Numerical Simulations of Mechanical Tests For Knee Implants

J. Soulhat¹, D. Dan², M. Beaugonin², H. Ploeg³, C. Reinschmidt³, J. Krevolin⁴
¹Sulzer Innotec, Winterthur/Switzerland
²ESI Group, Rungis Cedex/France
³Sulzer Orthopedics Ltd., Winterthur/Switzerland
⁴Sulzer Orthopedics Inc., Austin/USA

Introduction
Various preclinical tests are typically performed to evaluate knee replacement systems. For instance, the intrinsic mechanical stability is tested using laxity tests such as the “Greenwald tests” or the wear behaviour can be evaluated with the Stanmore knee simulator. The numerical simulations of these mechanical tests with virtual implants are of great interest for the prosthetic designer to obtain initial feedback of the implant behaviour and characteristics prior to manufacturing and experimental work. The purpose of this study was to set-up and validate dynamic finite element (FE) models of the Greenwald test and the Stanmore knee simulator.

Methods
A commercially available FE package (PAM-Crash™) allowing explicit formulation was used for this study. The femoral component of a knee system (Natural Knee, Sulzer Orthopedics) was modeled as a rigid body with 4-noded QUAD where the tibial insert was modeled also rigid or using deformable 8-noded HEX elements with elastic/plastic material properties. Contact conditions with friction were defined between the tibial and the femoral components. With the laxity test, the mechanical stability of the knee implant is evaluated. The intrinsic stability of an implant system is defined as the capacity of the implant to limit rotational, anterior-posterior and medio-lateral displacements within normal ranges [Greenwald et al., 1996]. The laxity test can be carried out in different directions. For example in the posterior laxity test (see Figure 1), an axial compressive load is applied first on the femoral component and after that a controlled displacement is applied onto the tibial insert in the posterior direction. The induced reaction force in the anterior-posterior direction is then recorded, providing a measure of the maximum ability of the knee design to constrain displacement during gait. Table 1 shows the compressive loads used in the tests and simulations and the load levels of maximal constraint as determined experimentally in the tests.

<table>
<thead>
<tr>
<th>Test direction</th>
<th>Femur flexion</th>
<th>Compressive load</th>
<th>Load at failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>anterior</td>
<td>0°</td>
<td>1668 N</td>
<td>725 N = 1xBW</td>
</tr>
<tr>
<td>posterior</td>
<td>0°</td>
<td>2890 N</td>
<td>1450 N = 2xBW</td>
</tr>
<tr>
<td>posterior</td>
<td>90°</td>
<td>1780 N</td>
<td>1200 N</td>
</tr>
<tr>
<td>int. rotational</td>
<td>15°</td>
<td>1913 N</td>
<td>11.5 Nm</td>
</tr>
<tr>
<td>ext. rotational</td>
<td>15°</td>
<td>1913 N</td>
<td>10.7 Nm</td>
</tr>
</tbody>
</table>

Table 1: Parameters for the laxity tests
The Stanmore knee simulator is used to test experimentally the wear behaviour of artificial knee replacement systems by reproducing millions of gait cycles through the application of realistic forces and constraints. The knee flexion, the axial force, the A/P force and the I/E torque as a function of one gait cycle are given as input parameters. The machine will cyclically apply these loads and constraints to the knee implant shown in Figure 2.

Results & Discussion
The FE predictions of the maximum subluxation force given by the Greenwald laxity test simulations for both deformable and rigid tibial inserts were compared with experimental data for anterior, posterior and rotational shear loads (see Figure 3). The deformable FE models for the Greenwald test compare well with the experimental data.

The FE predictions of the Stanmore simulator were obtained for a set of loads and kinematic constraints representing the gait cycle, as described in ISO standards. The predicted time history of the anterior/posterior (A/P) displacements and internal/external (I/E) rotations were compared with experimental measurements (see Figure 4).

In addition, the simulator’s response under ideal ISO inputs were compared to real simulator inputs in terms of kinematic outputs and contact behaviour (contact area, contact pressures) between the tibial insert and the femoral component, using the FE model. The FE models compare well with the experimental data, although the friction behaviour at the tibial/femoral interface is not precisely known. The FE models also give information on the contact stresses that can not be easily obtained experimentally. The explicit FE method is a useful and reliable tool for investigations of knee components involving large displacements such as the Greenwald laxity test and the Stanmore knee simulator for wear testing.

References
ISO 14243-1.4