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A systematic approach to predicting the risk of unicompartmental knee arthroplasty revision

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SUMMARY

Objective: Unicompartmental knee arthroplasty (UKA) revision is usually due to the degenerative degree of knee articular osteochondral tissue in the untreated compartment. However, it is difficult to simulate the biomechanical behavior on this tissue accurately. This study presents and validates a reliable system to predict which osteoarthritis (OA) patients may suffer revision as a result of biomechanical reasons after having UKA.
Design: We collected all revision cases available ($n = 11$) and randomly selected 67 UKA cases to keep the revision prevalence of almost 14%. All these 78 cases have been followed at least 2 years. An elastic model is designed to characterize the biomechanical behavior of the articular osteochondral tissue for each patient. After calculated the force on the tissue, finite element method (FEM) is applied to calculating the strain of each tissue node. Kernel Ridge Regression (KRR) method is used to model the relationship between the strain information and the risk of revision. Therefore, the risk of UKA revision can be predicted by this integrated model.
Results: Leave-one-out (LOO) cross-validation (CV) is implemented to assess the prediction accuracy. As a result, the mean prediction accuracy is 93.58% for all these cases, demonstrating the high value of this model as a decision-making assistant for surgical plaining of knee OA.
Conclusions: The results of this study demonstrated that this integrated model can predict the risk of UKA revision with theoretically high accuracy. It combines bio-mechanical and statistical learning approach to create a surgical planning tool which may support clinical decision in the future.

Introduction

Osteoarthritis (OA) is a progressive disease of the joints, known as “wear and tear” arthritis. The knee is the largest and strongest joint in human body. Knee OA onset usually occurs after 50 years of life, but may occur in younger people, too. Although the causes OA is proposed to relate to genetic, metabolic and mechanical loading. Joint angular deformity remains the most convincing determinants in OA patients. Other factors of OA such as age, obesity, trauma, repetitive loading, etc. are all mechanical-related[1]. Unicompartmental knee arthroplasty (UKA)[2] has been developed over the years to treat OA in patients with degenerative changes in a single knee compartment. Recently, robotic-assisted technology has been developed to facilitate UKA surgical procedures[3]. As part of the UKA procedure, preoperative CT scans are made to document the knee joint anatomy specific to each patient[4–6]. There are advantages of UKA compared to total knee arthroplasty (TKA)[7]. Successful outcomes with UKA require proper patient selection[8] and meticulous surgical technique to avoid revision from UKA to TKA. According to the Swedish knee arthroplasty register annual reports[9], around 14% of UKA patients need revision during the

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following 3–5 years. Kozinn and Scott[10] described the strict selection criteria for UKA, which is designed for patients with arthritic wear limited to a single medial or lateral tibiofemoral compartment. Indeed, to prevent the risk of rapid extension of OA to the opposite compartment, the UKA procedure should be limited to restoring the patient's constitutional axis before degeneration phenomena had appeared in the opposite compartment. This increases the risk of failure of UKA due to micro degeneration in the opposite compartment. Heck's[11] work indicated that patients with higher weight have increased risk of revision rate after UKA, but some patients with normal weight may also undergo revision. This suggests there is no direct relationship between patients with normal weight and revision, but the behaviors of knee articular osteochondral tissue in the opposite compartment may vary with different loading forces. The loading force is mainly generated by the femoral bicondylar angle change after UKA and the individual body weight. It is worth pointing out that distribution of excessive strain will cause pain with degeneration. Thus we proposed to study the biomechanical properties of each patient who needs revision.

In this study, we established a statistical model to describe the relationship between the biomechanical strain information and the risk of UKA revision. The novelty of the proposed approach lies in: (1). design of equivalent material tissue properties in multiple layers of knee articular osteochondral tissue based on volumetric proportion of each layer; (2). calculation of the loading force on knee articular osteochondral tissue with patient body weight and angle change measured by femur center line correction of UKA; (3). use of a Kernel Ridge Regression (KRR) statistic model that relates the distributions of strain change information associate with the risk of the UKA revision in the knee articular osteochondral tissue finite elements.

The purpose of this paper is predicting which OA patients are going to fail due to biomechanical factors when they have UKA. We hypothesize that cartilage is microdamaged in the untreated compartment on account of initial stage of OA degeneration, but the meniscus is considered to be intact in this stage. The biomechanical information of knee articular osteochondral tissue in the untreated compartment following virtual correction can be accurately simulated by integrating a finite element method (FEM) with statistical learning model.

Patients and methods

This study presents an integrated approach to accurately simulate articular osteochondral tissue behavior in opposite compartment for pre and post operation respectively for the purpose of predicting of revision risk for OA patient. Figure 1 describes the flowchart of the whole process consisting of two phases. Both of the training phase and the prediction and validation phase having following steps: (1) a collection of patient body weight, preoperative CT and preoperative and postoperative X-ray data (Section 2.1); (2) extraction of strain information from these data by FEM with the force calculated by patient body weight and femoral bicondylar angle change (Section 2.2).

Participants

From 2011 to 2013, over 100 OA patients have received robotic-assisted UKA and have been followed for at least 2 years to assess risk of UKA revision in the Wake Forest Baptist medical center. We collected all revision cases available ($n = 11$) and randomly selected 67 UKA cases to keep the prevalence of UKA revision samples as about 14%, which has been reported in the Swedish knee arthroplasty register annual reports[9] for the general population.

There are 78 cases, among which 35 are males and 43 are females with average age of 65 yrs, ranging from 42 to 88 yrs, and average body mass index (BMI) of 35.2 kg/m^2, ranging from 20.8 to 47.5 kg/m^2. The average time difference between primary operation and revision is 24.6 months, ranging from 20 to 36 months.

Although MRI data can assess the degree of OA in both compartments by measuring the thickness of cartilage, as a practical matter, OA diagnosis is mainly performed by X-rays and CT images prior to UKA surgery. In clinical practice, doctors monitor cases by X-ray data with severe OA to determine whether immediate surgery is required or not, and CT data is primarily used to guide UKA surgery. The assessment of knee OA using X-ray has limited ability to discriminate conditions of the knee cartilage by grading joint space narrow visually. This method increases the risk of UKA failure due to the inappropriate patient selection.

Preoperative CT scans for 78 patients pre and post-operative X-rays, body weight in clinical database, Oxford Knee Score[12,13] (followed by 24–48 months) were collected at Wake Forest Baptist Medical Center (IRB00025566 has been approved prior to the study). All patients underwent UKA surgery with robotic-assisted (MSK, MAKO Surgical Corporation, Fort Lauderdale, FL, USA).

Feature extraction

The basic idea to measure femoral bicondylar angle change by surgical correction from pre-operative and post-operative X-ray images, and then calculate the force on knee articular osteochondral tissue, caused by individual body weight and femoral bicondylar angle change. Afterwards, the force is used to calculate the strain information by FEM in the knee articular osteochondral tissue mesh data, generated from pre-operative CT images. Individual biomechanical information, including stress, strain and displacement will be extracted based on the calculated force. Both stress and displacement have dense relations with strain, so the strain was used as biomechanical feature in this work.

The preoperative CT data is imported into the Mimics software (Materialise, Belgium), the knee articular osteochondral tissue were segmented in Mimics which would be further used to generate the mesh data for FEM computing.

Determine tissue material property based on multiple layers segmentation

Knee articular osteochondral tissue is composed of meniscus and cartilage layers. Different material parameters for these two layers were given by the previous work depending on characterization method and material model[14–18]. To calculate knee articular osteochondral tissue property, we have to segment meniscus layer and cartilage layer; however it is extremely difficult to segment these two layers from clinical CT data. Fortunately, there is a template of meniscus which can be obtained from the Open Knee(s)[19] at NIH. Thus we can calculate the volume of cartilage layer by subtracting the volume of a template of meniscus from the whole volume, and then the knee articular osteochondral tissue property by weighting the tissue properties of meniscus and cartilage based on their volumetric proportion in the mesh data. The details are described in below:

(1) The whole knee articular osteochondral tissue composed of the meniscus and the cartilage is calculated by measuring the volume of whole tissue using Mimics software.
(2) The volume of cartilage layer is calculated by subtracting the volume of a template of meniscus (the Open Knee(s)[19]) from the whole volume of knee articular osteochondral tissue. The geometry data of meniscus will be used for volume calculation, because we assume that cartilage is microdamaged in