FE DYNAMIC ANALYSIS OF A KNEE JOINT PROSTHESIS DURING THE WALKING CYCLE

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INTRODUCTION

Knee is one of the most complex joints of the human body, from both structural and kinematical point of view. It is composed by two different joints; the femoro-tibial joint between the distal part of the femur and the proximal part of the tibia and the patello-femoral joint, consisting of the patella, which articulates with the femoral trochlea.

The cruciate and collateral ligaments stabilize the complex movements of the first joint. Menisci are fibrous structures which increase the contact area between tibial and femoral surface.

Every mentioned element has a specific role in the complex kinematics of the knee joint. The replacement through a prosthesis of a part or of the whole articulation requires accurate investigations in order to guarantee its functionality. The ISO/DIS 14243-1 draft establishes the loads and the flexions which must be applied to the prosthesis during the experimental tests performed by means of a walking cycle simulator in order to estimate the tibial component wear.

This study concerns a finite element analysis of a commercial knee joint prosthesis. The numerical analysis have been performed in order to simulate the loading conditions applied to the device during the walking cycle in order to estimate the contact area, the contact pressure and the stress status of the polyethylene tibial components, reproducing the same boundary conditions applied during the experimental tests by a knee simulator.

MATERIALS AND METHODS

The three-dimensional model of the knee joint was performed on the basis of the prosthesis technical drawings. The 3-D FE models performed in this work consists of: i) the Co-Cr-Mo alloy femoral component; ii) the UHMWPE polyethylene tibial component; iii) Co-Cr-Mo alloy tibial support (fig.1a). Moreover, a pin inserted in the tibial support and a grip structure connected to the pin were added to apply loads to the prosthesis, according to the loading set up described for the walking cycle simulator used during the experimental tests (Stanmore/Instron Knee Simulator, Instron Ltd, High Wycombe, UK). After discretization, the model consists of 22097 eight node hexahedral elements. The 3-D model and discretization were performed by means of GAMBIT commercial software (Fluent Inc., Lebanon, NH, USA).

The Young Modulus and Poisson ratio assumed for the Co-Cr-Mo alloy component were 210 GPa and 0.3, respectively. The UHMWPE polyethylene was assumed as non linear elastic-plastic material [1-2]. The pin and the grip structure were considered rigid, in order to apply the entire load to the prosthesis (E=1000 GPa and ν=0.3).

Sliding contacts with friction coefficient equal to 0.07 were defined between between the pin and the tibial support, as well as between the femoral and the polyethylene tibial component. Tide contacts were applied between the pin and the grip support.

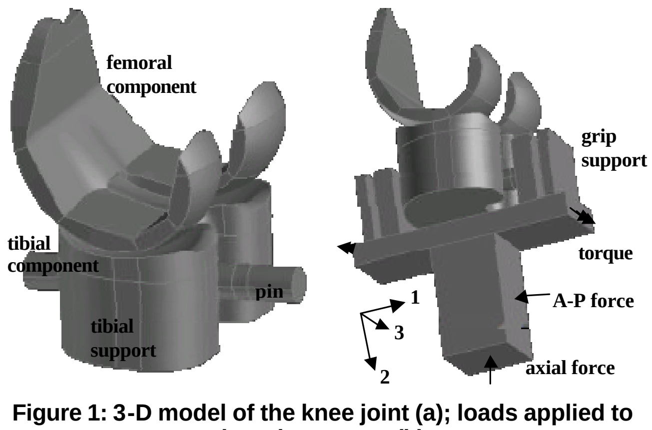

Figure 1: 3-D model of the knee joint (a); loads applied to the grip support (b).

A dynamic analysis of the joint was performed and the overall walking cycle was simulated (applying loads of a complete step cycle and imposing the femoral rotation, according to the waveform reported in the ISO/DIS 14243-1 draft. The axial force, the anterior-posterior force (A-P force) and the torque are applied to the grip support as shown in fig.1b.

In particular the most critical points of the walking cycle (S1, S2) were investigated in terms of contact pressure and stress status at the surfaces of the joints, which correspond to the maximum values of the axial load during the walking cycle. Input data concerning the loads applied at 13% (S1) and 46% (S2) of the walking cycle are reported in Table 1.

	step [%]	***flexion angle*** [deg]	***axial force*** [N]	***A-P force*** [N]	***torque*** [Nm]
S1	13	15.3	2600.0	109.6	-0.903
S2	46	9.5	2408.8	-147.1	5.829

Table 1: Loads applied at 13% (S1) and 46% (S2) of the walking cycle.

To simulate the action of the soft tissues of the knee, a torsional spring and a spring acting in anterior-posterior direction were considered. This springs take into account for the 4 bumpers of the knee simulator. The stiffness of the two springs was defined according to ISO/DIS 14243-1, which states stiffness values of 0.6 Nm/deg for the torsional spring and of 30 N/mm for the anterior-posterior spring (simulations $S1_{ISO}$ and $S2_{ISO}$). Analyses with stiffness values reported by Des Jardins et al. [3] (0.28 Nm/deg for the torsional spring and 20 N/mm for the anterior-posterior spring) were also performed ($S1_{DJ}$ and $S2_{DJ}$).

ABAQUS code (ABAQUS Explicit, Hibbitt, Karlsson & Sorensen, Version 6.2.1) was used to perform the numerical analyses.

RESULTS

Figure 2 shows the the laxity waveforms (anterior-posterior displacement, internal-external and varus-valgus rotation) of the knee joint with ISO DIS 14243-1 (black line) and Des Jardins (dotted line) spring stiffness values obtained with the dynamic simulation of the overall walking cycle.

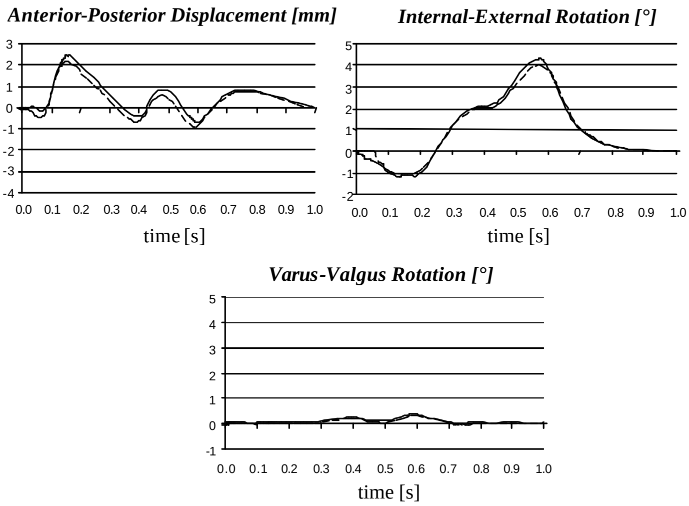

Figure 2: Laxity waveforms during the overall working cycle simulation.

Table 2 summarizes the results obtained at 13% and 46% of the walking cycle (S1 and S2 points); data concerning contact pressures (P_C), contact areas (A_C), CPU time (CT), Von Mises stress values (σ_{vM}) and vertical direction stress values (σ_{22}) are reported both in the case of ISO/DIS 14243-1 ($S1_{ISO}$, $S2_{ISO}$) and Des Jardins ($S1_{DJ}$, $S2_{DJ}$) spring stiffness values. Figure 3 shows the contact pressure maps in the tibial component obtained for simulation $S1_{ISO}$ at 60% and 100% of the applied load.

				femoral component		***tibial component***	
	A_C [mm^2]	P_C [MPa]	**CT** [h,min]	σ_{vM} [MPa]	σ_{22} [MPa]	σ_{vM} [MPa]	σ_{22} [MPa]
$S1_{ISO}$	468.6	15.19	13.19	9.556	-14.45	8.159	-15.36
$S1_{DJ}$	460.2	15.09	13.40	9.662	-14.54	8.152	-15.35
$S2_{ISO}$	460.3	15.60	12.25	9.753	-13.19	9.201	-16.76
$S2_{DJ}$	458.0	15.61	13.34	9.770	-13.20	9.206	-16.77

Table 2: Data concerning static simulations S1 and S2.

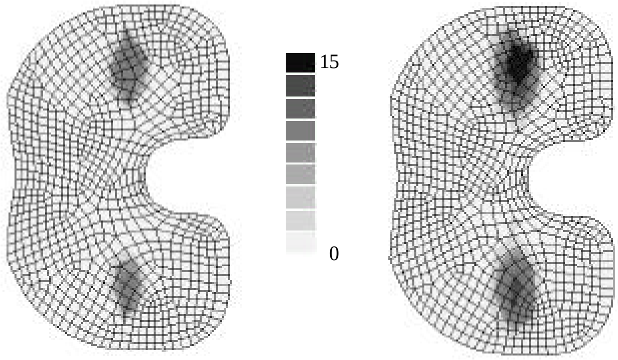

Figure 3: Tibial component contact pressure at 60% (a) and 100% (b)of the applied load ($S1_{ISO}$).

DISCUSSION

The laxity waveform obtained with the dynamic analysis show that the results are slightly influenced by the spring stiffness values adopted to simulate the action of the soft tissues. The laxity-curve variations are 1.75% for the anterior-posterior displacement, 1.52% for the internal-external rotation and 9.83% for the varus-valgus rotation.

The comparison between the results obtained in this study and experimental data reported in literature is quite difficult due to the differences in terms of conformity and profile shape of the tested prostheses. Experimental tests of the modeled prosthesis by means of a knee simulator are mandatory.

A limitation of the study is the simplistic representation of the polyethylene as elastic-plastic material, which was derived from literature uniaxial test data, not considering its viscous behavior.

REFERENCES

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