Biology and Biomechanics in Osteosynthesis of Proximal Humerus Fractures

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Abstract

Surgical treatment of proximal humeral fractures still remains a challenge. This is primarily due to the fact that sufficient implant fixation in humeral head fractures is often not achieved due to substantial bone tissue loss with increasing age. In the last few years the locking plates and locking nails have been introduced into clinical practice with varying results. The biomechanical studies have focused on locking plate osteosynthesis as well. The following paper focuses on bone quality, biomechanical studies and biology of proper osteosynthesis and reviews the most recent literature.

Key Words

Proximal humerus fracture · Biomechanics · Locking plate · Locking nail · Bone mineral density

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Introduction

A threefold increase of proximal humeral fractures is expected until 2030 [1]. Especially women undergo the highest age-specific incidence of proximal humeral fractures [2]. Co-morbidity is increasing, as well [3]. Compared to undisplaced two-part fractures, which have a good prognosis with conservative treatment, the management of displaced fractures remains controversial. It is widely agreed that early mobilization after surgical procedure is a key feature of good functional outcome. A variety of fixation techniques have been advocated, including plate osteosynthesis, minimally invasive procedures such as percutaneous fixation, intramedullary nailing, tension band wiring, buttress plating and blade plate [4]. The change of emphasis from mechanical to biological priorities of internal fixation has led to the principles of ''biological internal fixation''. It is based on the use of locked internal fixators, which have minimal bone contact, long-span bridging and fewer screws [5]. The first clinical experiences have been described for the metaphyseal regions of distal femur [6], proximal tibia [7] and proximal radius [8].

Surgical treatment of proximal humeral fractures still remains a challenge. This is primarily due to the fact that sufficient implant-fixation in humeral head fractures is often not achieved due to substantial bone tissue loss with increasing age [9].

Age- and Gender-Related Bone Quality in the Proximal Humerus and its Impact on Implant Anchorage

Loosening of implants are serious complications following surgical treatment of proximal humeral fractures. Although the importance of bone quality has been emphasized for successful outcome of these surgeries, only a few studies have investigated a real bone mineral density of the humeral head. Knowledge about bone strength is important for the understanding of the origin of fractures as well as for optimising fracture fixations in weak bone [9–14]. As early as 1947, Berndt [15] demonstrated definitive age- and sex-related differences in bone structure and density of the proximal humerus by means of X-ray analyses. In 1963, Hall et al. [16] found, in their radiological structure analyses of cadaveric proximal humeri, an increasing age-dependent bone tissue loss especially beneath the area of the epiphyseal scar, the central area, and the area of the greater tuberosity. In contrast to the bone mass analyses of vertebrae and the proximal femur, only a few studies on bone mineral density of the proximal

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humerus had been performed [14, 17–20]. Some studies only referred to conventional X-ray [17] and dual X-ray absorptiometry (DXA). Others presented comparisons of computed tomography (CT) with mechanical testing [18, 20]. Saitoh et al. [14] performed Dual Photon Absorptiometry and mechanical testing. However, that study was limited to embalmed human cadavers. Extensive analyses of the proximal humerus in regard to the bone mineral density (BMD) and its relation to this bone's strength were not yet available. In the last few years intensive work was performed to analyse the regional differences in bone quality and their effect on the screw placement and led to in-depth information about bone mass distribution and bone strength of the proximal humerus [9–11, 21–23]. In an analysis of age- and gender-related characteristics of bone quality and bone strengths in a cadaver study we could demonstrate a statistically significant correlation between increasing age and decreasing BMD in female specimens. In contrast to male specimens, a significant decrease of the BMD was found in female individuals of age 70 years and older. In all age groups, the highest BMD was found in the most cranial aspects of the medial and dorsal regions of the proximal humerus (Figures 1, 2). Along with increasing age, the osseous density was found to constantly decrease at different levels and regions [9]. In further analysis, structural and connectivity parameters, bone strength, and trabecular orientation, showed region- and level-related characteristics [21]. For the proximal humerus, bone strength seems to be related primarily to the number of trabecular connections. Maximum bone quality and quantity were observed in the medial and dorsal aspects of the bone. We concluded that screws should be placed in exactly those areas of maximum bone stock. Plates should be designed in a way to take into account the findings, allowing an anchorage in the medial, dorsal, and cranial aspects of the proximal humerus. Stabilization must protect, not weaken, the existing trabecular network. Tingart et al. [23] investigated the 3-dimensional trabecular bone mineral density (BMD) in the humeral head and determined the effects of trabecular BMD on the pullout strength of cancellous screws. They concluded that trabecular BMD of the humeral head has a significant effect on the pullout strength of cancellous screws. On the basis of their results and in accordance with the findings of Liew et al. [22], placement of cancellous screws in the superior-anterior region of the humeral head should be avoided, whereas the central region is deemed to be more favorable. The differing conclusion to our results is due to a methodological difference. As we analysed

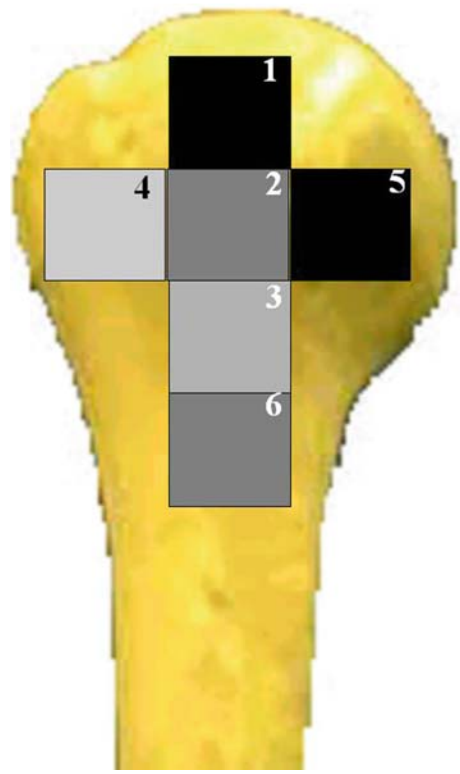


Figure 1. Schematic results of dual X-ray absorbtiometry (DXA) of the proximal humerus with regions of interest (*1* proximal, *2* central, *3* distal, *4* lateral, *5* medial, *6* shaft). The regions of same grading of coloration showed no significant difference in BMD. The *darker* the coloration the higher the BMD value.

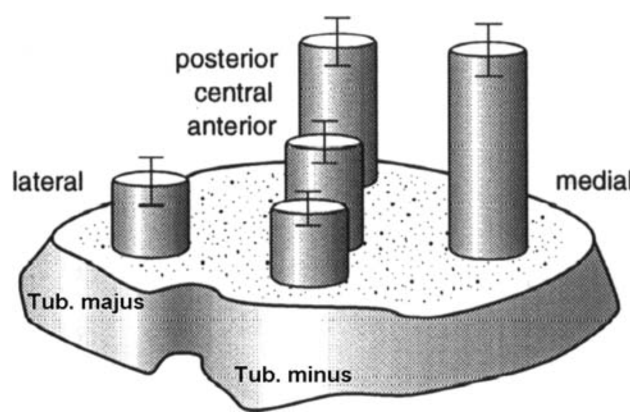


Figure 2. Schematic illustration of the region dependent distribution of BMD of the proximal humerus.

the clinical relevant regions of the complete proximal Humerus (Figures 1, 2), including Tub. minus and Tub. majus, Tingart et al. and Liew et al. [22, 23] cut the proximal humerus at the anatomical neck and considered the head fragment alone.

Figure 3. Axial view of the proximal Humerus with different locking plate configurations. *Plus* region with lower bone strength, *asterisks* region with higher bone strength. *Left* anchonrage of a standard locking plate (LPHP®): the screws are not optimally anchored in the region of good bone strength. Middle: proper anchorage of the screws in region of high BMD with a polyaxial plate (Humeral Suture Plate, Arthrex) *Right* disadvantage of polyaxial option with improper anchorage of the screws outside the region of higher bone strength (Humeral Suture Plate, Arthrex).

Locked-plate fracture-fixation techniques and designs continue to evolve and are taking into account the findings of bone quality in different regions. Polyaxial locking plates that allow screw angulation and end-point locking have become available. On the one hand they facilitate a well-directed placement in regions of high bone strength. On the other hand improper placement may lead to early loosening or loss of reduction (Figure 3). However, to our knowledge there are no *in vitro* or clinical data documenting their strength and efficacy at the proximal humerus.

In vitro Biomechanical Studies: Results and Limits

Implant fixation in patients with osteoporosis poses a great challenge to our surgical experience and the suitability of the implant. A central question for the clinician is: how stiff does an implant need to be? Additionally, stabilization of the proximal humerus fracture has to both minimize the soft-tissue damage, and allow sufficient fracture stability for early functional treatment.

In the last few years the locking plate has been introduced into clinical practice with varying results [24–34]. The biomechanical studies have focused on locking plate osteosynthesis as well [35–43]. The stability of an osteosynthesis after proximal humeral fracture is very difficult to determine *in vivo*, because the fracture is subject to varying stress, and the quality of the bone shows a wide degree of variation [39]. The number of scientific papers concerning biomechanical investigations of proximal humerus osteosynthesis is high [37–52]. But these studies differ in implant selection, experimental set-up, fracture situations, loading applications and definitions of implant failure, which makes a comparison between them impossible. In studies we hypothesized that under cyclic loading, stiff implants would lead to an earlier load reduction due to failures of the bone-implant interface than elastic implants [38, 39]. A goal of the studies was to develop an experimental set-up that would take into account clinically important fracture displacements, and quantify the stability of the osteosynthesis under approximately physiological loading. A further aim was to compare conventionally designed implants for fracture stabilization at the proximal humerus with more flexible implant solutions, while looking at the implant-bone anchorage in the weakened osteoporotic bone. The results were intended to lead to a better understanding of the load transfer in fracture stabilization, particularly in patients suffering from weakening of bone, e.g., osteoporotic bone.

The humerus T-plate represents a large and stiff standard implant which involves a high risk to the surrounding soft tissues and, due to the lack of angular stability of the plate-screw connection, frequently leads to screw loosening in the humeral head [53]. Locked plate implants appear rather elastic and allow a minimally invasive surgical approach. In comparison with the conventional implant designs, these new ones appeared to be rather too flexible and not sufficiently stable to allow a rigid fixation even in complex fracture situations. In the light of this question, conventional and rather stiff implants needed to be compared with the rather elastic new design concepts. It was therefore the goal of our studies to compare the stiffness and stability of different implant concepts for the treatment of fractures of the proximal humerus in elderly patients. Our investigations were carried out under standardized laboratory conditions. The applied boundary conditions represented critical fracture displacement: subsequent sintering, malrotation of the humeral head and varus displacement. The number of test cycles was set at 1,000; since in the preliminary tests and according to Wheeler and Colville [51], it has been shown that the highest load reduction and loss of fracture stabilization occur in the first 100 cycles. In response to axially applied loading, there was no statistically significant difference between the T-plate, nail und locking plate. Ruch et al. [48], who are the only authors to compare an intramedullary nail with the classic plate osteosynthesis, found a higher torsional stiffness of the intramedullary nail in comparison with the plate osteosynthesis. This is in contrast to our results. This could be caused by the multiplanar locking device of the nail introduced by Ruch et al. [48]. Dalton et al. [54] demonstrated the advantages of the crossed locking device in regard to rotation and bending stiffness during mechanical investigations of humeral shaft fractures. Wheeler and Colville [51] as well as Ruch et al. [48] reported clear advantages of nail osteosynthesis and plate osteosynthesis over the K-wire osteosynthesis and/or tension band plus Ender nails with respect to torsional stiffness. The locking plate offers the advantage that two additional screws can be inserted in the humerus head in a crossed and angularly stable manner, thus further enhancing the stability of the fixation. Regarding torsional stiffness, the results lie between those of the nail and the T-plate on the one hand, and the screw osteosynthesis on the other. Here, the relatively poor torsion stiffness is also due to the elasticity of the plate. Bending stiffness at the proximal humerus has only been reported by a few groups [39, 42, 46, 48]. This is most likely due to the difficult experimental set-up required for bending loads at the proximal humerus. In agreement with these investigations, Ruch et al. [48] found the highest bending stiffness (varus) with plate osteosynthesis, followed by the intramedullary nail and Ender nails with tension-band wiring. The load application on the proximal humerus fracture *in vivo* is a complex event, comprising rotational, bending, compressive and distraction forces. Cyclic displacement testing in our studies was accomplished with the application of a varus-bending load. It represents a frequent physiological displacement of the proximal humeral fracture, which primarily occurs as the result of strong tension of the supraspinatus tendon. Secondary valgus displacements are rarely observed. The load reduction, which is an indicator of implant loosening and migration was the lowest with the locking plate and the highest with screw osteosynthesis. The locking plate also presented a low decrease in the slope, which means that it has a relatively low load level but presents itself in the test process as very stable with a low load reduction. This is primarily caused by the angular stability of the plate-screw connection, which exhibits little or no loosening under cyclic loading. The T-plate and the nail showed high load reductions, which indicate that stiff implants under load do not necessarily exhibit a low load reduction.

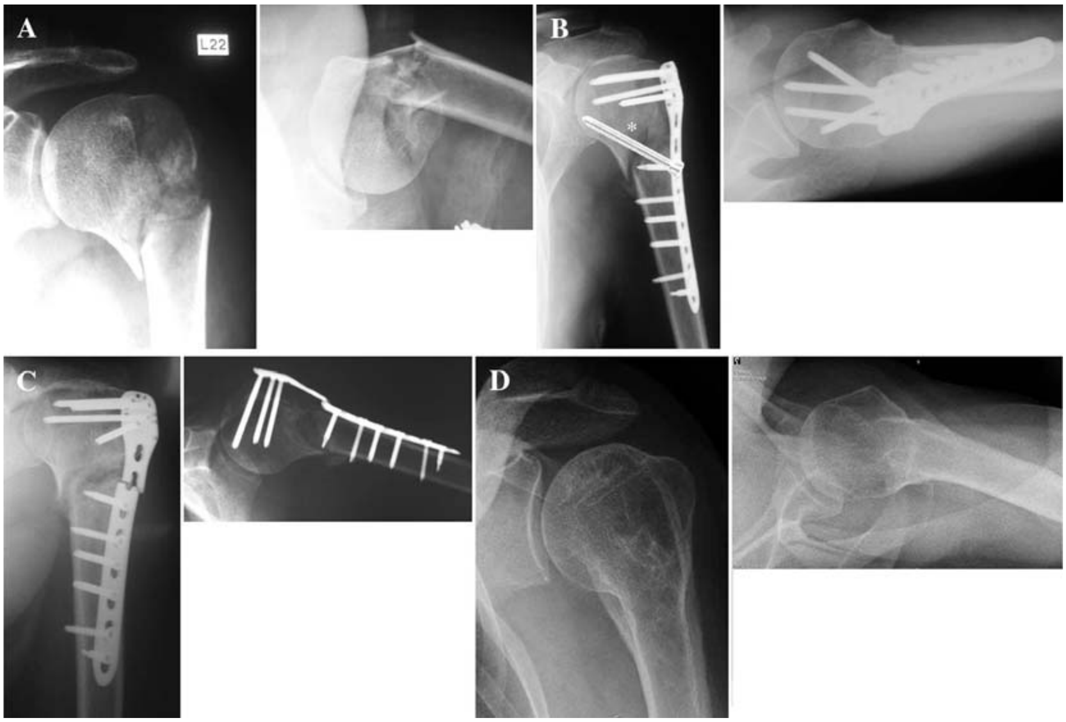
In summary, the results of cyclic testing on implant bone constructs revealed that stiff implants (T-plate and nail) exhibited a high initial maximum load with a high loading level, which did not however benefit the load reduction and the expected stability. In contrast, the more elastic locking plate showed a low load decrease with a low load level and a steady curve, which is promising for long-term stability.

In contrast to the above-mentioned results and recently published studies [41, 42], Hessmann et al. [55, 56] hypothesized that elastic implant properties of locked plates were not advantageous for the management of fractures of the proximal humerus. These differing results might be explained by the experimental set-up: Though performing cycles of axial loading and torque followed by load to failure they did not test clinical-relevant bending forces. Recently locking nail implants have been introduced into clinical practice [57]. In a biomechanical study Kitson et al. [58] pointed out higher stiffness of the locking nail compared with locking plate in bending in four different directions and torsion. However, no cyclic loading tests were performed showing the performance in the bone-implant interface.

The fracture model is a major limitation of most studies dealing with biomechanical properties in proximal humerus fractures. The two-part osteotomy model corresponds to the displaced two-part Neer fracture and the AO 11-A 3 fracture. Future biomechanical tests should take the multifragmentary three- and four-part fractures into account [37, 58]. Additionally the influence of rotator cuff forces is neglected in most of the existing models. Walsh et al. [59] present a novel approach including the rotator cuff in their experimental set-up. The mechanism of failure into varus corresponds to the force vector supplied by the rotator cuff. According to the authors, testing biomechanical stability of any proximal humeral fixation using the rotator cuff musculature intuitively reproduces a more physiologic failure mechanism. This is in contrast to the previous biomechanical studies in which the simulated failure mechanism involved a direct downward force on the humeral head or a distracting force at the surgical neck.

Locking Plate and Augmentation in Finite Element Analysis

Clinically, in rare cases augmentation is considered a final chance to achieve a somewhat stable reconstruction in complex fractures with weak bone stock and significant voids [60, 61]. The potential effect of



Figures 4a to 4d. a) Displaced proximal humerus fracture (2-part) with lacking medial support and metaphyseal fracture zone in a 71-year-old woman, *asterisks* schematic positioning of a screw placement for medial support according to [34], b) postoperative radiograph with locked plate osteosynthesis (LPHP®), c) plate breakage after three months presumably because of the absence of mechanical support of the medial region: "material surrendered to biology". The plate was removed after 6 months, d) fracture healing and remodelling after 45 months.

bone augmentation on the remaining bone stock as well as on the bone cement used remains unclear. Maldonado et al. [60] in a finite element analysis determined the straining of the intact and fractured proximal humerus under physiological-like loading conditions. Furthermore, they evaluated the impact of augmentation on tissue straining. Even though the analyzed locking plate was quite flexible as compared to the conventional osteosynthetic devices for the proximal humerus (T-plate, nails), cancellous tissue straining increased due to osteosynthetic treatment. Weak bone stock was found to be more strained than the healthy counterparts. In this respect, implant design considerations should not only account for implant stabilization in healthy but also in weak bone stock. They hypothesised that a more flexible cement augmentation would help to avoid excessive shear straining and thereby reduce the risk of failure at the bone–cement interface. Kwon et al. [61] in their biomechanical study concluded that the observations that calcium phosphate cement supplementation reduced interfragmentary motion during cyclic testing, increased construct stiffness, and increased torsional load to failure suggest that calcium phosphate cement indeed helps to stabilize the interface between the implant and the host cancellous bone and may help to overcome the deleterious effect of osteoporosis on fixation stability.

Biomechanical and Biologic Factors Influencing the Outcome *in vivo*

When locking plates are placed on the lateral proximal humerus, the mechanical environment is such that the fixed angle screws are required to act as perpendicular struts to support the humeral head fragment and resist varus displacement. This led Gardner et al. [34] to determine what patient factors, fracture patterns, reduction variables, and implant placements affect the mechanical stability of fracture fixation. They hypothesised that mechanical support of the medial column would be particularly important for establishing a stable construct. When this construct characteristic was considered, neither age, sex, nor fracture pattern was associated with loss of reduction. According to Gardner et al. failure to recreate a medial buttress may lead to early loss of reduction, and it seems that locking screws are unable to support the medial column without anatomic reduction or carefully placed inferomedial screws (Figure 4).

Hertel et al. [62] pointed out two major additional criterions having influence on "survival" of the humeral head: first the length of the medial metaphyseal head extension. The longer the extension the more likely the head is to be perfused. Second the integrity of the medial hinge. Integrity of the hinge is a predictor of both ischemia and the practical feasibility of reduction.

Conclusion

To successfully treat complex proximal humerus fractures and reduce the failure risk of the bone implant anchorage, precise information about the quality and distribution of trabecular bone within the humeral head is mandatory. Knowledge of the patterns of osteoporosis and their relationship to the bone mineral distribution and mechanical properties are the basis for an optimisation of implant anchorage in trabecular bone. In addition, knowledge of the distribution of bone strength through all ages allows prognostic statements about proximal humerus fractures. Future implant design should allow a more optimal implant-bone anchorage, leading to a structure-based development of implants and a reduced rate of postoperative dislocations and delayed unions.

Based on the literature and on the findings of our work it appears that less rigid and small-dimensioned implants exhibit advantages in dynamic loading in respect to rigid and over-sized osteoysnthetic devices. A sufficiently stable osteosynthetis – flexible enough to unload the implant-bone interface and rigid enough to minimize fracture movements – will prove success in the clinical use. Stiff, large implants should only be used in young patients with good bone stock. The importance of dynamic and flexible osteosynthesis at advanced age increases.

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