3D FINITE ELEMENT MODEL FOR PREDICTION OF TOTAL KNEE REPLACEMENT MOTIONS AND STRESSES

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Introduction

Performance and long term function of Total Knee Replacements (TKR) are closely related to the joint kinematics after implantation and to the stresses occurring within the prosthesis components. Computer models can play a major role to evaluate TKR designs before clinical use. However, since now, there is no simple way of simulating the kinematics of the replaced knee and at the same time derive the component internal stresses. Previously developed models were restricted to predict either motions or stresses and were rarely validated against experimental data [1]. A 3D finite element model was developed using the explicit dynamic code PAM-SAFE™ with the final goal of predicting both TKR motions and stresses, under complex loading conditions. This model was first validated in terms of stress predictions under simple compression loads [2]. The purpose of this work is to assess its quality in terms of 3D motion predictions. For this purpose, Anterior-Posterior (AP) and Internal-External (IE) laxity tests were simulated and the FE results were compared to experimental data.

Methods

FE simulations were carried out on a cruciate-retaining TKR. The femoral component was modelled as a rigid body and meshed using shell elements while the tibial plastic insert was modelled using solid elements with non-linear polyethylene properties. Contact between the TKR components was modelled using an advanced contact algorithm. The boundary conditions of the FE model were set up to reproduce the mechanical arrangement of the Stanmore knee simulator [3] as shown on figure 1. Anterior-posterior, medial-lateral motions and internal-external rotation of the tibial insert were allowed. The flexion motion of the femoral component was controlled while its distal-proximal translation remained free. Anterior-Posterior (AP) laxity tests and Internal-External (IE) rotary laxity tests were simulated at various flexion angles. These tests, carried out following the ASTM F1223 requirements, consisted in applying a compressive force to the femoral component, an external shear force or torque to the tibial insert and in recording the resulting TKR motions.

Results

The relative displacements of the TKR components predicted by FE were compared to experimental data (Tables 1 and 2). When friction between the components was taken into account, displacements were within 10% to 30% of the experimental data. For IE laxity tests, dislocation occurred in all cases and the rotational angles predicted by FE were lower than those recorded experimentally. Calculation of the constraint ratios, APC and RLC as defined by the ASTM F1223 (cf. formula below), showed a good agreement between FE and experimental results. The model was also used to determine the pressure distribution at the tibial insert surface as a function of time, giving information on the peak pressure magnitudes and successive locations (Figure 2).

Discussion

Considering the facts that the frictional effects occurring within the testing machine were not taken into account and that the experimental standard deviation was close to 10%, FE predictions of AP laxity were considered to be in good agreement with the experimental data. In the case of IE Laxity tests, the angles to dislocation predicted were lower than the experimental data. The instant of dislocation is however hard to determine precisely during experiments. Further IE laxity simulations were carried out using loads that did not lead to dislocation and results were in a good agreement with published data [3]. The explicit FE code was shown to be a good tool for both motion and stress predictions under simple load cases. It is now further developed to simulate a full gait cycle. Such a 3D FE model can be used by surgeons and manufacturers to evaluate and optimize TKR designs based on both kinematics and stress considerations.

Acknowledgments: Special thanks to the Engineering Materials Department of the University of Southampton.

References

[1] Estupinan et al., J Orthop Res 16:80-88, 1998.
[2] Godest et al., Proceedings of the 17th ISB conference, 1999.
[3] Walker et al., J Biomechanics 30:83-89, 1997.

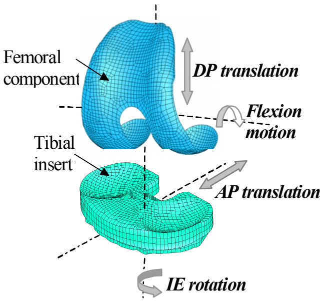

Figure 1 : FE Model of TKR and motions allowed during the FE simulations.

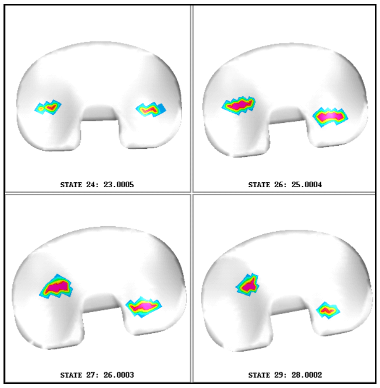

Figure 2 : Pressure distribution at the tibial insert surface during IE laxity test simulations.

Flexion angles	Experimental Data		FE simulations PAM-CRASH™			
			No friction		Friction coeff. 0.07	
	T_{AP} (mm)	**APC**	T_{AP} (mm)	APC	T_{AP} (mm)	**APC**
0°	4.2	**2.7**	5.7	2.6	5.6	**2.6**
15°	4.9	**2.6**	7.4	2.4	6.6	**2.5**
45°	12.2	**2.1**	14.4	1.9	13.5	**2**

Table 1 : Total AP displacements and AP constraint ratios recorded experimentally and predicted by FE, for AP laxity tests. Compressive force of 44.5N, AP shear force of ±20N.

Flexion angles	Experimental Data		FE simulations PAM-CRASH™	
	ANG_1+ANG_2 (°)	**RLC**	ANG_1+ANG_2 (°)	**RLC**
0°	21.4	**2.5**	13.9	**2.5**
15°	22.5	**2.4**	19.2	**2.5**
45°	30.4	**2.2**	23.8	**2.4**
90°	36.4	**2.1**	37.9	**2.1**

Table 2 : Total Angles at dislocation and IE constraint ratios recorded experimentally and predicted by FE, for IE rotary laxity tests. Compressive force of 44.5N, IE Torque ±10Nm.

Formula

$$APC = \left(1 - \frac{X_1 + X_2}{TAP}\right) \times 3$$

X_1, X_2 : Absolute values of AP displacements for a ±20N force.
TAP : overall AP bearing surface dimension of the tibial insert.

$$RLC = \left(1 - \frac{ANG_1 + ANG_2}{TANG}\right) \times 3$$

ANG_1, ANG_2 : Absolute values of IE rotations for a ± 0.75Nm torque.
TANG : overall rotary surface dimension of the tibial insert.

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