Dynamic implant cut-out is governed by peri-implant bone microstructure

INTRODUCTION

Implant cut-out is a frequent complication after surgical treatment of osteoporotic fractures. Long-term dynamic loads have been shown to be relevant for the stability or failure of bone-implant constructs, for example in the proximal femur. Therefore, dynamic test setups have been developed, which apply physiologically realistic loading profiles [1]. These methods, however, assess the failure mostly at a global level and give little insight into the micromechanics of the bone-implant constructs.

Image-guided failure assessment (IGFA) is an experimental technique combining mechanical testing and high-resolution CT scanning. Using IGFA, the failure behavior of bone-implant constructs under quasi-static loads has been studied at the microstructural level of trabecular bone [2]. The aim of this study was to visualize the cut-out behavior of implants under dynamic loading and to quantify the role of the peri-implant bone microstructure.

METHODS

Fifty human femoral heads were obtained from the donor program of the Schulthess Clinic, Zurich, Switzerland with informed consent by the patients (ethics committee approval EK 29-2007). MicroCT scanning and standard trabecular bone morphometry were carried out (µCT80, Scanco Medical AG, Brüttisellen, Switzerland), and six specimens were selected to obtain a wide range of bone volume fractions (BV/TV between 31% and 57%).

Commercially available dynamic screw sets (DHS, Synthes GmbH, Solothurn, Switzerland) were replicated from carbon-fiber reinforced PEEK polymer to avoid imaging artifacts during CT scanning. In order to minimize bending of the screw, it was supported by a specially designed solid block of PEEK. With this type of setup, it was not possible to insert the screw into an intact femoral head. After pre-drilling and tapping, the bone was therefore cut open with correct anatomical orientation to allow insertion of the DHS. The articulating side of the femoral heads was molded into a special testing jig, which allowed it to rotate around its natural center of rotation (Fig 1).

Loading was applied using a dedicated mechanical loading device, which is compatible with an HR-pQCT patient scanner (XtremeCT, Scanco Medical AG, Brüttisellen, Switzerland) providing a nominal image resolution of 82 µm. Dynamic hip loading [3] was applied in sets of 500 cycles at an angle of 23 degrees to the femoral neck axis. The initial force peak and valley were 200 N and 100 N, respectively. After mechanical loading, there was a relaxation period of 10 min. CT scanning was performed both after the first application of the force peak (quasi-static deformation) and after the subsequent 499 force profiles (dynamic migration). For each following sequence of 500 cycles, the force peak was increased by an increment of 500 N. Four to five series were applied, depending on the migration rate.

Load-displacement data were logged and analyzed for each loading series. Image processing routines were used to visualize and quantify implant migration, such as failed trabecular bone volume. For this, the bone after each loading series of 500 cycles was matched onto the bone prior to loading, and the difference between the two was calculated.

RESULTS

Visualization of the progressively failing trabecular bone volume yielded migration trajectories comparable to clinical outcomes (Fig 2) [1]. The failed trabecular bone volumes were highly correlated with the resulting displacements after each loading step ($R^2 = 0.97$). The final quasi-static displacements correlated well with initial $BV/TV$ ($R^2 = 0.71$), while the final dynamic displacements correlated very well with the initial $BV/TV$ ($R^2 = 0.98$) (Tab 1).

<table>
<thead>
<tr>
<th>BV/TV</th>
<th>Tb.N</th>
<th>Tb.Sp</th>
<th>Tb.Th</th>
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<tr>
<td>0.98</td>
<td>0.96</td>
<td>0.99</td>
<td>0.80</td>
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Three groups of two specimens with similar $BV/TV$ could be identified, which exhibited similar mechanical performance. The low $BV/TV$ specimens showed an early increase in migration rate (Fig 3).

DISCUSSION

Strong correlations were obtained between initial BV/TV and final displacement as well as failed volume. This finding underlines the importance of the trabecular microstructure in determining dynamic implant fixation failure.

The final dynamic displacements were much better predicted by the initial BV/TV than the final quasi-static displacements. This finding stresses the importance of conducting dynamic tests to study bone-implant interaction.

Our results confirm that a strong connection exists between trabecular microstructure and dynamic implant cut-out behavior.

SIGNIFICANCE

In-depth knowledge about the dynamic cut-out mechanisms of orthopedic screws at the microstructural level is largely lacking. Filling this gap has the potential to lead to new implant fixation strategies for fracture treatment in osteoporotic bone.

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REFERENCES