INTRODUCTION:
Screws are commonly used for the fixation of bone fractures. In general they are very successful; but they may fail in some cases. A site with a relatively high complication rate is the proximal humerus [1]. A commonly assumed reason for this decreased implant performance is low bone quality, as may be induced by osteoporosis. Indeed, biomechanical measurements have demonstrated the obvious importance of bone quality; nevertheless, reported correlations between bone density and implant stability were moderate at best [2]. We hypothesized that part of the remaining variance may be explained by local variations in bone quality.

METHODS:
Twelve humeral heads with similar outer dimensions and without malformations were selected from an ongoing study (ethics committee approval EK-29/2007). All samples were measured using micro-computed tomography (µCT80, Scanco Medical AG, Switzerland) with a spatial resolution of 30 µm, which was the highest resolution available for the present sample size. Cylindrical volumes of interest (VOIs) were virtually extracted from the bones' central trabecular region, where the main fraction of screws is usually positioned. The VOIs had a diameter of 26.5 mm and a height of 9.3 mm. Subsequently, screws with a diameter of 3.5 mm, widely used for anchorage in the humeral head, were inserted virtually at 25 different positions in the VOI, leading to 300 bone-implant models (Fig. 1a). Additionally, 300 virtual bone biopsies with a diameter of 7 mm were taken at the screw locations.

Using a direct voxel-to-element conversion, one micro-finite element (µFE) model was created for each bone-implant construct and for each bone biopsy. Similar to standardized biomechanical tests, the mechanical competence of the bone biopsies was tested by simulating an axial compression test using µFE and the apparent Young’s modulus was determined. For the bone-implant constructs, pull-out tests were simulated using a previously validated µFE technique [3]; the mechanical stiffness was calculated. Bone and screw were taken as linear-elastic isotropic materials; the interface between screw and bone was assumed perfectly bonded. The µFE models consisted of up to 227 million degrees of freedom. They were solved using the finite element solver ParFE [4] on 1024 processors of a supercomputer (CRAY XT5) which allowed solving each model in less than two minutes (Fig. 1b).

In order to quantify the connectivity between implant and bone, percentage bone interface (%BI) was calculated. Bone volume fraction (BV/TV) was determined for the large VOIs as well as for the local bone-implant models (Fig. 1b). Additionally, state-of-the-art three-dimensional bone morphometry was performed to quantify trabecular microarchitecture.

RESULTS:

Bone morphometry and µFE analyses revealed high intra- and inter-specimen differences in local bone quality and bone-implant stiffness. Global assessment of bone volume fraction (BV/TV) allowed only moderate predictions of implant stability ($R^2 = 0.52$) (Fig. 2a). In contrast, bone-implant stiffness correlated highly with local BV/TV ($R^2 = 0.91$; Fig. 2b) and even better with the apparent Young’s modulus of peri-implant bone ($R^2 = 0.97$; Fig. 2c). Extending BV/TV with information about local trabecular thickness and trabecular separation allowed the increase of predictability ($R^2 = 0.93$) compared to BV/TV alone. Percentage bone interface correlated well with bone-implant stiffness ($R^2 = 0.79$). Structural model index was a moderate predictor ($R^2 = 0.42$) for the pooled samples; by including trabecular number and trabecular separation predictability increased substantially ($R^2 = 0.92$).

DISCUSSION:
In this study a pure in silico approach using validated techniques was developed for quantifying the relationship between bone and implant stability. In fact, only by using an in silico approach could we test multiple implants within one single bone sample; it would not have been possible when using experimental biomechanical measurements, because such tests are destructive. We found that bone-implant stiffness is strongly dependent on the spatial localization of the implant. We showed that the immediate peri-implant bone density is a good predictor of implant stability, and we demonstrated that the predictability of implant stability can be improved by including information about peri-implant trabecular microarchitecture. Our findings show that the anchorage of relatively small implants in trabecular bone is mainly determined by immediate peri-implant bone quality. Conventional measurements of local bone quality, such as DXA, are typically assessing relatively large volumes. Hence, such measurements cannot predict the failure risk of single screws. The results of the present study may explain implant failure in clinical practice where apparent bone density is suggesting good bone quality. Furthermore, the results provide important information that may help to improve the design of future implants.

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