XVII International Symposium on Computer Simulation in Biomechanics
July 28th – 30th 2019, Alberta, Canada

ALGORITHM FOR INTRAOPERATIVE DETECTION OF COMPONENT MALALIGNMENT DURING TOTAL KNEE ARTHROPLASTY

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INTRODUCTION

About one in five patients are not satisfied after total knee arthroplasty (TKA) [1]. Sources of dissatisfaction include pain, stiffness, and instability [1]. One primary surgical variable linked to sources of dissatisfaction is component malalignment.

During TKA, the surgeons must precisely set the 6-degree-of-freedom positions and orientations of each component, which are frequently set using manual guides. To confirm that the desired 6-degree-of-freedom positions and orientations have been achieved, surgeons commonly rely on manual assessments of joint laxities. More recent technological advances have enabled more precise intraoperative assessments of joint kinematics (e.g., computer navigation [2]) and tibiofemoral contact forces (e.g., OrthoSensor [3]). Thus, these technological advances might enable the surgeon to more accurately detect and correct component malalignment.

Accordingly, the objectives of the present study were (1) to characterize the relationships between kinematics, laxities, and contact forces, which can be measured intraoperatively, and component malalignments, and (2) to determine the errors in predicting component malalignments based on kinematics, laxities, contact forces, and a combination of all three. Because these biomechanical variables are difficult to measure in a large number of knees either in vivo or in vitro to account of patient-to-patient variability, a probabilistic modeling framework was utilized for this study.

METHODS

TKA was virtually performed on a 12-degree-of-freedom multibody model of the knee [4] (Fig. 1). This model included ligaments represented by bundles of non-linear springs and articular surface contact using a penalty-based method. The femoral and tibial components from the sixth edition of the Grand Challenge were aligned to best restore the distal and posterior femoral joint lines and the proximal tibial joint line, respectively. The anterior cruciate and deep medial collateral ligaments were removed as occurs during the standard TKA procedure, but all other ligaments were left intact.

To account for patient-to-patient variability in the passive biomechanics of the knee, the stiffness and reference strain of each ligament were randomly sampled to generate 1000 virtual TKA patients (Fig. 1). The stiffness for all springs within a ligament was sampled from a normal distribution centered on the nominal model values with a standard deviation of 30% of the nominal value. Reference strains across the width of each ligament were not necessarily uniform in the nominal model so changes in the reference strains of each ligament were sampled from a normal distribution centered at zero with a standard deviation of 2% strain. The same change in reference strain was applied to all springs within a ligament.

Three degrees of freedom of component malalignment were randomly introduced to each of the 1000 virtual TKAs (Fig. 1). Varus-valgus

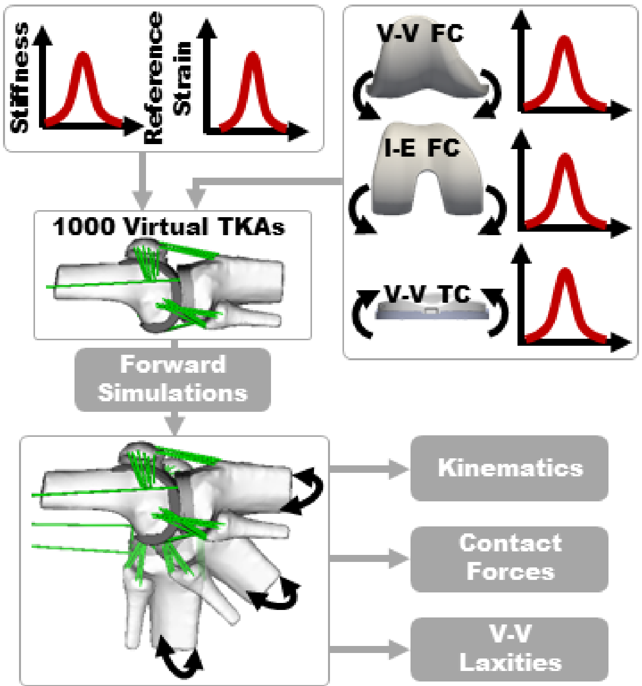

Fig 2: Flowchart of methods shows how 1000 virtual TKA models were created with randomly selected ligament properties and component malalignments. Tibiofemoral kinematics, contact forces, and V-V laxities were determined for each model.

(V-V) and internal-external rotation (I-E) malalignments of the femoral component and V-V malalignments of the tibial component were sampled from normal distributions centered at zero with standard deviation of 2.3°, 4.6°, and 2.1°, respectively, which represent the changes in joint line caused by common alignment landmarks in mechanically aligned TKA [5].

Forward simulations of passive flexion, passive flexion under a 10 Nm varus torque, and passive flexion under a 10 Nm valgus torque from 0° to 90° of tibiofemoral flexion were performed on each of the 1000 virtual TKAs. Passive kinematics at 0°, 45°, and 90° of tibiofemoral flexion in V-V, I-E, anterior-posterior (A-P) translation, compression-distraction (C-D) translation, and medial-lateral (M-L) translation along with the medial, lateral, and difference between medial and lateral contact forces of the femur on the tibia were extracted from the passive flexion simulations. The V-V laxities at 0°, 45°, and 90° of tibiofemoral flexion were computed as the difference between the V-V rotation during the passive flexion under varus/valgus torque and that during passive flexion. The changes in each biomechanical variable from 0° to 45°, 45° to 90°, and 0° to 90° of tibiofemoral flexion were also computed.

To determine the errors in detecting component malalignment based on intraoperative biomechanical variables, results from the 1000 models were divided into 500 training and 500 validation models. The V-V laxities, contact forces, kinematics, and a combination of all three described above for the 500 training models were input as the explanatory variables of linear regression models with interactions to predict the response variables of the V-V and I-E malalignments of the femoral component and the V-V malalignment of the tibial component (*Regression Learner*, MATLAB R2017a). Each regression equation was evaluated by computing the differences between the actual and predicted malalignments using the V-V laxities, contact forces, kinematics, and a combination of all three determined in the 500 validation models. The bias, precision, root-mean-square error (RMSE), and 99% tolerance interval with 95% confidence of these differences were computed. The tolerance intervals indicate the range representing 99% of the population of errors with a 95% confidence.

RESULTS AND DISCUSSION
All regression models showed a strong fit to the data with r^2-values between 0.7 and 1.0. The passive kinematics were the best biomechanical variable for predicting component malalignment (Fig. 2) because the 99% tolerance intervals were smallest (99% of errors in the predicted component malalignments below 0.7°). Interestingly, adding the laxities and the contact forces did not greatly improve the prediction capability of the regression models.

Kinematics are likely the best predictor in this study because the articular surface geometry is a primary determinant of passive kinematics [6]. Thus, passive kinematics might be less sensitive to variability in ligament properties present in the population than the contact forces and laxities. Future work will focus on validating these regression equations in cadaveric knees where component malalignments can be introduced in a controlled manner.

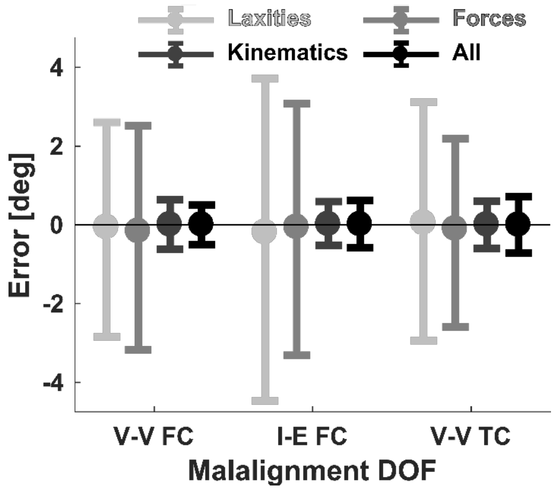

Fig 2: Scatter plot shows bias (dot) and 99% tolerance interval with 95% confidence (error bars) of the errors in the predicted component malalignments of the 500 validation models using only the V-V laxities, contact forces, kinematics, and all three together.

CONCLUSIONS
The findings from this study indicate that the patterns of biomechanical variables measured intraoperatively might help surgeons to identify and correct component malalignment. Proper detection and correction of component malalignment should help surgeons to reduce the risk of patient dissatisfaction after TKA.

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ACKNOWLEDGEMENTS

This project was funded by THINK Surgical Inc. and NIH (2T32AG000213-27). We thank Colin R. Smith, PhD for technical support on this project.