm); weight 94.4 ± 14.5 kg (range 70.3 to 120.2 kg). Exclusion criteria were posttraumatic arthritis, rheumatoid arthritis, or valgus knees. Eight healthy control subjects (5 males and 3 females, 7 right and 1 left knees) from a previous investigation were also included as normal references (Qi et al., 2013). These subjects were 31 ± 9 years old (range, 19–51 years), had a height of 170.0 ± 10.0 cm (range, 150.0–190.0 cm) and body weight of 75.0 ± 14.0 kg, (range, 50.0–98.0 kg).

2.2. Magnetic resonance imaging (MRI)-scans and MRI-based 3D modeling

Both OA knees and the healthy knees were MRI scanned using a 3.0-Tesla MRI Scanner (Siemens, Malvern, PA, USA) with a fat suppressed 3D spoiled gradient-recalled-echo sequence. Sagittal-plane images (repetition time=48 ms, echo time=4.3 ms, flip angle=45°, thickness 1 mm, resolution 512×512 pixels, field of view 180×180 mm) were obtained.

The MR images of the knee were processed using a canny filter programmed in a commercially available mathematics software package (Matlab, Mathworks, Natick, MA, USA). The Canny filter calculated gradients in pixel intensity to detect edges between objects (Canny, 1986). The calculated edges were used to help trace the outlines of the femur, tibia, and fibula within each sagittal plane image using solid-modeling software (Rhinoceros, Robert McNeel and Associates, Seattle, WA, USA). The contours were then used to construct the surfaces of the knee joint according to a previously validated and published method (Defrate et al., 2006). The 3D computer-aided design (CAD) models of the TKA knees were obtained from the manufacturer.

2.3. Dual fluoroscopy imaging system (DFIS)

Each subject was instructed to perform a weight-bearing, quasi-static single leg lunge from full extension to maximal flexion at every 15° increments, without altering the orientation of the foot and torso, under the surveillance of the DFIS. (Yue et al., 2011). During experiment, the subject flexed the knee to a target flexion angle and hold for one second for fluoroscopy imaging and then flexes to another position. Following the experiment, the series of fluoroscopic images were imported into a solid-modeling software to establish a virtual fluoroscopic setup. The 3D MR image-based models of the OA knees and 3D CAD models of the TKA knees were also imported and individually manipulated in six degrees of freedom (6-DOF) until they matched their projections on the dual fluoroscopic images captured during the actual weight-bearing activity (Yue et al., 2011, 2012). The process was repeated for every 15° of flexion (0–90°) and at maximum flexion. The knee joint positions along the flexion path were then represented by a series of 3D knee joint models (Figs. 1 and 2).

2.4. Total knee arthroplasty surgery

All the OA knees received a high-flexion CR-TKA (NexGen CR-Flex, Zimmer, Warsaw, IN, USA). In all of the patients, the extension-flexion gaps were well balanced intra-operatively (at 0° and 90° of flexion) without posterior cruciate ligament recession. After surgery (average 8 ± 2.5 months; range: 7–15 months), all patients returned for the second fluoroscopic surveillance and clinical evaluation, including passive ROM and Knee Society Scores. No patient had a history of surgical complication, dislocation or component subluxation.

2.5. sTEA and GCA definitions, tibia coordinate system and kinematic measurements

The sTEA and GCA were determined based on existing methods (Berger et al., 1993; Most et al., 2004). Briefly, the sTEA was defined as the line connecting the sulcus of the medial condyle and the lateral condyle prominence (Fig. 2) (Berger et al., 1993), whereas the GCA was constructed by fitting circles to the medial and lateral condyles in sagittal plane and by connecting the centers of these circles with a line (Most et al., 2004). The medial and lateral condyle centers were defined on both sTEA and GCA. A previously published proximal tibia anatomical coordinate system was established to quantitatively describe the distance from the sTEA or GCA to the tibial surface area (Fig. 2) (Chen et al., 2012). The tibial long axis was parallel to the posterior wall of the tibial shaft. The medial-lateral axis was defined as a line connecting the centroids of the two circles fit to the medial and lateral tibial plateau surfaces (Fig. 3) (Qi et al., 2013). The anterior–posterior axis was