DYNAMIC SIMULATIONS OF A TOTAL KNEE REPLACEMENT: ASSESSING THE PERFORMANCE ENVELOPE USING PATIENTS SPECIFIC LOADS

Kheng H Tan (1), Patrick Costigan (2), Mark Taylor (1)

(1) Bioengineering Research Sciences Group
University of Southampton
Southampton
United Kingdom

(2) School of Physical and Health Education
Queen's University
Kingston, Ont.
Canada

ABSTRACT

A three-dimensional finite element (FE) knee model was developed to predict the performance envelope of a knee prosthesis for a group of patients. Level gait knee joint forces of seven healthy patients were used to drive the FE model. The only kinematic input used was the flexion-extension (F-E) angles. The parameters examined include the anterior-posterior (A-P) displacements, internal-external (I-E) rotations and the polyethylene (PE) stresses. A performance envelope was obtained for each of the parameters of interest. The maximum femoral component posterior displacement was 3.6 mm and the maximum anterior displacement was 4.8 mm. The highest internal rotation of the femoral component was 4.3° while the highest external rotation was approximately 7°. The highest maximum von Mises stress was 22.1 MPa.

INTRODUCTION

There is considerable variation in the kinematics of TKR between patients, as has been shown by various clinical studies. Uvehammer et al. [1] assessed the kinematics of 22 knees implanted in 20 patients using radiostereometry. They found that the tibial component externally rotated up to 7.3° and also internally rotated up to 7.3° when the knee joint was flexed at 45°. The minimum and maximum anterior femoral component translations were 2.3 mm and 10 mm, respectively. In a fluoroscopy study by Stiehl et al. [2], the kinematics of five different prosthetic designs were studied in 47 patients, who performed a single-leg deep-knee bend. Overall, they found that during full extension, the tibiofemoral contact points of all knees started at 10 ± 5 mm posterior to the midline in the sagittal plane of the tibial joint surface. During flexion, all the knees translated to a point 5 ± 3 mm anterior to the midsagittal point. A wide range of kinematics performance of the prostheses was observed and suggested that these differences in movements depend on factors such as patients' gait (wide variety of patients), loading conditions and prosthetic designs. Most of the clinical studies were only able to investigate the kinematics without knowing the magnitude and direction of the load applied in the total knee system. Due to this reason, the resultant contact pressures in the polyethylene component are unknown.

Meanwhile, in FE studies, only a few dynamic knee models are available [3-4]. These FE studies used the ISO standard as the input for the force and flexion angle data. To date, there are no dynamic FE studies that have used different patients gait data as the input force. The knee joint in each individual is subjected to different values of joint forces. Some individuals may have higher axial, A-P forces or torques values, while some may have less. Therefore, the objective of this study was to examine the TKR over a range of patients to assess the 'performance envelope' of replaced knees.

METHODS

FE Knee Model

A previously developed 3-D FE model of a PFC Sigma (DePuy) knee [3] was used. The tibial tray was modelled as a rigid body and it was assumed that the PE insert was rigidly attached to the tibial tray. The femoral component was modelled as a rigid body using four noded shell elements. The PE insert was modelled using hexahedral solid elements and was assigned elastic-plastic material properties. The femoral component was allowed to translate in the proximal-distal direction, to rotate about its transverse (flexion-extension) and frontal (varus-valgus) axes. The tibial component was allowed to translate in the anterior-posterior, medial-lateral directions and to rotate about its longitudinal axis (internal-external). An inferiorly directed axial force tending to compress the insert (F_C) was applied at the centre of gravity of the femoral component and an anterior-posterior force (F_{ap}) applied to the tibial component. Torque was applied to the joint via two nodes that were tied externally at the medial-lateral side of the tibial component. Horizontal medial and lateral springs were used to represent the soft-tissue structures of the knee.

Joint Forces

The kinematics and force plate data were obtained for 7 healthy elderly patients during level gait. Inverse dynamics were then applied to calculate the joint reaction force at the knee for each patient [5].

The axial force, A-P forces, torques and flexion angles for these patients are shown in Figure 1. These values were used to drive the knee model. The kinematics and von Mises stresses distributions of the knee prosthesis were reported for each of the patients' load case.

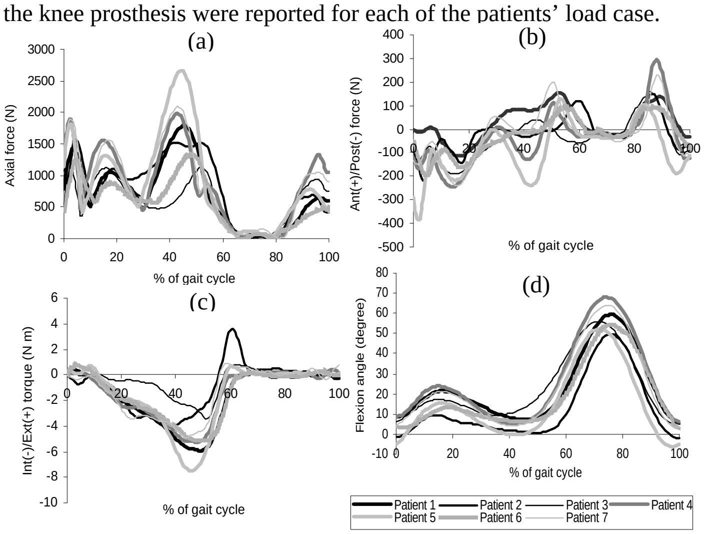

Figure 1: a), axial forces; b), A-P forces; c), I-E torques and d), flexion angles, for the seven patients.

RESULTS AND DISCUSSIONS

The predicted kinematics and von Mises stresses were shown in Figure 2. The simulations were run for one full gait cycle. A range of A-P displacement was observed. The highest peak posterior displacement of the prosthesis was 3.6 mm (Patient 5), at 20% of the gait cycle. At this period, the patient's knee was subject to 1100 N of axial force but at the highest A-P force value of approximately 180 N among the patients. The highest peak anterior displacement was 4.8 mm, occurred during the swing phase when the A-P force was the highest, 292 N. The A-P displacement during the stance phase of all the knees fell in the range of –3.8 mm to +2 mm. From the predicted I-E rotation, the femoral components internally rotated from the beginning to approximately 57% of the gait cycle. Six patients except Patient 2, exhibited the highest peak internal rotation between 50% and 57% of gait cycle. The highest peak internal rotation was from Patient 1 with 5.7°. At this period of time, the six patients were subjected to the highest torque and this explained the highest internal rotation. Patient 2 exhibited the highest peak internal rotation of 2.9° at about 26% of the gait cycle and then started to rotate externally and reached peak external rotation of 7.1° at approximately 63.5% of the gait cycle. This was because at this point, Patient 2 was subjected to the highest external torque of 3.5 N m. During the swing phase, all the knees returned to a neutral rotational position. The greatest maximum von Mises stress was 22 MPa (Patient 4). Patient 5 also showed high von Mises stresses. The von Mises stresses were sensitive to the axial forces at the joint. As the axial force increased, the stresses also increased. A range of von Mises stresses, between 7 – 22 MPa, was observed during the stance phase. The stresses data were smooth from the beginning to about 50% of the gait cycle. Starting from 50% till the end of the gait cycle, large transients were observed. Since the peak stresses were higher than the PE yield stress, the PE insert showed signed of plastic strains.

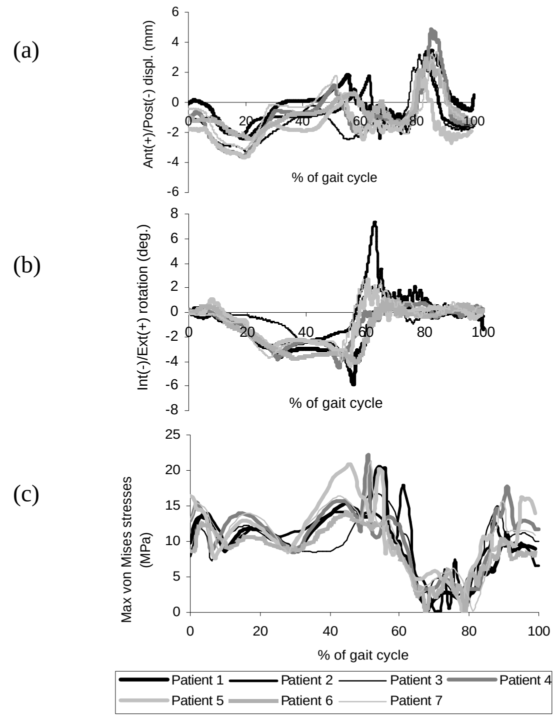

Figure 2: Predicted kinematics, a), A-P displacements; b), I-E rotations and c), von Mises stresses distributions.

CONCLUSION

A performance envelope of TKR under patients' specific loading was obtained. Inter-patients' kinematics variability was low. The A-P translations and I-E rotations were consistent despite variations in the applied load. Greater variability in the PE stresses were observed, typically a 5 – 10 MPa range was seen during the stance phase. For this knee design, the kinematics seemed to be insensitive to changes in load, however the PE stresses were affected to a greater extent. These findings may vary for other designs.

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