INTRODUCTION

Micro-motions at the stem-bone interface are an important factor in the success of total hip arthroplasty (THA). These micro-motions can be estimated using finite element (FE) techniques. Current FE analyses, however, have a limited applicability because of several limitations. Generally, they do not consider a whole gait cycle, do not include a complete and consistent set of muscle loads and have rather unrealistic boundary conditions (e.g. the femur is completely constrained at the diaphyseal area).

In the present study, an FE model of a femoral uncemented THA reconstruction including a consistent set of muscle forces was used to answer: a) Is the maximum micro-motion different when a loading cycle is applied to the FE model compared to single moment loading? b) How does the magnitude and the direction of micro-motions depend on the used set of boundary conditions?

METHODS

A combination of gait data and modeling techniques were used to obtain results (Figure 1). A CT-based FE model of a femur was created and a cementless prosthesis was virtually implanted (CLS Spotorno stem, Zimmer Inc., USA) with an ideal proximal fit and an interface gap of 0.3 mm in the distal area. The implant, was assigned a stiffness of 105 GPa; bone stiffness were related to bone density. The bone-implant interface friction coefficient was set to μ=0.3.

The FE model was subjected to forces occurring during walking. The walking cycle was divided into 37 moments, including two stance phases and a right swing phase. Muscle forces were calculated using the musculoskeletal modeling system Anybody® (Anybody Technology A/S, Denmark). The femur geometry of the FE model was imported into Anybody, after which the anatomical data set was adapted to obtain a geometrically consistent set of muscle forces. In addition, a single moment loading was studied as well by applying muscle and hip joint reaction forces at the moment of maximal hip joint reaction force.

An in-house algorithm was used to track the incremental and maximal micro-motions over time. Six nodes on the surface of the implant were selected for analysis of micro-motion distribution (two proximal, two mid stem and two distal). In order to study the dependency of interface micro-motions on various boundary conditions, four constraint sets were applied to the FE model:

- (1) Three translations at hip joint centre; three rotations at the knee
- (2) All d.o.f. constrained at the diaphysis ~60mm below implant tip
- (3) Spring constraints: FE model suspended using weak springs
- (4) Hip joint displacement only allowed towards knee center

In total, six individual cases were analyzed (Table 1). The femur geometry of the FE model was imported into Anybody, after which the anatomical data set was adapted to obtain a geometrically consistent set of muscle forces. In addition, a single moment loading was studied as well by applying muscle and hip joint reaction forces at the moment of maximal hip joint reaction force.

An in-house algorithm was used to track the incremental and maximal micro-motions over time. Six nodes on the surface of the implant were selected for analysis of micro-motion distribution (two proximal, two mid stem and two distal). In order to study the dependency of interface micro-motions on various boundary conditions, four constraint sets were applied to the FE model:

- (1) Three translations at hip joint centre; three rotations at the knee
- (2) All d.o.f. constrained at the diaphysis ~60mm below implant tip
- (3) Spring constraints: FE model suspended using weak springs
- (4) Hip joint displacement only allowed towards knee center

RESULTS

In the proximal region, a unidirectional pattern of micro-motions was visible in proximal-distal direction. Mid stem micro-motions were very small, whereas at the tip motions in the transverse plane occurred.

At all points on the implant, the greatest incremental micro-motion was generated near the time increment when the greatest hip joint reaction forces occurred (immediately after swing phase). However, large incremental micro-motions were also found during the swing phase when the hip joint reaction forces were relatively low.

The single moment loaded case (case F) resulted in maximal micro-motions similar to those found in time dependent loaded cases, but at the tip area these micro-motions were smaller (Table 2).

Table 2: Maximal micro-motions during the whole loading cycle (except case F which was a single loading moment).

<table>
<thead>
<tr>
<th>Case</th>
<th>Constraint set</th>
<th>Muscle model</th>
<th>Loading configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1</td>
<td>full muscle set</td>
<td>whole gait cycle</td>
</tr>
<tr>
<td>B</td>
<td>2</td>
<td>simplified hip joint contact force, abductors, Vastus Lateralis</td>
<td>whole gait cycle</td>
</tr>
<tr>
<td>C</td>
<td>2</td>
<td>semi complete, all remaining muscles above fixation</td>
<td>whole gait cycle</td>
</tr>
<tr>
<td>D</td>
<td>1</td>
<td>full muscle set</td>
<td>whole gait cycle</td>
</tr>
<tr>
<td>E</td>
<td>1</td>
<td>full muscle set</td>
<td>whole gait cycle</td>
</tr>
<tr>
<td>F</td>
<td>1</td>
<td>full muscle set</td>
<td>single moment</td>
</tr>
</tbody>
</table>

Table 1: Studied cases with varying muscle sets and loading configuration.

Figure 1: gait analysis and musculoskeletal modeling techniques were combine with FE techniques to calculate distributions of micro-motions (right picture).

Figure 2: Micro-motion paths of the tip of the stem in the six cases studied.

Consistent magnitude and path development of interface micro-motions was calculated for all time dependent cases that included a complete set of muscles (cases A, C, D and E, Figure 2). Simplified constraints of the FE model in combination with a simplified muscle set (case B) did reveal different micro-motion magnitudes and direction development paths with respect to the other time dependent loaded cases.

CONCLUSIONS

This study showed that conventional FE model constraints for THA reconstructions (diaphyseal constraints) and single moment loading (when maximal hip reaction forces occur) actually provide a relatively good estimation of the distribution of micro-motions during walking.

Applying different constraints did not result in different micro-motions. Simplifications of the loading set, on the other hand, did have an effect on the micro-motions. The results of this study show that realistic loading configurations (full set of consistent muscle forces and time dependent loading) can provide more details about micro-motion development during a walking cycle. Based on the present and previous studies, it is believed that the focus towards a more realistic peri-prosthetic micro-motion prediction, lies in the further enhancement of personalized and dynamic modeling details such as including patient-specific muscle and joint reaction forces of entire movements.

Acknowledgements: Zimmer provided us with the solid model of the implant. Gait data was provided by the EU-FP7 TLEMsafe project (www.tlemsafe.eu).