Archives of Orthopaedic and Trauma Surgery (2019) 139:1069–1074
https://doi.org/10.1007/s00402-019-03175-x

TRAUMA SURGERY

The influence of screw length on predicted cut-out failures for proximal humeral fracture fixations predicted by finite element simulations

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Received: 30 October 2018 / Published online: 20 March 2019

Abstract

Background The aim of this study was to identify the effect of screw length on predictions of fixation failure in three-part proximal humeral fractures using a finite element-based osteosynthesis modelling toolkit.

Methods A mal-reduced unstable three-part AO/OTA 11-B3.2 fracture with medial comminution was simulated in forty-two digitally processed proximal humeri covering a spectrum of bone densities and fixed with the PHILOS plate using three distal and six proximal locking screws. Four test groups were generated based on the screw tip to joint surface distance (TJD), with all proximal screws being shortened from 4 mm TJD to be 8, 12 or 16 mm TJD. Average bone strains around the screw tips, correlating with biomechanical cyclic cut-out-type failure, were evaluated in three physiological loading protocols representing simple shoulder motions. Six further groups were tested, where five of the proximal screws were inserted to 4 mm TJD and the sixth screw to 8 mm TJD.

Results Exponential increases in the predicted risk of fixation failure were seen with increased tip-to-joint distances ($p < 0.001$). When one of the proximal screws was placed 8 mm from the joint, with the remaining five at 4 mm distance, significant increases ($p < 0.001$) were registered in the strains around the screw tips in all except the two superior screws. This effect was maximal around the calcar screws ($p < 0.001$) and for lower density samples ($p < 0.001$).

Conclusions These results suggest that longer screws provide reduced risk of cut-out failure, i.e. distalisation and/or varisation of the head fragment, and thus may decrease failure rates in proximal humeral fractures treated with angular stable plates. These findings require clinical corroboration and further studies to investigate the risk of screw perforation.

Keywords Proximal humerus fracture · Locking plate fixation · PHILOS plate · Fixation failure · Screw length · Finite element analysis

Introduction

The quantitative effects from variations in screw length when fixing osteoporotic proximal humeral fractures with locking plates are not known. Overall complication rates in proximal humeral fractures have been shown to be up to 49% [1–5], with causes including screw cut-out, varus angulation, fixation failure (occurring in 18.4% of cases [3]), infection and nerve injury. Screw cut-out has been reported at 6–8%, potentially occurring as a secondary event due to varus collapse [3]. These fractures frequently occur in patients with poor bone stock; unstable fracture patterns in osteoporotic bone represent a challenging scenario that surgeons frequently encounter. It is also the target group where the need for improvement is the highest. Locking plates have transformed fracture fixation and continue to be the most common operative method employed [2, 6]. However, the patient's bone density greatly affects the strength of the created constructs [7, 8]. Analysis of the bone density distribution within the humeral head has shown that it rapidly reduces with increasing distance from the cortical surface

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[9]. This potential implies that stronger fixation would be possible with longer screws; screws abutting the subchondral bone have been shown to generate larger pullout forces than screws 5 mm shorter [10].

Research is required to maximise the use of implants and understand the consequences from variations in fixation methods and techniques, especially related to the risks of failure, such as screws cutting out of the humeral head under loading. This can result in loss of reduction by distalisation and/or varisation of the head fragment. However, the multifactorial nature of these risks can make experimental discoveries difficult. To explore this, we developed [11] and validated [11, 12] a computational osteosynthesis testing kit and applied it to address fixation placement questions. This has shown that experimental cyclic construct failure of proximal humerus plating can be predicted via finite element (FE) analysis [11]. We hypothesised that longer screws would reduce the risk of screw cut-out failure under physiological loading schemes when modelled using our testing kit.

Materials and methods

Forty-two humeri were digitally processed using high-resolution peripheral quantitative computer tomography (HR-pQCT, XtremeCT, Scanco Medical AG, Brüttisellen, Switzerland) scans from a previous study [9]. These were sourced under appropriate local ethical guidelines. All were left-sided humeri from 18 females and 24 males, age range 64–98 (median 82 years). The bone mineral density (BMD) of the humeral head region was evaluated with the method proposed by Krappinger et al. [13]. The average BMD was 120.6 ± 25.5 mg/cm^3 (mean ± SD), with a range of 68.9–178.2 mg/cm^3; the mean was used to separate the samples into lower and higher BMD categories. Unstable three-part proximal humeral fractures AO/OTA 11-B3.2 with medial comminution and mal-reduction (gapping between the articular and greater tubercular fragments), though maintained pre-fracture coronal and sagittal alignments, were simulated on each sample via virtual osteotomies. The fractures were fixed with a PHILOS plate (DePuy Synthes, Zuchwil, Switzerland) using three locking screws distally to connect to the shaft fragment and six locking screws [rows A, B and E (Fig. 1)] to fix the proximal fragments to the plate. The plate was positioned according to the surgical technique manual; being 5–7 mm distal to the tip of the greater tubercle and 2–4 mm posterior to the bicipital groove [14]. Screw lengths were standardised based on the distance from the screw tip to the medial subchondral cortical surface when measuring along the screw axis, defining the tip-joindistance (TJD). The surgical technique recommends that the tip of the screw be located approximately 5–8 mm below the joint surface [14]. The screw length was adjusted in the

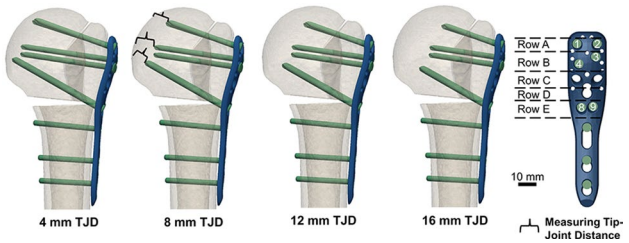

Fig. 1 Screw hole configuration utilised and method for measuring tip-joint-distance. Screw holes numbered 1–4, 8 and 9 identify the individual screws

models automatically to match the prescribed TJD, including the modelling of commercially unavailable screw lengths to ensure the TJD remained as targeted.

The models were meshed using Simpleware v7.0 (Simpleware Ltd., Exeter, UK). All materials were modelled as linear elastic, with the stiffness of the bone elements based on the BMD values sourced from the CT scans. Each model was subjected to three physiological loading modes replicating simple motions that can occur in the early post-operative phase of restricted range of motion: (i) 45° shoulder abduction with 0° internal rotation; (ii) 45° shoulder abduction with 45° internal rotation; and (iii) 45° shoulder flexion with 0° internal rotation. The glenohumeral load and the forces of the infraspinatus, supraspinatus, subscapularis and deltoid muscles were obtained with musculoskeletal models in Anybody (AnyBody Technology A/S, Aalborg, Denmark), which estimated these forces for each motion via inverse dynamics simulations [15]. The magnitude (ranging between 317 and 342 N; corresponding to approximately 40% body weight of an average person of 80 kg) and direction (angle in the frontal plane, versus vertical, ranging between 22.8° and 38.9°) of the joint reaction forces were in good agreement with the data available in the OrthoLoad database (http://www.orthoload.com) that were acquired using instrumented prostheses [16, 17]. The FE simulations were performed in Abaqus 6.13-3 (Simulia, Dassault Systemes, Velizy-Villacoublay, France). The outcome measure of the FE models was average compressive principal strain in a cylindrical bone region around the tip of the proximal screws, which has been demonstrated previously to be strongly correlated ($R^2 = 0.9$) with the biomechanically measured number of cycles for construct failure [11], representing loss of reduction in a cut-out mode, i.e. residual distal displacement of the head fragment. All pre-processing, analysis and post-processing methods were previously established by this group [11, 12] and performed in a fully automated way without user interaction.

To investigate the effect of screw length, testing was performed in two phases. In the first phase, four study groups were defined. All six proximal screws within this phase were

selected to have the same TJD from the subchondral bone; being either 4 mm, 8 mm, 12 mm or 16 mm. Results from these tests were stratified by BMD. A second phase was used to evaluate the individual influence of each proximal screw. Here, six further study groups were defined by sequentially shortening only one of the six proximal screws from the original 4 mm to 8 mm TJD whilst keeping the other five screw TJDs at 4 mm.

All statistical tests were performed with R v3.3.3 [18]. Normality of the data was evaluated with the Shapiro–Wilk test. For the first phase, as the data was found to be non-normal, the results of all four groups were compared with a Wilcoxon signed-rank test with Bonferroni corrections for multiple comparisons. Spearman correlation was used to assess the effect of screw length variation as a function of BMD on changes in the peri-screw bone strains. For the second phase analysis, Wilcoxon signed-rank tests were used, with Bonferroni corrections for the multiple tests. For all tests, statistical significance was defined as $p < 0.05$.

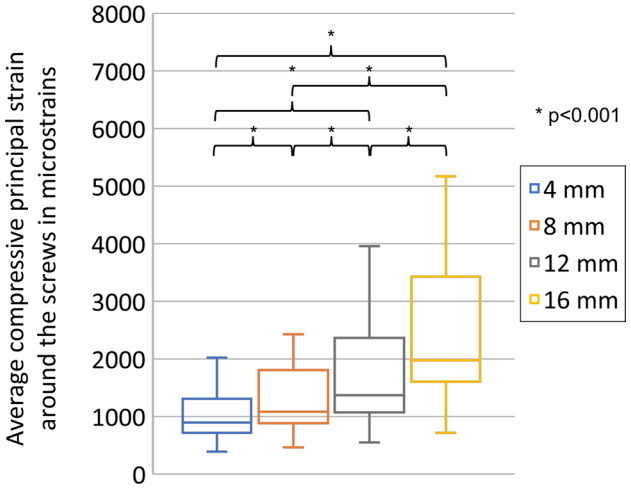

Fig. 3 Box and whisker plot showing the effect of varying the tip-to-joint distance of all proximal screws from 4 to 8, 12 or 16 mm, with significant changes in the peri-screw strain seen for each 4 mm screw shortening

Results

Shorter tip-joint distances were associated with smaller bone strains around the screw tips (Fig. 2), meaning reduced predicted screw cut-out failure. In phase 1, as TJD increased, an exponential increase in average bone strain around the screws was found, with significant ($p < 0.001$) differences between all groups (Fig. 3). Increasing TJD from 4 to 8 mm, 8 to 12 mm and 12 to 16 mm created increases in average bone strains of $24 \pm 9\%$, $28 \pm 10\%$, and $40 \pm 12\%$ respectively ($p < 0.001$ for all comparisons including 4–12 mm, 4–16 mm and 8–16 mm).

When increasing the TJD from 4 to 8 mm, in all loading modes, the peri-screw bone strains were proportionally more affected in the lower density samples compared to the higher density humeri [average adjusted $R^2 = 0.37$, $p < 0.001$ (Fig. 4)]. This effect was also seen for the other length change comparisons (8–12 mm: adjusted $R^2 = 0.27$, $p < 0.001$; 12–16 mm: adjusted $R^2 = 0.24$, $p < 0.001$). The dependence on density was 62% greater with the 12–16 mm contrast compared to the 4–8 mm.

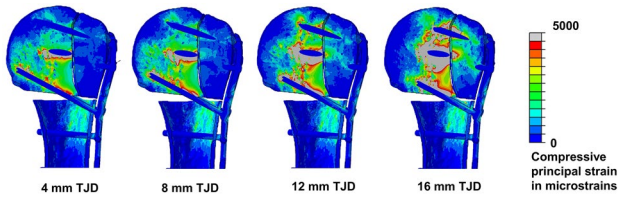

Fig. 2 Contour plot of compressive principal strain predicted by the finite element simulations, showing increasing bone deformation when shortening the screws

When changing one screw's TJD in isolation to 8 mm, whilst maintaining 4 mm for the others (phase 2), significant ($p < 0.001$) increases in the strain around the screws were seen in all except when the anterosuperior screw was changed to 8 mm in two loading modes ($p = 0.9$ and $p = 0.24$) and when the posterosuperior screw was changed to 8 mm in another mode ($p = 0.48$) (Fig. 5). The greatest change in peri-screw bone strains was seen with changes in the length of the calcar screws (screw numbers 8 and 9).

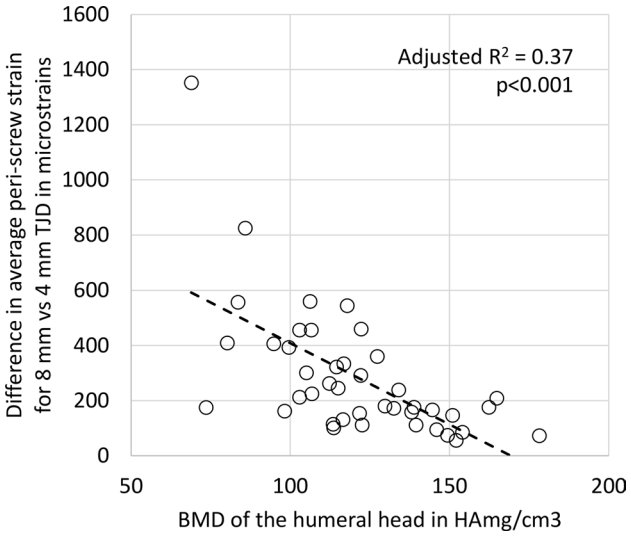

Fig. 4 Difference in peri-screw strain when all screws shortened from 4 to 8 mm as a function on bone mineral density, averaged for the three loading modes, showing larger effects for lower density humeri

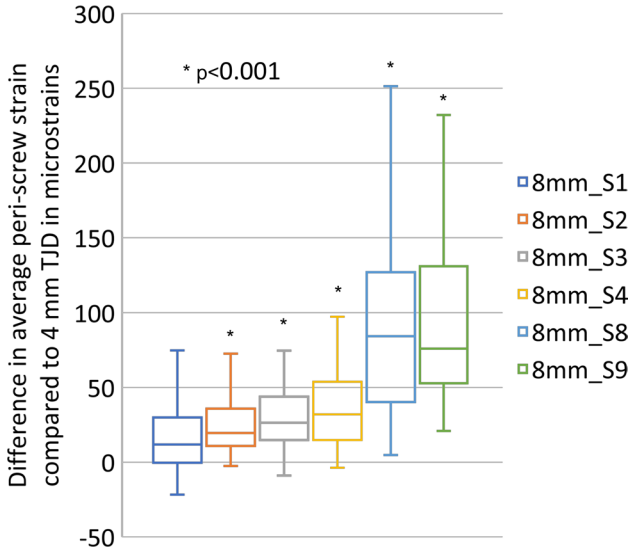

Fig. 5 Average peri-screw strain changes when the tip-to-joint distance of one of six proximal screws changed to 8 mm (with the others remaining at 4 mm)

Discussion

Using our computational osteosynthesis tool kit, the predicted risk of mechanical cut-out failure significantly increased with greater screw tip distance to subchondral bone, especially in lower bone densities.

To the authors' knowledge, no work has quantitatively shown the effect of screw length on the predicted failure risk, nor the impact at different bone densities. Knowing this establishes the measurable importance of screw length on failure risk. In the present study, in 15 out of the 18 tests even small variations (from 4 to 8 mm) of an individual screw length significantly ($p < 0.001$) increased the risk of screw cut-out failure, most dramatically with the calcar screws. Based on this, we advise that special emphasis should be placed on ensuring that the calcar screw lengths are carefully selected.

Fixation has been shown to be enhanced using calcar screws, their importance being seen both biomechanically [3, 19] and clinically [7, 20]. Their key role is expressed in this study given the considerably differences even with 4 mm shortening in their length. Interestingly, we found that reducing the length of the posterior or the anterior calcar screw had a similar effect. It is postulated that the bone mineral density is changing more rapidly in the region of the calcar screws compared to regions around other screws when shortening their length. Thus, changes in the screw lengths in the calcar area have comparatively greater impacts on purchase than length variations in other parts. Whilst investigating the exact reasons behind these findings is beyond the scope of the present study, the results of our simulations incentivise extra attention to ensuring that calcar screws tips are located no more than 8 mm from the joint surface, as per the recommended surgical technique [14].

The uncertainties regarding the role for fixation in managing proximal humeral fractures [21] may in part be due to poor and/or variable surgical techniques and experience [22], and a failure to understand ways to maximise the fixation possible with the implant. Retrospective analysis of patients' radiographs has shown that the quality of reduction achieved predicts clinical and radiological outcomes [3, 23] and that leaving screws absent from constructs increases rates of fixation failure [3]. However, these studies have not analysed the effect of screw tip distances from the cortex, merely the impact when certain screws were present or absent. One study by Padegimas et al. found, in a series of 161 patients, a trend ($p = 0.21$) towards a difference in the distance from screw tips to the subchondral surface of 12.6 mm in fixations that failed and 10.9 mm in fractures that healed [23]. Both of these distances are above the recommended screw tip distance in the surgical guide (suggesting placement should be 5–8 mm from the joint surface [14]).

Ultimately, screw length selection may be viewed as a balance between screw purchase (to reduce cut-out) and the risk of screw perforation either intra- or post-operatively. Results of this study suggest that screw purchase improves exponentially with longer screws. Whilst the prevalence of screw perforation is reported at 6–8% [7, 8], the mechanisms causing it are unclear, though likely due to surgical techniques [1, 24]. It is thought that perforation is greater should the humeral head collapse into varus during healing, which has even led to the idea of leaving the superior screws shorter than would be done otherwise in anticipation of failure and collapse [1]. However, the findings of this study indicate that this may be a self-fulfilling prophesy due to the increased chance of fixation failure caused by varus collapse from having shorter screws [23].

The tactile feedback when drilling and measuring holes can make manual assessment difficult, especially within 4 mm of the cortex, and aggressive targeting of such a length may potentially increase the risk of intraoperative cortex penetration. Techniques such as only drilling the lateral cortex [1] or drilling in reverse to negate the cutting tips of the drill bit [24] have been suggested as methods to enable more accurate awareness of where the limit of the subchondral bone is. Whilst this study shows that there is a difference between screws placed 4 or 8 mm from the subchondral bone, the greatest effect on predicted failure risk, and likely greatest clinically relevant finding, is seen when screw tips are located further than that recommended by the surgical technique guide (5–8 mm) [14]. This finding underlines the relevance of these guidelines by demonstrating the exponential increase of predicted failure risk with shorter screws. At a minimum, efforts should be primarily focused on getting

all screws to within 8 mm of the subchondral surface rather than targeting 4 mm TJDs for specific screws. Using the techniques stated may reduce perforation risk alongside performing meticulous examination of intraoperative fluoroscopy to ensure that the correct screw lengths are chosen; intraoperative targeting aids [14, 25] would help greatly with this aspect of the operation to enable deep, but safe screw placement.

This study utilised a novel and advanced osteosynthesis tool kit validated based on biomechanical tests. The benefits of using computational simulations for predicting bone competence have been established [26] including their role in evaluating bone implant systems [26, 27]. A few computational studies have addressed issues related to proximal humeral fixation [28–30], but all have limitations, such as being based on only a single patient, using simplified material properties or simple loading conditions and/or not being validated biomechanically. In comparison, our model is constructed using data from 42 patients and was tested in three physiological loading modes, vastly increasing the generalisability and transferability of the results to encountered clinical populations. Additionally, the strains around screw tips predicted by these models have been demonstrated to predict cyclic construct failure.

An advantage of FE models is that they allow the investigation of details that are not available in biomechanical testing, such as the contribution of individual screws. Our model computed the equivalent of 10 screw configurations in 42 humeri under three physiological loading schemes; the ethical and financial implications of an equivalent in vitro study would be prohibitive. Biomechanical study designs often use contralateral pairing to reduce the variation that may be seen from using bones from different cadavers. However, significant differences between pairs in terms of anatomy and bone density have been shown [31], potentially limiting the reliability of the comparison, whilst additionally only allowing for assessment of two study groups. Our experiments simulated three loading modes seen postoperatively. Whilst there are examples of sophisticated biomechanical test setups of physiological loading [32], most loading modes frequently employed in biomechanical testing utilise failure schemes that may not properly represent functional situations [1, 19]. While experimental testing is still the state-of-the-art technique to evaluate biomechanical behaviour of implant fixations, the advantages of numerical simulations are expected to complement and partially replace aspects such as reducing the number of specimens needed for testing.

However, there are limitations with the methods employed in this study. Though well validated, the model used, and thus the results generated, may not represent all failures seen in clinical situations. The results are limited to the assessment of mechanical cut-out, distalised loss-of-reduction-type fixation failure observed in our biomechanical validation experiments and may not be applicable to other failure modes. Indeed, only primary implant stability behaviours related to screw tip cut-out were modelled and there was no assessment of the risk of late screw perforation. The mechanisms and risks for secondary screw perforation are not known, including whether longer screws increase or decrease its occurrence either intraoperatively or during healing. The screw lengths used in the models were selected to ensure that the TJD remained exactly as intended, meaning that commercially unavailable screw lengths were used. This is unrealistic as screw lengths are clinically only available in 2 mm increments. However, the nature of this experiment requires screw lengths that are sufficiently adjustable to not introduce another variable to the testing. Additionally, as screws are available in 2 mm intervals (at least up to 50 mm in length [14]), screw placement can be achieved within a maximum accuracy of 2 mm of wherever they were sited in the model, and within 4 mm of the cortex.

Despite the benefits of computational modelling, especially with the extensive volume of patient data used in its design and validation, clinical corroboration through implementation and analysis of these biomechanical findings remains a requirement. Nevertheless, the numerous variables of proximal humeral fracture fixation (such as plate position or cement augmentation) imply that such clinical validation would require thousands of patients to be appropriately powered.

Conclusions

Finite element analyses in this study indicate that, in proximal humeral fractures treated with angular stable plates, longer screws are beneficial in reducing the risk of cut-out type fixation failures. Surgeons should be aware of the considerable increases in the predicted risk of cut-out failure even when one screw is 4 mm shorter, with these effects greater with reduced bone density and especially when being outside of the TJD range (max 8 mm) suggested by the surgical guide. These findings are seen most noticeably in variations in the lengths of the calcar screws, further emphasising the importance they play in proximal humeral fixation. Clinical judgement will continue to be required to balance the risks of cortex penetration against fixation failure from shorter screws, but should become easier and safer in the future with advancements to intraoperative targeting aids. Further clinical studies are required to confirm the findings of this computational study.

Funding This study was performed with the assistance of the AO Foundation via the AOTRAUMA Network (Grant No.: AR2013_01).

Compliance with ethical standards

Conflict of interest The authors are not compensated and there are no other institutional subsidies, corporate affiliations, or funding sources supporting this work unless clearly documented and disclosed.

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