INTRODUCTION

Complications related to the patellofemoral (PF) joint remain a common cause for revision of total knee replacements (TKR) [1]. Relative alignment of patellar and femoral components is an important factor impacting the functional performance of the PF joint and success of the TKR. In a prior probabilistic study [2], 5 and 95% bounds of PF kinematics and contact mechanics were predicted for dome and anatomic designs subjected to alignment variability. Sensitivity of knee mechanics to alignment variability is dependent on component geometry and is design-specific. Principal component analysis (PCA) can be used to identify relationships between combinations of alignment parameters and resulting knee mechanics. The purpose of this study was to use PCA to identify critical alignment parameters affecting PF mechanics in two patellar designs (dome and anatomic), and to evaluate the predictive capability of the approach for new sets of initial component alignment.

METHODS

This study applied PCA to a probabilistic finite element (FE) analysis of the PF joint. A subject-specific model of a healthy normal subject was created from magnetic resonance scan data. Patellar and femoral dome and anatomic cruciate-retaining components were sized and positioned by a surgeon in a neutral alignment. The probabilistic analysis included seven input parameters reported to affect PF mechanics, including: femoral internal-external (I-E) rotation, patellar I-E, flexion-extension (F-E) and adduction-abduction (A-A) rotation, patellar mediolateral (ML) and superior-inferior (SI) translations, as well as percentage of the quadriceps load on the vastus medialis obliqus (VMO) tendon. The lateral retinaculum and extensor mechanism of the knee were incorporated into the model as fiber-reinforced 2D membranes [3]. A 2000 N ramped load was applied to the quadriceps and a deep squat was simulated. The alignment parameters and output mechanics (six-degree-of-freedom kinematics, contact pressure and area, and internal stresses sampled at 101 points over the flexion cycle) from the 100-trial Monte Carlo simulation were used as variables in a PCA. PCA was used to reduce the overall variability from the FE analyses into the dominant relationships (modes of variation) between initial alignment and resultant mechanics. To demonstrate predictive capability, 10 new sets of alignment parameters were randomly generated and predictions from the PCA relationships and new FE analyses were compared.

RESULTS

Contributions of alignment parameters (Figure 1) and their relationship to mechanics (Figures 2 and 3) are presented for the first two modes. The first mode of variation for both dome and anatomic components was dominated by femoral I-E alignment. External femoral alignment resulted in external rotation, adduction and lateral shift of the patella and also reduced peak contact pressure in early flexion in the dome patella. Contributions in the second mode of variation differed between designs. For the anatomic component, the main alignment parameter was patellar F-E, which primarily influenced contact mechanics. Posterior rotation of the superior pole of the anatomic patella resulted in substantially lower contact area and higher contact pressure mid-cycle. For the dome patella, the second mode was a combination of F-E and translation (ML and SI), and primarily affected kinematics. Three and five modes were necessary to account for 85% of the overall variability in the dome and anatomic analyses, respectively. Comparing PCA predictions, based on these modes, and FE model results for 10 new alignment sets, kinematic differences averaged 0.6° and 0.2 mm throughout flexion. Peak contact pressure, contact area and Von Mises stress predictions were within 8% and 11% for dome and anatomic components, respectively (Figure 4).

DISCUSSION

Current surgical procedure places particular emphasis on femoral I-E alignment, the importance of which has been confirmed in this analysis. However, the probabilistic-PCA approach also gives insight into more subtle relationships between alignment parameters; highlighting the effect of coupling of alignment parameters, such as the patellar F-E and translation relationship described for the dome component. Understanding the relationships and design-specific dependencies between alignment parameters can add value to surgical pre-operative planning, and may help focus instrumentation design on those alignment parameters of primary concern.

The predictive capability of the PCA has potential applications in a computer assisted surgery environment, where mechanics predictions for a set of alignment conditions could be obtained instantly. Ongoing work to incorporate subject-specific geometry and soft-tissue constraint into the predictive tool may have benefits for inter-operative decision-making on a subject-specific basis.

REFERENCES