The Knee 21 (2014) 359–363

Contents lists available at ScienceDirect

The Knee

A method for assessing joint line shift post knee arthroplasty considering the preoperative joint space

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ARTICLE INFO

Article history:
Received 25 September 2012
Received in revised form 23 January 2013
Accepted 13 March 2013

Keywords:
Joint line
Total knee arthroplasty
Total knee replacement
Joint space
Knee
Arthroplasty

ABSTRACT

Background: Accurate comparison of outcomes regarding various surgical options in knee arthroplasty can benefit from an improved method for joint line analysis that takes into account the preoperative joint space.
Methods: This article describes a new *preoperative-based registration* method that measures changes in the joint line by overlaying the 3D models of the bones with implants using preoperative CT along with preoperative and postoperative biplanar radiography. The method was tested on six cadaveric specimens for measuring alteration to the medial and lateral joint lines in extension and flexion.
Results: The joint line shift, when measured using the new method, was in the range of −0.2 to 1.3 mm on average (SD = 1.3 to 3.8 mm, for medial and lateral, in flexion and extension positions). This was significantly different ($p \leq 0.01$) from the results of a previous *postoperative-based registration* method which did not account for the cartilage thickness in calculating alterations of the joint line (mean = 3.9 to 6.8 mm, SD = 1.2 to 4.3 mm).
Conclusion: These results further highlight the importance of considering the preoperative joint space in analyzing the joint line, and demonstrate the utility of the newly introduced method for accurate assessment of changes in the joint line after arthroplasty.
Clinical relevance: The introduced method provides accurate means for investigating joint line alterations in relation to different surgical techniques and the subsequent biomechanical effects after knee arthroplasty

1. Introduction

A change in the joint line after total knee arthroplasty (TKA) is one of the important factors influencing joint stability, range of motion, and patellofemoral mechanics. Even small changes to the normal level of the joint line can compromise the clinical outcome: deviations as small as 5 mm can cause joint instability [1] and changes as small as 2 mm can have a considerable effect on the range of motion post-arthroplasty [2]. For cruciate-retaining prosthesis designs these effects can be even more substantial: a 4 mm elevation of the joint line can produce significant additional strains in the posterior cruciate ligament [3,4]. The patellofemoral joint can also be adversely affected by changes in the joint line; a 3 mm distal shift to the joint line has been reported to cause patellofemoral pain and subluxation [5,6]. Because of these significant effects on the outcomes of knee arthroplasty, measurements of the joint line shift have been appreciated as an important factor in research studies that compare different surgical options and implant designs [7–9]. For these investigational studies an accurate and reproducible method is required to detect small alterations to the joint line for extension and flexion positions and for the medial and lateral sides of the joint individually.

Current methods for measuring joint line alterations have limitations. Commonly used techniques are based on anteroposterior or lateral radiographs, and they measure landmarks that define the joint line with reference to common points such as the fibular head, the medial femoral epicondyle [10], or the tibial tuberosity [11]. These radiographic methods lack the ability to measure important differences between the medial and lateral joint lines [12,13], and they are prone to poor accuracies due to sensitivity to patient and X-ray beam positions [14]. To overcome these shortcomings, a more recent method overlays the 3D models of the preoperative bones and implants with reference to postoperative radiographs, using two-dimensional and three dimensional (2D–3D) matching [12]. This particular method, called '*postoperative-based registration*' from this point forward, measures variations of the tibial and femoral joint lines in addition to the posterior condylar offsets (PCO), individually for the medial and lateral sides of the joint. Since in this method the joint line is measured based on subchondral bone levels that appear on the radiographs and not the

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http://dx.doi.org/10.1016/j.knee.2013.03.011

cartilage surfaces, it does not account for the preoperative joint space [12]. This limitation, as has been acknowledged by the authors of the paper, will be less if the cartilage on the articular surfaces is completely worn away in all regions. However, this is not usually the case, and typically there is a non-uniform pattern of cartilage degeneration.

Although accounting for the cartilage thickness for joint line assessment seems trivial, there has not been a method available that can accurately measure joint line alterations after knee arthroplasty by directly comparing post-operative with pre-operative status. A recent study has shown considerable variability in the thickness of the cartilage of the posterior condyles, concluding that intraoperative measurements of the cartilage thickness must be added to the corresponding postoperative radiographic measurements [15]. This method, however, is not useful for the retrospective studies in which intraoperative caliper measurements of the cartilage thickness are not available. Even when the intraoperative assessment is available, since the bone cuts are made parallel to the coronal and transverse planes, measuring the cartilage thickness is only limited to flexion and extension points and not the important mid-flexion range for which alteration to the joint line has been shown to have the highest effects on instability [1]. Considering the shortcomings of the current techniques, there is need for an improved method that can assess the joint line shift after knee arthroplasty based on the preoperative joint space.

The aim of this study was a) to introduce an accurate method to measure the joint line shift for any desired flexion angle of the joint by taking into account the cartilage thickness on both of the medial and lateral sides of the joint; and b) to compare this new method of assessing joint line shift to a previous post-operative based registration method that does not account for cartilage.

2. Methods

The method requires a) preoperative joint imaging; b) postoperative joint imaging; c) registration of the 3D models of the bones and implants to the postoperative radiographs to determine implant positions relative to the corresponding bones; d) registration of the 3D models of the bones to the preoperative radiographs and subsequently finding the relative positions of the implant components according to the preoperative bone positions; and e) analyzing the changes in the joint line on the medial and lateral sides for both extension and flexion. This method, called '*preoperative-based registration*' from this point on, takes into consideration the preoperative joint gap that represents the sum of tibial and femoral cartilage thicknesses. This technique superimposes the component onto the preoperative bone positions and measures the joint line shift as inter-penetration or separation of the implant components.

2.1. Preoperative imaging

Computer models of intact cadaveric knee specimens were generated. Six previously frozen cadaveric knees from two male and four female donors (ages: 34 to 90), were obtained and prepared for testing. A computed tomography (CT) scan of each specimen was acquired using a Toshiba Aquilion scanner (TOSHIBA, Tokyo, Japan) with the specimens in an orientation simulating a supine patient position using the following settings: 120 kV, 160 mA, slice thickness = 2.0 mm, slice spacing = 2.0 mm, Bone Boost smoothing algorithm. Three-dimensional models of the bones were constructed by segmenting the bone volumes using Analyze software, version 10 (AnalyzeDirect Inc., Overland Park, KS, US).

The preoperative positions of the bones at knee extension and flexion were determined. Metal rods were fixed in the distal and proximal intramedullary canals of the tibia and femur using bone cement. Specimens were placed, using these rods, into a custom jig that held the specimens, simulating the patient's weightbearing poses at 0° or 90° of flexion (referred to as extension and flexion positions). Orthogonal biplanar images of the specimens were acquired using a multi-planar imaging method (previously described [16]) that used a C-arm fluoroscope (Siemens Arcadis Orbic; Siemens AG, Munich, Germany) and motion tracking camera (Optotrak Certus, NDI, Waterloo, ON, Canada). The relative locations of the bones at both extension and flexion were reconstructed (Fig. 1a) by matching the 3D CT models of the bones to the biplanar fluoroscopic images using an edge and intensity matching algorithm [17] implemented in JointTrack biplanar 2D–3D registration software (University of Florida, Gainesville, US; http://sourceforge.net/projects/jointtrack/).

2.2. Postoperative imaging

Total knee arthroplasty was performed on each specimen using posterior stabilized knee replacement prostheses (NexGen Legacy Posterior Stabilized; Zimmer, Warsaw, IN) and following the recommendations of the standard protocol. Each knee was then placed in extension, and biplanar images were acquired as described for the preoperative imaging. The tibia and femur were imaged separately to include as much bone as possible for each of the bones for the 2D–3D registration. 3D models of the femoral component and the metal tibial tray (obtained from high dose CT imaging of the components) were registered to the 2D biplanar postoperative images (Fig. 1b) using the JointTrack software.

2.3. Joint line analysis

Joint line shift for the medial and lateral sides of the joint was assessed by transferring the implant position information from the postoperative to the preoperative images of the joint. The 3D models of the implant components were superimposed on the preoperative positions of the bones using Rapidform XOV (INUS Technology, Seoul, Korea) (Fig. 1c). This was done by combining the results from preoperative and postoperative 2D–3D registrations (as discussed above), and translating the relative coordinates of the 3D models of the implant components with respect to the bones from the postoperative into the preoperative cases.

To determine the tibial joint line, the three-dimensional model of the polyethylene inlay was added to the metal tray according to the design of its locking mechanism. Two-dimensional cross-sectional slices of the combined bone and implant models were obtained using a sectioning plane that was passed perpendicular to the tibial tray and through the two most distal points on the medial and lateral condyles of the femoral component. Joint line shift was measured as the distance between the most distal point on the condyle of the femoral component and the most proximal point on the articular surface of the tibial polyethylene in the direction normal to the mediolateral edge of the tibial tray in the cross-sectional slice (Fig. 2a and c).

It was assumed that for ideal restoration of the joint line, and for cases where no deformity or soft tissue contracture exists, there would be no joint line shift (after taking into consideration thickness of the worn cartilage) therefore for these cases zero distance is expected between the 'predicted preoperative' positions of the tibial and femoral TKA components. A positive shift in the joint line level according to this definition indicates interference between the components and suggests that TKA increased the joint gap, forcing extra tension in the corresponding collateral ligament. A negative shift indicates separation of the components, suggesting reduced ligament tension (or slackness compared to normal) after TKA.

For the sake of comparison, the previously suggested postoperative-based registration method was applied to the same cross-sectional planes described above as an alternative way to measure the joint line shift as the sum of the tibial and femoral *implant–bone* distances. The implant–bone distance was defined as the distance between the articular surface of the implant and the corresponding subchondral surface of