



Augmentation of plate osteosynthesis for proximal humeral fractures: a systematic review of current biomechanical and clinical studies

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Abstract

Introduction Secondary dislocation due to loss of fixation is the most common complication after plate fixation of proximal humeral fractures. A wide range of different techniques for augmentation has been described to improve the primary and secondary stability. Nevertheless, comparative analyses on the specific advantages and limitations are missing. Therefore, the aim of the present article was to systematically review and evaluate the current biomechanical and clinical studies.

Materials and methods The databases of PubMed and EMBASE were comprehensively searched for studies on augmentation techniques for proximal humeral fractures using defined search terms. Subsequently, all articles identified were screened for eligibility and subdivided in either clinical or biomechanical studies. Furthermore, the level of evidence and study quality were assessed according the Oxford Centre for Evidence-Based Medicine and the Coleman Methodology Score, respectively.

Results Out of 2788, 15 biomechanical and 30 clinical studies were included. The most common techniques were structural allogenic or autologous bone grafting to enhance the medial support, metaphyseal void filling utilizing synthetic bone substitutes or bone grafts, and screw-tip augmentation with bone cement. Biomechanical data were available for structural bone grafting to enhance the medial support, void filling with synthetic bone substitutes, as well as for screw-tip augmentation. Clinical evidence ranged from level II–IV and study quality was 26–70/100 points. Only one clinical study was found investigating screw-tip augmentation. All studies included revealed that any kind of augmentation positively enhances mechanical stability, reduces the rate of secondary dislocation, and improves patients' clinical outcome. None of the studies showed relevant augmentation-associated complication rates.

Conclusions Augmentation of plate fixation for proximal humeral fractures seems to be a reliable and safe procedure. All common techniques mechanically increase the constructs' stability. Clinically evaluated procedures show reduced complication rates and improved patient outcomes. Augmentation techniques seem to have the highest significance in situations of reduced bone mineral density and in high-risk fractures, such as 4-part fractures. However, more high-quality and comparative clinical trials are needed to give evidence-based treatment recommendations.

Keywords Humerus · Augmentation · Cement · Allograft · Autograft

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Introduction

Proximal humeral fractures are among the most common fractures in the adult with an incidence of 304/100.000 [1]. At least 70% of all fractures occur in patients older than 65 years of age [2]. Osteoporosis-associated low-energy trauma account for the majority of injury patterns in the elderly [3–5]. As the population at risk continuously expands a profound understanding of the optimal treatment options for these fractures becomes more important [6].

In general, treatment options include a variety of operative and non-operative strategies, but evidence-based recommendations are missing. The majority of fractures,

especially with little or no displacement, is treated non-operatively with good clinical outcome [7–9]. Displaced and unstable fractures are often indicated for surgery according to the Neer criteria [10]. Open reduction and internal fixation with locking plates is the most widely performed procedure allowing for high primary stability in the osteoporotic bone [11]. Long-term clinical results show excellent and good results in approximately two-thirds of the patients. Unfortunately, moderate and poor results are still reported for one-third of all patients [12]. Unsatisfactory clinical outcome is often related to a significant rate of complications and subsequent revision surgery [13, 14]. Loss of fixation leading to secondary varus displacement of the humeral head and sometimes even articular screw penetration is the most common complication [15]. To prevent these particular complications, primary arthroplasty can be considered as an alternative in complex fractures. Nevertheless, arthroplasty shows inferior clinical outcomes when compared to uneventful clinical course after anatomic reconstruction [14, 16]. Therefore, many efforts have been made to improve the constructs' stability and to minimize the risk of locking plate failure.

In this context, the augmentation of locking plate osteosynthesis is an often reported and promising approach. An increasing number of biomechanical and clinical studies have been published. These studies evaluate a large variety of augmentation techniques in different biomechanical models and fracture situations using allografts, autografts, or synthetic bone substitutes. Most of the studies are retrospective outcome studies and the number of comparative studies is limited. An assessment and a comprehensive summary of the different techniques with regard to their specific limitations and advantages are missing. Therefore, the intent of the present study was to systematically review all available biomechanical and clinical studies investigating augmentation techniques to enhance plate fixation of proximal humeral fractures.

Materials and methods

The literature research was conducted in a sequential approach according to the principles of Evidence-Based Practice (EBP). Prior to the identification of articles, guidelines of national and international standard were discovered searching the databases of the “Guidelines International Network” (and <http://www.g-i-n.net/>) and National Guideline Clearinghouse (<https://www.guideline.gov/>). According to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (<http://www.prisma-statement.org>), a systematic review of the literature was then conducted [17]. The databases of PubMed and EMBASE have been comprehensively searched for

meta-analysis, systematic or narrative reviews, and primary clinical and biomechanical studies until January 2018 using various connections of the keywords “humer*” in combination with either “augment*”, “cement*”, “graft*”, “cancel*”, “allograft*”, or “autograft*”. Journals not published in English or German language have been excluded yielding 2788 relevant studies. Subsequent primary screening included the manuscripts title and abstract. Studies without an abstract were excluded and the full text was obtained if the abstract did not allow finding the defined inclusion and exclusion criteria. Studies investigating shaft fractures, distal humeral fractures, pathological fractures, prosthetic replacement, nerve damage, rotator cuff augmentation, or arthroscopic repair were excluded. To minimize selection bias, all reviewers independently screened each abstract and close read the gathered data of all articles. A cross-reference research was also conducted to obtain every available and relevant source and maximize accuracy. Subsequently, full-text articles were assessed for eligibility and excluded, respectively. We then subdivided the final studies in two groups containing biomechanical investigations and clinical trials. To define the quality of the studies, the Coleman Methodology Score (CMS) was utilized. It assesses the scientific quality using ten criteria, giving a total score ranging between 0 and 100 points. A score of 100 indicates that the study largely avoids chance, various biases, and confounding factors. The final score can be defined as excellent (85–100 points), good (70–84 points), fair (50–69 points), and poor (< 50 points) [18].

Results

Out of 2788 studies, 15 biomechanical and 30 clinical studies have been included. 2702 studies have been excluded according to the screening process and 58 full-text articles were assessed for eligibility. Subsequently, 13 studies have been excluded after full-text analysis due to the exclusion criteria (Fig. 1). The most commonly described techniques were structural allogenic or autologous bone grafting to enhance the medial support, filling the metaphyseal void with synthetic bone substitutes or bone grafts as well as screw-tip augmentation with bone cement (Table 1).

Biomechanical data were available for augmentation techniques enhancing the medial support by fibular strut ($n=5$) or bone block grafts derived from femoral heads ($n=1$) using cadaveric or synthetic bone models. Filling-the-void techniques have been described in three biomechanical studies, all using injectable calcium phosphate cements as synthetic bone substitutes. Furthermore, six studies could be identified using screw-tip augmentation with polymethyl methacrylate (PMMA) ($n=5$) or strontium-containing hydroxyapatite ($n=1$) (Table 2).

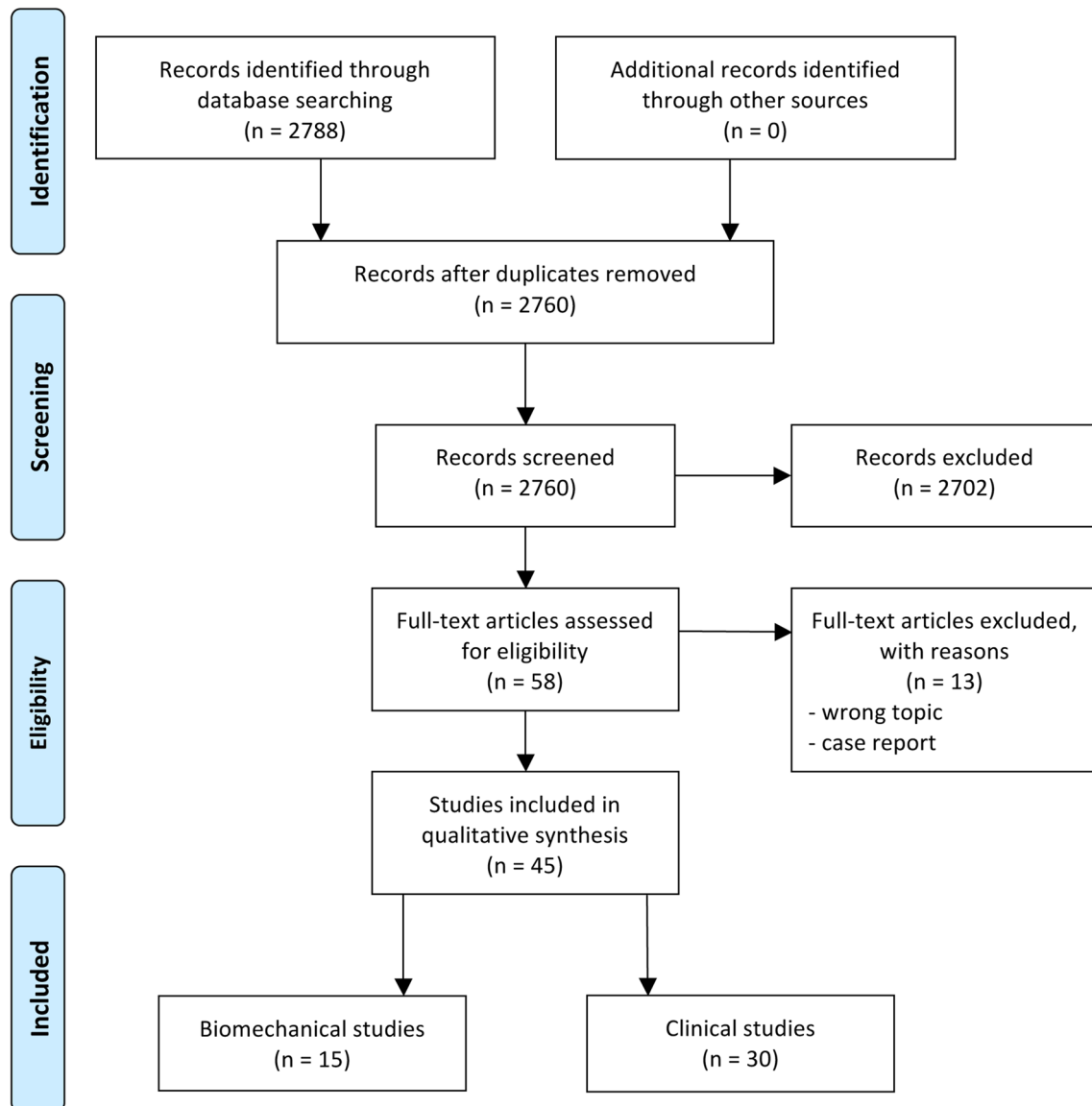


Fig. 1 Research protocol according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (<http://www.prisma-statement.org>) [17]

Nineteen clinical studies described structural bone grafting to enhance medial support. Allogenic bone grafts have been used in 15 and autologous bone grafting in four studies. Techniques for filling the metaphyseal void have been identified in 14 studies, using bone grafts, synthetic bone substitutes or metallic implants in eight, four, and two studies, respectively. One clinical study reported on 1-year clinical results after screw-tip augmentation. Clinical evidence ranged from level II–IV (LoE II: 1, LoE III: 9, LoE IV: 20 studies) according to the Oxford Centre for Evidence-Based Medicine. According to the CMS scoring system 23 studies revealed a poor, six studies a fair, and one study a good methodology (Table 3).

Biomechanical studies

Bone grafts to enhance medial support

A total of five biomechanical studies investigated on fibular strut grafts for augmenting the medial support. Mathison et al. investigated on augmented locking plates (Philos, Synthes, Switzerland) with an intramedullary fibular allograft under the stress of varus bending. Stiffness and failure load increased when using the strut graft by 3.8 and 1.7 times, respectively [19]. Osterhoff et al. used the same graft technique in single-plane abduction for unstable two-part fractures in a synthetic bone model. Fragment motion and

Table 1 Included studies summarized according to the augmentation type and principle for biomechanical and clinical studies

	Number	References
Biomechanical studies		
Structural bone grafting to enhance the medial support		
Fibular strut grafts	<i>n</i> = 5	[19–23]
Corticocancellous bone block from femoral head	<i>n</i> = 1	[24]
Filling the void		
Synthetic bone substitutes	<i>n</i> = 3	[25–27]
Screw-tip augmentation	<i>n</i> = 6	[28–33]
Clinical studies		
Structural bone grafting to enhance the medial support		
Allogenic	<i>n</i> = 15	[38–52]
Autologous	<i>n</i> = 4	[34–37]
Filling the void		
Allogenic bone grafts	<i>n</i> = 6	[48, 53–55, 61, 62]
Autologous bone grafts	<i>n</i> = 2	[56, 57]
Synthetic bone substitutes	<i>n</i> = 4	[58–60]
Metallic implants	<i>n</i> = 2	[43, 62]
Screw-tip augmentation	<i>n</i> = 1	[63]

change in gap distance were significantly less when using the strut graft [20]. Similar results were shown by Bae et al. who tested fibular allografts fixed by locking plates (Philos, Synthes, Switzerland) in axial loading for unstable three-part fractures. Displacement, stiffness and maximum load were significantly superior in augmented locking plates [21]. Chow et al. demonstrated no loss of reduction in unstable two-part fractures augmented by locking plates (LCP, Synthes, Switzerland) with an intramedullary fibula strut graft when applying varus force to the humeral shaft. No augmentation leads to an average of 75% collapse rate [22]. Lately, Hsiao et al. compared unstable two-part fractures augmented by a cortical bone allograft fixed with a locking plate (Unify, United Orthopedic Corporation, Taiwan) to no form of augmentation. The mechanical strength as measured by interfragmentary motion and maximum load to failure were doubled by the augmentation under cyclic axial loading [23]. Katthagen et al. compared non-augmented locking plates (Philos, Synthes, Switzerland) in osteoporotic specimens with and without calcar screws vs. an additional augmentation of the medial fracture gap with corticocancellous bone block grafts derived from femoral heads. The mechanical effect of additional calcar screws was non-significant when compared to no calcar screws, whereas bone block augmentation significantly increased the construct's stiffness and failure load [24].

Filling the void

Kwon et al. compared K-wire fixation vs. cloverleaf plates vs. blade plates each augmented with calcium phosphate cement or non-augmented in unstable three-part fractures.

All augmented implants showed superior results regarding interfragmentary motion and maximum load with the exception in abduction when using K-wires. The addition of calcium phosphate cement increased the stiffness of even the most osteoporotic specimens to levels that were higher than those of the most osteodense specimens that had been treated with internal fixation alone [25]. Gradl et al. tested calcium phosphate augmented locking plates (AxSOS; Stryker Trauma, Switzerland) in unstable two-part fractures under axial loading. They found higher values for stiffness and a maximum load to failure [26]. As much as 20% volume of the humeral head was replaced with calcium triphosphate by Kennedy et al. who then investigated locking plates (Arthrex Suture Plate, Arthrex, USA) in unstable three-part fractures under axial loading. With the void augmented, the mean difference in failure load changed to 300 N and interfragmentary motion was 1 mm and 6.4 mm for the augmented and non-augmented groups, respectively [27].

Screw-tip augmentation

Unger et al. tested PMMA (Traumacem V+, Synthes, Switzerland) augmented locking screws in unstable three-part fractures. The augmentation led to significantly increased cycles to failure in varus bending and axial rotation [28]. Röderer et al. presented similar results after augmenting only two locking screws aiming at the lowest bone mineral density. PMMA-augmented implants showed superior cycles to failure when compared to no augmentation [29]. The difference of screw-tip augmentation (Philos/PMMA, Synthes, Switzerland) in stable and unstable fracture models was investigated by Kathrein et al. For stable fractures,

Table 2 Biomechanical studies of augmentation techniques for proximal humeral fractures

References	Fixation/augmentation	Number of specimens	Grouping	Fracture model	Load direction	Testing protocol	Testing machine	Interfragmentary motion	Stiffness	Max. load to failure	Summary
Mathison et al. [19]	PHILOS (Synthes, Switzerland)/fibular strut autograft (same cadaver)	Six pairs	Two groups: strut graft augmentation ($n=6$) vs. no augmentation ($n=6$)	Unstable 2-part	Axial	Varus bending, displacement rate: 4 mm/min	Mechanical test frame (Type T30K, Lloyd Instruments)	Na	Stiffness increased in LPSG by 3.84 (1.9) ($p=0.005$)	Failure load increased in LPSG by 1.7 (0.54) ($p=0.02$)	The intramedullary bone peg significantly decreased the relative movement at the bone interface
Osterhoff et al. [20]	PHILOS (Synthes, Switzerland)/fibular strut graft (Fibula Left, Synbone)	20 composite analog humerus models (Synbone, Malans, Switzerland)	Two groups: strut graft augmentation ($n=10$) vs. no augmentation ($n=10$)	Unstable 2-part	Abduction	Single-plane abduction between 45°–60° simulated M. deltoideus and supraspinatus: 50 N–125 N, constant 25 N, speed: 300 mm/min, arm weight: 3.75 kg	UPM 1475; Zwick, Ulm, Germany	Intercyclic fragment motion in non-aug.: 5X higher than in augmented fragment migration and change in gap distance in non-aug.: 2X higher than in augmented. residual fragment gap deformation in non-aug.: 2X higher than in augmented. ($p=0.014$)	Na	Na	Medial support with strut graft augmentation increased overall stiffness and reduced migration of humeral head fragment
Bae et al. [21]	PHILOS (Synthes, Switzerland)/fibular strut graft	Seven pairs	Two groups: strut graft augmentation ($n=7$) vs. no augmentation ($n=7$)	Unstable 3-part	Axial	Cyclic axial loading: 10–80 N, 5 Hz, axial load to failure	Servo-hydraulic materials testing system (Model 8511; Instron, Norwood, Massachusetts)	Displacement: LPSG = 0.15 mm (0.02–0.27) vs. Lp = 0.63 mm (0.18–0.88) ($p=0.031$)	LPSG: 693.5 N/mm (551.2–882.3) vs. Lp: 292.3 N/mm (251.4–411.2) ($p=0.035$)	LPSG: 1985.5 N (1324.6–2505.4) vs. Lp: 1291.8 N (903.4–1754.3) ($p=0.024$)	Strut graft augmentation significantly increased maximum failure load and stiffness
Chow et al. [22]	LCP (Synthes, Switzerland)/fibular strut autograft (same cadaver)	Eight pairs	Two groups: strut graft augmentation ($n=8$) vs. no augmentation ($n=8$)	Unstable 2-part	Varus force	Force applied to shaft with immobilized head, cyclic loading: 110 N, force displacement rate: 600 mm/min	Synergie 400 materials testing system (MTS Systems, Eden Prairie, MN, USA)	Varus collapse: none in aug. vs. 6 in non-aug. ($p<0.05$), 25,000 cycles with no collapse vs. 6604 ± 1984 cycles average to collapse	Na	Na	Augmentation increased the ability to withstand repetitive varus loading and might help to treat osteoporotic fractures with medial comminution

Table 2 (continued)

References	Fixation/augmentation	Number of specimens	Grouping	Fracture model	Load direction	Testing protocol	Testing machine	Interfragmentary motion	Stiffness	Max. load to failure	Summary
Hsiao et al. [23]	Unify (locking plate, United Orthopedic Corporation, Taiwan)/corical bone strut graft	Ten humeri	Two groups: strut graft augmentation ($n=5$) vs. no augmentation ($n=5$)	Unstable 2-part	Axial	Cyclic axial load = 10–450 N, 1 Hz, load to failure = 5 mm/s displacement rate	Instron ElectroPuls E3000, UK	LPSG: 3.5 mm vs. Lp: 5.7 mm ($p=0.01$)	Na	LPSG: 1988 N (309) vs. Lp: 991 N (98) ($p<0.0001$)	The mechanical strength is doubled when locking plates were augmented with an intramedullary strut graft
Kaathagen et al. [24]	PHILOS (Synthes, Switzerland) / bone block from femoral head graft	32 humeri	Four groups: head screws only (basic setup) vs. basic setup + calcar screws vs. all screws as dynamic locking screws vs. calcar screws + augmentation with bone block	Unstable 2-part	Axial, rotational	Torsional load 3.5 N m with 0.1 deg/s in 0° tilting and 2 fixed fulcrums, vertical load 0.1 mm/s to max. 200 N in 20° abduction and adduction, cyclic axial loading 50–250 N, 1 Hz, axial load to failure with 0.1 mm/s	MiniBionix 858 (MTS, Eden Prairie, MN, USA)	Decreased fracture-gap deflection ($p=0.005$) with femoral allograft	Stiffness under axial compression 509 N/mm ($p=0.009$) and adduction 890 N/mm ($p=0.005$) increased with femoral allograft, calcar screws and dynamic locking screws did not influence stiffness	Increased with femoral allograft 1294 N, ($p=0.007$)	Augmentation with additional calcar screws or dynamic locking screws did not improve stiffness in an unstable 2-part fracture model. Using a femoral bone block seemed to be a reliable alternative way of augmentation
Kwon et al. [25]	Cloverleaf plate ($n=6$) vs. blade plate ($n=6$) vs. K-wires ($n=6$) / void filling with Norian SRS (calcium phosphate cement) vs. each fixation technique non-augmented	18 pairs	6 groups: all fixation devices augmented ($n=3$) vs. non-augmented ($n=3$)	Unstable 3-part	Abduction and external rotation	Cyclic abduction: 30°–120°, 0.1 Hz, compressive load: 0.2–0.5x body weight, cyclic external rotation: 0.1–2.1 N m, 0.5 Hz, compressive load: 10 N, external rotation to failure 1°/s	Biaxial servohydraulic machine (machine 8874, Instron, Canton, Massachusetts)	Abduction: significant less only when using K-wires ($p=0.028$) external rotation: cement superior with all implants ($p=0.043$, 0.08, 0.028)	Na	Rotation to failure: cement superior in all ($p=0.028$)	All tested parameters significantly improved by augmentation

Table 2 (continued)

References	Fixation/augmentation	Number of specimens	Grouping	Fracture model	Load direction	Testing protocol	Testing machine	Interfragmentary motion	Stiffness	Max. load to failure	Summary
Gradi et al. [26]	Proximal humerus locking plate (AxSOS; Stryker Trauma, Selzach, Switzerland)/void filling with HydroSet (Stryker) (calcium phosphate)	Eleven pairs	Two groups: void filling augmentation (<i>n</i> = 11) vs. no augmentation (<i>n</i> = 11)	Unstable 2-part	Axial	Varus bending, specimen restrained in 20° lateral angulation, 50–100 N, 0.2 Hz, axial load to failure	Servo-hydraulic materials testing machine (Zwick Materials Testing Machine 1445; Germany)	Na	Aug.: 117 N/mm vs. non-aug.: 79 N/mm (<i>p</i> = 0.04)	Aug.: 1936 ± 609 N vs. non-aug.: 1373 ± 590 N (<i>p</i> = 0.01) 28% higher median load to failure with augmentation	Augmentation decreased the rate of glenohumeral screw perforation in unstable 2-part fractures in a cadaveric model
Kennedy et al. [27]	Arthrex Suture Plate (Athrex, USA)/void filling with Hydroset injectable (Stryker) (calcium triphosphate)	14 humeri (11 donors, 3 pairs)	2 groups: void filling augmentation (<i>n</i> = 7) vs. no augmentation (<i>n</i> = 7)	Unstable 3-part	Axial	Cyclic axial loading, 100 N, 1 Hz, specimen fixed in 52.2° to horizontal plane, axial load to failure	Biaxial servo-hydraulic	Aug.: 1 mm vs. 6.4 mm in non-aug	Na	Mean difference in the failure load was 300 N (<i>p</i> < 0.05)	Construct stability and failure load improved significantly when humeral bone void was filled with calcium triphosphate cement
Unger et al. [28]	PHILOS (Synthes, Switzerland)/Screw-tip augmentation with PMMA (Traumacem V+, Synthes, Switzerland)	12 pairs	Two groups: screw-tip augmentation (<i>n</i> = 6) vs. no augmentation (<i>n</i> = 6)	Unstable 3-part	Axial and rotation, with head mounted in device allowing for free rotation in a-p plane	Varus bending, 15–85 N, 0.25 Hz, axial load to failure, axial rotation: constant 20 N axial load, 0.25 Hz, –3.0 to +3.0 N m, rotation to failure	Biaxial servo-hydraulic material testing machine (MTS, 858 MiniBionixII, Eden Prairie, MN, USA)	Na	Na	Varus bending: non-aug.: 583 cycles to failure (245.4 N) vs. 8516 cycles to failure in aug. (348.1 N) (<i>p</i> = 0.014), axial rotation: non-aug.: 2050 cycles to failure (5.62 N) vs. 3316 cycles to failure in aug. (8.79 N) (<i>p</i> = 0.003)	Augmentation is a feasible way to enhance screw anchor-plate but only seems reasonable in cases with low bone mineral density

Table 2 (continued)

References	Fixation/augmentation	Number of specimens	Grouping	Fracture model	Load direction	Testing protocol	Testing machine	Interfragmentary motion	Stiffness	Max. load to failure	Summary
Röderer et al. [29]	PHILOS (Synthes, Switzerland)/Screw-tip augmentation with PMMA (Traumacem V+, Synthes, Switzerland)	6 pairs	Two groups: screw-tip augmentation ($n=6$) vs. no augmentation ($n=6$)	Unstable 3-part	Axial	Varus bending: 15–85 N, 0.25 Hz	Biaxial servohydraulic material testing machine (MTS, 858 MiniBionixII, Shaikopec; MN, USA)	Na	Na	Aug.: 6900 ± 690 cycles (291.5 ± 24.2 N) vs. non-aug. 4600 ± 810 cycles (211 ± 28.7 N) ($p=0.01$)	For screws placed in areas with low bone mineral density augmentation might be a good way to enhance primary stability
Kathrein et al. [30]	PHILOS (Synthes, Switzerland)/Screw-tip augmentation with PMMA (Traumacem V+, Synthes, Switzerland)	Six pairs	Four groups: stable fracture/screw-tip ($n=3$) vs. no augmentation ($n=3$) vs. unstable fracture/screw-tip ($n=3$) vs. no augmentation ($n=3$)	Stable 2-part vs. unstable 2-part	Ab- and adduction	Cyclic abduction between 15 and 45°, 5 Hz	Customized shoulder test bench with active muscle forces	Stable fractures: no significant difference vs. non-aug. unstable fractures: aug.: max. 0.81° per cycle motion, max. -1.46° varus vs. non-aug.: max. 2.31° per cycle motion, max. -4.26° varus ($p<0.05$)	Na	Maximum resulting forces: 453 N in stable vs. 459 N in unstable	In an unstable fracture model, augmentation decreased the per cycle motion and varus deformation
Scola et al. [31]	PHILOS (Synthes, Switzerland)/Screw-tip augmentation with PMMA (Traumacem V+, Synthes, Switzerland)	6 pairs	2 groups: screw-tip augmentation ($n=6$) vs. no augmentation ($n=6$)	Unstable 3-part	Axial	Varus bending: 15–85 N, 0.25 Hz, axial load to failure	Biaxial servohydraulic testing machine (MTS, 858 MiniBionixII, MN, USA)	Aug.: 6900 ± 690 cycles vs. non-aug.: 4600 ± 810 cycles	Na	Aug.: 291.5 ± 24.2 N vs. non-aug.: 211 ± 28.7 N	Screw augmentation increased primary stability. Targeted augmentation in areas with low bone mineral density was almost as effective as untargeted augmentation with more cement

Table 2 (continued)

References	Fixation/augmentation	Number of specimens	Grouping	Fracture model	Load direction	Testing protocol	Testing machine	Interfragmentary motion	Stiffness	Max. load to failure	Summary
Schliemann et al. [32]	CFR-PEEK DiPhos-H plate (Lima Corporate, Udine, Italy)/Screw-tip augmentation of anterior directed head screws with PMMA (Traumacem V+, Synthes, Switzerland)	Six pairs	Two groups: screw-tip augmentation ($n=6$) vs. no augmentation ($n=6$)	Unstable 3-part	Axial	Cyclic loading with specimen in 25° lateral angulation, 1 Hz, 0.035 N-100 N, load to failure: 5 mm/min	Biaxial servohydraulic testing machine (Instron model 8874, Instron, Pfungstadt, Germany)	Motion at bone-implant interface: less with Lp + aug. at loads > 137.5 N ($p < 0.05$)	Lp: 453 (42.2) N/mm, Lp + aug.: 461 (64.3) N/mm ($p = 0.594$)	Mean load to failure: Lp: 669 (117) N, Lp + aug.: 706 (153) N ($p = 0.646$), max load: > 650 N	Screw-tip augmentation of anterior directed head screws significantly decreases motion between the bone-implant interface and might prevent varus collapse
Kuang et al. [33]	PHILOS (Synthes, Switzerland)/Screw augmentation with Strontium-containing hydroxyapatite bone cement	12 pairs	Two groups: augmentation ($n=12$) vs. no augmentation ($n=12$)	Unstable 3-part	Axial, rotational	Varus bending cyclic loading: 50–150 N, 2 Hz, 4000 cycles, Axial rotational cyclic loading: - 6 to + 6 N m for the first 2000 cycles followed by - 8 to + 8 N m for the second 2000 cycles, - 10 to + 10 N m for the third 2000 cycles, and - 12 to + 12 N m for the fourth 2000 cycles, 2 Hz, 8000 cycles	Biaxial servohydraulic material testing machine (Bose, 3510-AT, Eden Prairie, Minnesota)	Displacement: control: 10.4 mm (9.7–14.2) vs. augmented: 9.4 mm (8.9–10.3) ($p = 0.010$) Rotation: control: 4.9° (3.6–5.7) vs. augmented: 4.4 mm (3.8–4.5) ($p = 0.102$)	Compression stiffness: control: 1.7×10^5 N/m (1.2×10^4 – 2.1×10^5) vs. augmented: 2.3×10^5 N/m (1.9×10^5 – 3.54×10^5) ($p = 0.010$) Rotation stiffness: control: 15.9 N m/rad (9.7–26.7) vs. augmented: 11.5 (4.4–25.4) ($p = 0.337$)	Compression: control: 468.9N (321.36–904.24) vs. augmented: 958.59N (652.56–1248.13) ($p = 0.025$) Rotation: control: 9.08N (7.29–17.37) vs. augmented: 7.82 (3.28–20.92) ($p = 0.522$)	Sr-HA cement augments proximal humeral fracture fixation in terms of less maximal displacement per cycle, higher failure point, and stiffness in the humerus head construct in varus bending test. No significant difference was found between cemented control group and control group in axial rotational test

LPSG locking plate with strut graft, PMMA polymethylmethacrylate, CFR-PEEK carbon-fiber-reinforced polyether ether ketone

Table 3 Clinical studies of augmentation techniques for proximal humeral fractures

References	Fixation/augmentation	Study design/LoE/patient number	CMS	Age (years)	Follow-up	Fracture type	CS	DASH	Others	Related complication	Results
Walch et al. [34]	T plate (15) or blade plate (5)/autograft: tibia epiphysis ($n=6$), iliac crest ($n=11$), fibula ($n=3$)	Retrospective case-series/LoE: IV/ $n=20$	49	58 (21–83)	42 months (12–120)	Proximal humeral non-union	81.2 (61–100)	Na	Na	Total = 5 (stress fracture tibia = 3, fracture humerus = 1, rapture pectoralis major = 1)	The treatment of proximal humeral non-union with an intramedullary fixed autograft led to union rate of 94%
Ring et al. [35]	Blade plate/iliac crest autograft	Retrospective case-series/LoE: IV/ $n=25$	42	61 (22–80)	41 months (26–72)	Proximal humeral non-union	77 (43–98)	21 (1–53)	ESDS scale = 8 (0–25), ROM analysis	Total = 4 (persistent non-union = 2, fracture of the iliac wing = 1, blood transfusion due to iliac harvesting = 1)	Augmented blade plating provides stable fixation with good and reliable functional results when treating proximal humeral nonunion
Zhu et al. 2014 [36]	Fixed-angle locked plate/autologous iliac crest graft	Retrospective case-control/LoE: III/ $n=40$	53	51 (38–62)	25.4 months (13–48)	Neer: 4-part	Na	Na	SF-36: experimental group = 88 ± 5.7 vs. control group = 69.5 ± 9.5 ($p < 0.05$), VAS scale, ROM analysis	Total = 2 (group with augmentation = 0, group without augmentation = 2 (nonunion leading to total shoulder replacement))	Augmentation of locking plates with autografts showed superior clinical results with fewer complications when compared to no augmentation
Gao et al. [37]	Locking plate/fibular strut autograft	Retrospective case-series/LoE: IV/ $n=7$	39	58.4 (45–76)	22.7 months (15–36)	Surgical neck nonunion	77.7 (60–90)	Na	VAS scale = 0.57 (0–2), ROM analysis	Total = 2 (transient peroneal nerve palsy in the donor leg = 1, transient radial nerve palsy = 1)	Augmented locking plating of nonunioned surgical neck fractures resulted in bony consolidation in all cases without complication and further revision surgery

Table 3 (continued)

References	Fixation/ augmentation	Study design/ LoE/patient number	CMS	Age (years)	Follow-up	Fracture type	CS	DASH	Others	Related complication	Results
Gardner et al. [38]	PHP Plate (Synthes, Switzer-land)/ fibula strut allograft	Retrospective cohort study/ LoE: IV/n=7	37	62 (40–93)	3–6 months	Neer: 4-part	Na	Na	Na	Total = 3 (wound infection = 1, adhesive capsulitis = 2)	Support of locking plating with an intramedullary allograft helped to maintain reduction at short term follow-up
Badman et al. [39]	Fixed-angle locked plate/ intramedullary fibula or ulna strut allograft	Retrospective case-series/ LoE: IV/n = 18	26	60.4 (40–84)	26.5 month (12–49)	Proximal humeral non-union	Na	Na	ROM-analysis, VAS-scale, ASES-score	Total = 5 (persisting nonunion and blade breakage = 1, posterior cord neuropraxia = 2, adhesive capsulitis = 2)	The additional use of allografts to fixed-angle plating resulted in a union rate of 94% when treating proximal humeral nonunion
Rollo et al. [40]	PHILOS (Synthes, Switzer-land)/ extramedullary placed humeral shaft allograft	Retrospective case-series/ LoE IV/n = 16	44	62.3 (55–70)	32 (12–96)	Proximal humeral non-union	76.3 (68–88)	Na	SF-12 = 88.3 (64.3–88.4)	Total = 0	Medial extramedullary augmentation of locking plating of nonunioned surgical neck fractures resulted in bony consolidation in all cases
Neviaser et al. [41]	PHILOS (Synthes, Switzer-land)/ fibular strut allograft	Retrospective case-series/ LoE: IV/n = 38	42	65.5 (44.1–82.7)	49 weeks (49–155)	Neer: 2-, 3-, 4-part; AO/OTA: A2.A3.B1.B2.C1.C2.C3	87 (51–95)	15 (0–66.4)	SF-36 = 80 ± 18.5, ROM-analysis	Total = 5 (loss of reduction (varus collapse) = 1, partial osteonecrosis = 1, heterotrophic bone formation = 2, wound infection = 1)	Augmentation of locking plates with allografts reduced complication rates and led to good clinical results preventing joint replacement surgery

Table 3 (continued)

References	Fixation/ augmentation	Study design/ LoE/patient number	CMS	Age (years)	Follow-up	Fracture type	CS	DASH	Others	Related complication	Results
Matassi et al. [42]	Locking Plate (Philos, Synthes Switzerland ($n=9$), PERI-LOC, Smith & Nephew, USA ($n=8$)/ fibular allograft	Prospective case-series/LoE: IV $n=17$	57	62 (54–73)	28 months (13–56)	Neer: 3-, 4-part; AO/OTA: A, B, C	79 (56–100)	33 (22–52)	VAS scale = 1 (0–2), SF-36 = 83 (67–97), ROM-analysis	Total = 1 (superficial wound infection = 1)	Augmentation helped to stabilize the medial column and maintain reduction allowing for early physiotherapy with good clinical results
Hettrich et al. [43]	PHILOS (Synthes, Switzerland)/ fibular allograft ($n=23$) and endosteal semitubular plate ($n=4$)	Retrospective case-series/LoE: IV $n=27$	29	64.9 (44.1–80.1)	63.1 weeks (37–120)	Neer: 2,3 and 4-part; AO/OTA: A2,A3,B1,B2,C1,C2,C3	Na	Na	Na	Total = 4 (wound infection = 1, ectopic ossification = 3)	Endosteal allografts gave medial support maintaining operative reduction and preventing varus collapse
Little et al. [44]	PHP (Synthes, Switzerland)/ fibula strut allograft	Retrospective cases series/LoE: IV $n=72$	56	62 (26–90)	19 months (12–60)	Neer: 2-, 3-, 4-part; AO/OTA: A2, A3, B1, B2, C2	Varus group = 85.2 (10.3), valgus group = 88.7 (9.4) ($p=0.32$)	Varus group = 21.4 (19.7), valgus group = 13.9 (16) ($p=0.10$)	UCLA-score = 27.5 (14–35) ($p=0.32$), SF-36 = 85 (60–100) ($p=0.08$)	Total = 6 (superficial wound infection = 2, deep infection with revision = 3, avascular necrosis = 1)	There are no functional differences when comparing valgus and varus deformities of proximal humeral fractures when using augmented locking plates
Tan et al. [45]	PHILOS (Synthes, Switzerland)/ fibula strut allograft	Retrospective case-series/LoE: IV $n=9$	31	75.4 (62–86)	min. 12 weeks	Neer: 2-, 3-, 4-part	Na	Na	ROM-analysis	Total = 0	Strut graft augmentation minimized common complication found with low bone mineral density

Table 3 (continued)

References	Fixation/augmentation	CMS	Age (years)	Follow-up	Fracture type	CS	DASH	Others	Related complication	Results
Hinds et al. 2015 [46]	Locked plate construct/fibular strut allograft	62	63 (26–85)	34 months (12–83)	Neer: 2–4-part	Geriatric = 82.7 vs. non-geriatric = 86.3 ($p=0.12$)	Geriatric = 16.4 vs. non-geriatric = 15.2 ($p=0.28$)	UCLA-score: geriatric = 29.5 vs. non-geriatric = 28.9 ($p=0.63$)	Total = 1 (osteonecrosis with screw cut-out = 1)	No difference in clinical outcome for geriatric and non-geriatric patients both treated with locking plates augmented by fibular strut allografts
Panchal et al. [47]	PHILOS (Synthes, Switzer-land)/fibular strut allograft	53	68 (22–94)	min. 12 months	Neer: 2–4 part	Na	Na	ASES-score = 80.4 ± 13.7 (45–100), UCLA-score = 28.8 ± 5.1 (16–35), ROM-analysis	Total = 8 (varus collapse = 2, avascular necrosis = 2, adhesive capsulitis = 2, breakage of distal tip of drill bit = 2)	Dislocated fractures with medial comminution can be reliably treated with augmented locking plates and prevent joint replacement surgery
Chen et al. [48]	PHILOS (Synthes, Switzer-land)/contoured cancellous allograft (n = 7) or fibula allograft (n = 15)	47	67.2 \pm 9 (52–84)	33.4 months (24–48)	Neer: 4-part	Fibular shaft = 79.5 \pm 5 vs. cancellous allograft = 75.4 \pm 7; placed = 73.3 \pm 7.3 vs. non-displaced = 79.3 \pm 5.1	Fibular shaft = 7.5 \pm 1.9 vs. cancellous allograft = 9.3 \pm 2.1; displaced = 9.6 \pm 3.1 vs. non-displaced = 7.7 \pm 1.8	Na	Total = 2 (avascular necrosis = 1, varus displacement of head fragment = 1)	Shaping of structural augmentation in fracture fixation of comminuted fractures had no influence on the outcome
Cha et al. [49]	PHILOS (Synthes, Switzer-land)/frozen allografts	46	69.1 (55–87)	15 months (12–28)	Neer: 2–4 part	Na	Na	ROM-analysis, measurement of head-shaft angle and head height	Total = 5 (screw penetration = 2, screw loosening = 1, plate breakage = 1, heterotrophic ossification = 1)	Endosteal augmentation helped to stabilize locking plate fracture fixation and reduced complication rates

Table 3 (continued)

References	Fixation/ augmentation	CMS	Age (years)	Follow-up	Fracture type	CS	DASH	Others	Related complication	Results
Chen et al. [50]	PHILOS (Synthes, Switzerland)/ fibula allograft	35	Group I: 69.1 (60–85) Group II: 68.6 (60–83)	Group I: 35.2 (24–48) Group II: 33.5 (24–48)	Neer: 3- and 4-part	Group 1 = 70.3 Group 2 = 74.4 ($p=0.020$)	Group 1 = 49 Group 2 = 36.2 ($p=0.001$)	Subjective evaluation at 24 mo: group I: 23 excellent, 15 good, 3 fair, 1 poor Group II: 43 excellent, 4 good	group I: total = 17 (varus mal-union = 8, Screw perforation = 6, AVN = 3); group II: total = 8 (varus mal-union = 2, Screw perforation = 1, AVN = 5)	Patients treated by locking plate with fibular allograft had a better functional outcome and a lower complication rate compared to patients treated by locking plate alone
Kim et al. [51]	PHILOS (Synthes, Switzerland)/ fibula allograft	43	70 (65–75) ($p=0.0842$)	group I: 43 (24–68) group II: 40 (24–66)	Neer: 3- and 4-part with medial comminution in the elderly	3-part: group 1 = 77 (57–90), group 2 = 80 (54–96) ($p=0.128$) 4-part: group 1 = 69 (53–96), group 2 = 78 (57–94) ($p=0.038$)	Na	VAS: 3-part: $p=0.361$, 4-part: $p=0.045$ time to union [mo]: 3-part: $p=0.581$, 4-part: $p=0.756$ Neck: shaft angle: 3-part: $p=0.048$, 4-part: $p=0.023$	total = 27 (stiffness = 7, screw perforation = 6, varus malreduction = 8, plate impingement = 3, and greater tuberosity migration = 3; group I = 22; group II = 5; ($p=0.001$))	Patients treated with fibular allografts had clinically and radiologically superior results to the patients treated with inferomedial screws fixation in 4-part proximal humeral fractures. Fibular Allograft Augmentation can be applied as the primary treatment of 4-part proximal humeral fractures involving medial metaphyseal comminution

Table 3 (continued)

References	Fixation/ augmentation	Study design/ LoE/patient number	CMS	Age (years)	Follow-up	Fracture type	CS	DASH	Others	Related complication	Results
Chen et al. [52]	Locking plate/fibular allograft vs. hemiarthroplasty	Consecutive, prospective, controlled, comparative study/LoE: II/n=60	70	Hemiarthroplasty=68 (1.2–73.1), Lp+aug.=64 (53.1–81.3)	36.3 months (24–48)	Neer: 4-part	Hemiarthroplasty=75.4 ± 6.2 vs. Lp+aug.=80.1 ± 10.2 (<i>p</i> <0.05)	Hemiarthroplasty=7.1 ± 5.6 vs. Lp+aug.=10.3 ± 8.2 (<i>p</i> <0.05)	ROM-analysis, strength and pain measurement	Total = 10; augmentation = 2 (avascular necrosis = 1, articular screw penetration = 1); hemiarthroplasty = 8 (superficial infection = 2, shoulder stiffness and arthrolysis = 4 tuberosity migration and conversion to reverse shoulder arthroplasty = 2)	When compared to hemiarthroplasty, locking plates with allograft augmentation showed superior clinical and functional results
Euler et al. [53]	PHILOS (Synthes, Switzerland)/cancellous allograft from fresh-frozen femoral heads	Retrospective case-series/LoE: IV/n = 10	36	63 (52–78)	28.5 months (24–48)	Neer: 2-part (varus); AO/OTA: A2.2	72 (45–86)	Na	VAS scale = 1 (0–7)	Total = 1 (deep wound infection leading to conversion to reverse shoulder arthroplasty = 1)	Metaphyseal placement of cancellous allografts in valgus impacted fractures might prevent early varus collapse
Euler et al. [54]	PHILOS (Synthes, Switzerland)/femoral head allograft	Retrospective case-series/LoE IV/n = 10	41	63.8 (52–78)	31.8 months (24–48)	Neer: 2-part; AO/OTA: A2.2	72 (45–86)	Na	Measurement of postoperative varus angle	Total = 0	Allograft augmentation in varus displaced fractures lead to bony union in 90% of high-risk patients

Table 3 (continued)

References	Fixation/augmentation	Study design/LoE/patient number	CMS	Age (years)	Follow-up	Fracture type	CS	DASH	Others	Related complication	Results
Atalar et al. [55]	PHILOS (Synthes, Switzerland)/iliac crest allograft	Retrospective case-series/LoE: IV/n = 10	45	57 (34–77)	22.5 months (12–50)	Neer: 4-part (valgus impacted)	87.7 ± 4.4 (83–94)	7.6 ± 4.5 (2.5–16.7)	Na	Total = 1 (early screw penetration = 1)	Structural augmentation of fracture fixation of valgus impacted fractures gave good support reducing the anatomy preventing head collapse
Checchia et al. [56]	PFS 80 angled plate/autologous cancellous chips and iliac crest	Retrospective cohort study/LoE: IV/n = 13	42	58.5 (25–79)	51.4 months (12–130)	Proximal humeral non-union	Na	Na	UCLA-score, ROM-analysis	Total = 5 (persistent non-union = 1, plate loosening = 1, subacromial impingement = 2, hematoma = 1)	Proximal humeral nonunion achieved a 92% consolidation rate when using augmented blade plates
Kim et al. [57]	PHILOS (Synthes, Switzerland)/autologous iliac bone impaction grafts	Retrospective case-series/LoE: IV/n = 21	46	66.3 (24–87)	27.5 months (24–50)	Neer: 4-part	Na	Na	Neer score = 92 ± 6.3 (81–100)	Total = 0	Iliac autograft-augmented locking plates showed excellent results without complication in comminuted fractures
Robinson et al. [58]	Position Screws (n = 14) or buttress plate (n = 11)/SRS (Norian, USA) bone substitute	Retrospective case-series/LoE: IV/n = 25	48	67.2 (35–84)	24 months	Neer: 3-, 4-part, valgus impacted	80 (78–87.5)	22 (19–27)	SF-36	Total = 6 (superficial wound infection = 2, subacromial impingement = 3, adhesive capsulitis = 1)	Filling the metaphyseal defect with bone cement during open reduction of valgus impacted fractures led good short term results

Table 3 (continued)

References	Fixation/ augmentation	Study design/ LoE/patient number	CMS	Age (years)	Follow-up	Fracture type	CS	DASH	Others	Related complication	Results
Lee et al. [59]	PHILOS Plate (Synthes, Switzerland)/calcium sulfate (void filler)	Retrospective case-control Study/LoE: III/augmented $n = 14$ vs. non-augmented $n = 30$	45	64.4 (35–85)	27.8 months (24–48)	Neer: 2-, 3-, 4-part	Na	Na	UCLA-score aug. = 30.2 vs. non-aug. = 28.9 ($p = 0.32$)	Total = 9 (loss of fixation = 5, adhesive capsulitis = 3, deep infection = 1)	Calcium sulfate augmentation led to higher UCLA scores. Medial cortex integrity and absence of comorbidities are most likely to predict good clinical outcome
Somasundaram et al. [60]	PHILOS (Synthes, Switzerland)/calcium sulfate augmentation (void filler)	Retrospective case study/LoE: IV/ $n = 21$	34	64.6 (37–77)	24 months	Neer: 2-, 3-, 4-part; Hertl: I, II, VII, VIII, IX, XI, XII	64	16	Na	Total = 0	Metaphyseal cement augmentation helped to prevent secondary fracture collapse and lead to stable reduction of displaced fractures
Egol et al. [61]	PHILOS (Synthes, Switzerland)/allogenic cancellous chips ($n = 29$) vs. calcium phosphate cement (Hydrosset, Stryker, USA; void filler ($n = 27$) vs. no augmentation ($n = 36$))	Retrospective case-control/LoE: III/ $n = 92$	50	61 (22–84)	16 months	Neer: 2-, 3-, 4-part; AO/OTA: A,B,C	Na	Na	Na	Total = 20 (malunion = 1, heterotopic ossification = 1, implant failure = 1, avascular necrosis = 3, deep infection = 3, screw penetration = 1)	Significant less screw penetration and fracture settling with calcium phosphate cement augmentation

Table 3 (continued)

References	Fixation/augmentation	Study design/LoE/patient number	CMS	Age (years)	Follow-up	Fracture type	CS	DASH	Others	Related complication	Results
Russo et al. [62]	K-wires or osteosutures and/or thin and elastic non-locked or locked plates/iliac crest or dry bone bank block shaped as triangular trapezoidal block (group 1) vs. titanium triangular-shaped implant (group 2) (Da Vinci, Arthrex, USA)	Two retrospective case-series/LoE: IV/ n = 101 (group 1 = 23, group 2 = 78)	39	52.4 (19–78)	72 months (12–132)	Neer: 2–4 part	Group 1 = 77.8 group 2 = na	Group 1 = 51 Group 2 = na	Measurement of post-operative varus angle and dislocation	Total = 4 (wound infection = 2, avascular necrosis = 2)	Results according to Constant Score and DASH = 83.2% Good and excellent, 12.8% fair, 4% bad

Table 3 (continued)

References	Fixation/ augmentation	Study design/ LoE/patient number	CMS	Age (years)	Follow-up	Fracture type	CS	DASH	Others	Related complication	Results
Kaithagen et al. [63]	PHILOS (Synthes, Switzerland)/PMMA screw-tip augmentation	Retrospective comparative study (matched-pair)/LoE: III/PMMA screw-tip augmentation (group I) pt. n = 24 vs. no augmentation (group II) pt. n = 24	37	Group I: 74.2 ± 10.3 group II: 73.7 ± 9.7	Group I: 12 group II: 12	Neer: 2–4 part, Resch: varus- and valgus displaced	Group 1 = 72.9 ± 18.1 group 2 = 73.0 ± 13.1 (p = 0.557)	Na	Group I: SST = 9.2 ± 3.2, SSV = 77.2 ± 17.3%; group II: Na	Group i: total = 2 (varus non-union = 1, screw perforation = 0, avn = 1), 6 (25%) early arthroscopic revision surgery with arthrolysis, biceps tenotomy, and arthroscopically assisted implant removal between 3 and 5 months; group ii: total = 4 (varus mal-union = Na., screw perforation = 4, avn = Na)	Locked plating of displaced phf with additional cement augmentation showed similar clinical outcomes but reduced the rate of early implant-related complications compared to locked plating without additional screw-tip augmentation

Values are given as means with ± standard deviation or (range)

LoE level of evidence, CMS Coleman Methodology Score, CS Constant Score, DASH disability of the arm shoulder and hand questionnaire, ESDS Enforced Social Dependency Scale, ROM range of motion, SF-36 Short Form Health Survey, PMMA polymethylmethacrylate, ASES American Shoulder and Elbow Society, UCLA University of California at Los Angeles Shoulder Score, aug. augmentation, lp locking plate

no significant difference between augmented and non-augmented implants could be found. Regarding the unstable fracture situation, augmented implants showed significantly lower values for varus dislocation per cycle motion and in total [30]. Scola et al. tested PMMA-augmented locking plates (Philos, Synthes, Switzerland) in unstable three-part fractures and found significantly delayed varus collapse and higher maximum load in the augmented group [31]. One recent biomechanical studies derived from Schliemann et al. Screw-tip augmentation of the anterior directed head screws (DiPhos-H plate, Lima Corporate, Udine, Italy /PMMA, Synthes, Switzerland) under varus bending in unstable three-part fractures showed less motion at the bone-implant interface with no difference in stiffness and mean load to failure [32]. Kuang et al. utilized strontium-containing hydroxyapatite (Sr-HA) bone cement instead of PMMA for screw augmentation in an osteoporotic three-part fracture model. In comparison to non augmented locking plates (Philos, Synthes, Switzerland) Sr-HA cement-augmented fracture fixation showed a better biomechanical performance in varus bending tests revealing significantly less displacement, higher failure points, and higher stiffness. However, no significant differences were found between augmented and non-augmented specimens in axial rotational tests [33].

Clinical studies

Bone grafts to enhance medial support

Walch et al. reported on 20 proximal humeral nonunions after failed conservative and operative therapy treated with an intramedullary bone peg augmented t plate. Autografts were obtained from the iliac crest, anterior tibial crest, or fibula shaft. After a mean follow-up of 42 months, findings included a union rate of 96% with an overall age- and sex-adjusted Constant score of 81. Three pathologic tibial fractures occurred as procedure-related complications [34]. Ring et al. found similar results after treating 25 proximal humeral nonunions with an iliac crest-augmented blade plate. The mean Constant Score was 77 after a mean follow-up of 41 months. Complications included two persisting nonunited fractures and one fracture of the iliac wing near the bone harvesting site [35]. Zhu et al. compared four-part fractures treated by iliac crest-augmented locking plates to no form of augmentation. Using the intramedullary graft led to superior results in regard to patient satisfaction measured by a mean SF-36 of 88 and 69.5, respectively. The iliac crest autografts used in comminuted four-part fractures resulted in bony union in all cases, whereas two nonunion were found with no augmentation [36]. In 2012, Gao et al. investigated seven surgical neck nonunions treated with autologous fibular grafts fixed with a locking plate. After a mean of 6.1 months, all fractures showed radiographic signs of bony union and at

final follow-up patients presented with an overall Constant score of 77.7 and a 0.57 on the VAS Scale. Major complications according to the procedure were one transient peroneal nerve palsy in the donor leg and one transient radial nerve palsy [37].

Gardner et al. treated proximal humeral fractures with unstable medial column comminution using locking plates (PHP, Synthes, Switzerland) with fibular allografts as indirect medial support. All fractures healed without loss of reduction and all patients were followed to bony union [38]. Badman et al. used fibular and ulnar allografts fixed by locking or bent plates for the treatment of proximal humeral nonunion. Bony consolidation was achieved in 94% with minimal residual pain and improved functional results with an ASES score of 81 postoperatively [39]. Rollo et al. also investigated proximal humeral nonunion treated by an extramedullary humeral shaft allograft fixed by a locking plate (PHILOS, Synthes, Switzerland). No complication was noted after a mean of 63 months of follow-up and union was achieved in all the cases [40]. Neviasser et al. used locking plates (Philos, Synthes, Switzerland) and fibular allografts on 38 Patients with two-, three-, and four-part proximal humerus fractures. One loss of reduction and one partial osteonecrosis occurred with overall excellent clinical results and high subjective patient satisfaction as measured by Constant and DASH scores of 87 and 15, respectively [41]. Similar clinical results were shown by Matassi et al. who prospectively investigated three- and four-part proximal humeral fractures with metaphyseal comminution after the reduction with a fibular allograft-augmented locking plate (Philos, Synthes, Switzerland; PERI-LOC, Smith & Nephew, USA). No major complication was detected, and the mean Constant and DASH scores were 79 and 33, respectively [42]. Semi-tubular plates and fresh-frozen fibular allografts were used as endosteal implants by Hettrich et al. to prevent varus collapse and maintain the intraoperative head-shaft angle fixed by a locking plate. The authors reported on only one loss of reduction with an average of 2° change in head-shaft angle [43]. Little et al. reported about 72 patients after fracture reduction of displaced and unstable two-, three- and four-part proximal humeral fractures with a fibular allograft and locking plates (PHP, Synthes, Switzerland). The mean Constant Score was 89 and 85 for valgus and varus deformities, respectively. DASH and SF-36 scores did not differ between the two subgroups. One osteonecrosis was present at latest follow-up in the valgus group [44]. Tan et al. approached displaced and unstable proximal humeral fractures with an intramedullary fibular strut graft reduced by a locking plate. On radiographs after 12 weeks, all fractures showed signs of callus formation with a retained head-shaft angle. The range of motion was satisfactory allowing all patients for overhead activities [45]. To detect the influence of age related comorbidities of the aging population on structural augmented

proximal humeral fractures, Hinds et al. compared geriatric to non-geriatric patients suffering from 2-, 3- and 4-part fractures. Fibular strut graft augmented locking plates were used during fracture reduction. At a mean follow-up of 34 months, geriatric patients showed a mean Constant and DASH score of 82.7 and 16.4, respectively. Clinical results of non-geriatric patients did not differ significantly from the results of younger individuals. One geriatric patient developed an osteonecrosis with secondary screw cut-out [46]. Displaced 2-, 3-, and 4-part proximal humeral fractures with medial comminution were also treated with locking plating reinforced by fibular strut grafts by Pancha et al.. At latest follow-up ASES and UCLA-scores were 80.4 and 28.8, respectively. Varus collapse, osteonecrosis, and breakage of the drill bit were noted in two patients [47]. To investigate whether graft shape has an influence on the functional outcome when treating 4-part proximal humerus fractures with augmented locking plates (PHILOS, Synthes, Switzerland), Chen et al. compared anatomic-to-non-anatomic allografts to enhance the medial support. Anatomic allografts formed from frozen cadaveric donors to additionally fill the metaphyseal void resulted in a mean Constant and DASH score of 75.4 and 9.3, respectively, and did not differ significantly when compared to a fibular strut graft [48]. A case-control study was performed by Cha et al. who compared 2-, 3-, and 4-part fractures fixed by locking plates (PHILOS, Synthes, Switzerland) to locking plates augmented by fresh-frozen allografts. Augmentation showed significant fewer complications and helped to maintain the neck-shaft angle and the humeral head height [49]. Similar results have been reported by Chen et al. analyzing the effect of fibular allograft augmentation in 3- and 4-part fractures. In comparison to a retrospective, historic cohort of non-augmented locking plate fixation (PHILOS, Synthes, Switzerland), patients treated with fibular allograft augmentation showed significantly better functional and subjective outcome values as well as a significantly lower complication rate compared to patients treated with locking plate alone [50]. Kim et al. recently confirmed these findings in a cohort of elderly patients suffering from 3- and 4-part fractures with medial comminution. The authors compared fibular allograft augmentation of locking plate fixation with non-augmented locking plate fixation featuring additional inferomedial screws. In 4-part fractures patients treated with fibular allografts had significantly superior clinical and radiological results compared to the patients treated with inferomedial screws only. However, this effect was not observed in 3-part fractures [51]. Chen et al. compared locking plating augmented by fresh-frozen fibula strut grafts to hemiarthroplasty (Link, Germany) in a prospective randomized study. Superior clinical results with a better range of motion for the osteosynthetic reconstruction with a mean Constant score of 80.1 and 75.4 were found, respectively. Complications included one case of avascular

necrosis, one case of varus displacement, and one patient with screw perforation of the articular surface [52].

Filling the void

Euler et al. focused their investigation on high-risk and severely displaced varus 2-part fractures using a cancellous allograft from a frozen femoral head fixed with a locking plate (Philos, Synthes, Switzerland). After a mean follow-up of more than 2 years, the Constant score was 72 and pain decreased to an average of 1 on the VAS scale. Despite one deep infection leading to conversion to a reversed shoulder prosthesis, no major complication was noted. Bony union was achieved in 90% with further follow-up [53, 54]. Fractures with valgus deformities were investigated by Atalar et al. who used an iliac crest allograft for structural augmentation of impacted 4-part fractures fixed with locking plate (Philos, Synthes, Switzerland). All fractures healed with good functional results as measured by a Constant and DASH score of 87.7 and 7.6, respectively. Single postoperative complication was one case of early articular screw penetration [55]. Checchia et al. discovered high satisfaction rates and good fracture consolidation for the treatment of proximal humeral nonunion resulting from 2-part and minimal displaced 3-part fractures treated with a blade plate augmented by autologous cancellous chips and an iliac crest graft. Mean elevation, and lateral and medial rotation were 130°, 42°, and hand position at T10, respectively [56]. The treatment of displaced 4-part fractures using an iliac crest autograft-augmented locking plate is used by Kim et al. and resulted in good functional results with a Neer score of 92. At final follow-up, all fractures healed radiographically and imaging yielded a mean head-shaft angle of 129°. No complication was noted [57]. Robinson et al. investigated 25 consecutive patients with 3- and 4-part valgus impacted fractures who were treated with calcium phosphate cement (SRS, Norian, USA) to fill a metaphyseal defect. Fracture reduction was maintained by either a buttress plate or position screws only. After 12 months of follow-up, the mean Constant and Dash scores were 80 and 22, respectively. No major complication was detected [58]. A similar technique was used by Lee et al. who used calcium sulfate injections and locking plates (Philos, Synthes, Switzerland) to reinforce medial cortex stabilization in 14 patients with 2-, 3-, and 4-part proximal humerus fractures. With overall satisfactory clinical results patients receiving augmentation showed significant higher UCLA scores of 30.2 and 28.9, respectively. The reduction failure rate was not influenced by additional augmentation [59]. Calcium sulfate injections were also used by Somasundaram et al. who treated 2-, 3-, and 4-part fractures with locking plates (Philos, Synthes, Switzerland). Final Constant and DASH scores were 64 and 16.2, respectively. No complications were noted and reduction was

maintained in every case [60]. A case–control study was used by Egol et al. to compare the reduction with locking plates (Philos, Synthes, Switzerland) augmented by either cancellous chips, calcium phosphate injections, or no type of augmentation when treating 2-, 3- and 4-part proximal humerus fractures. Postoperative radiographs showed significantly less loss of reduction and fracture settling when using calcium phosphate cement augmentation compared to cancellous bone chips or no augmentation ($p=0.02$) [61]. A recent complex retrospective study was performed by Russo et al. The authors compared K-wires or osteosutures and/or thin and elastic non-locked or locked plates augmented by an iliac crest or cancellous bone shaped as triangular trapezoidal block to a titanium triangular-shaped implant (Da Vinci, Arthrex, USA). Results according to Constant and DASH scores were 83.2% good and excellent, 12.8% fair, and 4% bad [62].

Screw-tip augmentation

Only one clinical study evaluated the technique of screw-tip augmentation following locking plate fixation (PHILOS, Synthes, Switzerland) in a small cohort of 24 patients with 2-, 3-, and 4-part fractures and a follow-up of 1 year. When compared to a historic control group of locking plate fixation without augmentation, an additional PMMA screw-tip augmentation showed similar clinical outcomes, but reduced the rate of early implant-related complications, such as early loss of reduction and articular screw perforation [63].

Discussion

The intent of this overview was to systematically review all available biomechanical and clinical studies investigating augmentation techniques of plate fixation for proximal humeral fractures. The different augmentation techniques were then categorized according to their operative principles, the Levels of Evidence were assessed and the studies' quality was evaluated. The most commonly described techniques were structural allogenic or autologous bone grafting to enhance the medial support, filling the metaphyseal void with synthetic bone substitutes or bone grafts as well as screw-tip augmentation with bone cement. Although the evidence is limited and prospective or randomized clinical trials are still missing for any of the techniques described, all of the strategies appear to have a positive effect on primary and secondary stability after open reduction and plate fixation of proximal humerus fractures.

Five studies investigating fibular strut graft as enhancement of the medial support revealed biomechanically increased varus bending load, stiffness, and load to failure as well as reduced rate of loss of fixation and interfragmentary

movement [19–23]. Since none of these biomechanical studies utilized a four-part fracture model, these findings may only be transferred to a clinical scenario of unstable two- or three-part fractures. Furthermore, all biomechanical studies utilized servohydraulic testing machine without simulating rotator cuff muscle forces. Taken together, the biomechanical models represent only a time-zero situation and do not adequately reflect the clinical reality.

Nevertheless, 19 clinical studies using structural bone grafting to enhance the medial support could be identified. The major findings within these studies were higher rates of fracture healing, superior clinical outcome scores, and higher patient satisfaction as well as reduced loss of fixation and varus malunion. While the vast majority of studies utilized fibular allografts [38, 39, 41–52], autologous and allogenic bone grafts derived from the iliac crest seem to allow for likewise promising results [34, 36]. One comparative study was conducted by Chen et al., revealing good clinical and radiological outcomes for elderly patients with four-part fractures without significant differences between anatomical precontoured vs. non-contoured fibula strut allograft [48]. A total of three comparative study on fibular allograft augmentation in 2- to 4-part fractures found significantly better functional outcome, higher subjective patient satisfaction, and reduced loss of fixation after fibular strut graft augmentation of comminuted fractures compared to non-augmented fractures [49–51]. Kim et al. pointed out that augmentation of 4-part fractures with medial comminution in the elderly had the strongest effect on improving outcome and minimizing complications. Interestingly, the use of allografts to enhance the medial support is equally effective in geriatric patients compared to non-geriatric patients [46]. Furthermore, the joint preserving procedure with locking plate fixation with allogenic strut graft fixation showed significantly superior clinical outcomes when prospectively compared to hemiarthroplasty [52]. Taking the current data and the low level of evidence into account, availability, donor site morbidity, patient's or surgeon's preferences have a significant impact on the graft choice in clinical practice.

The concept of filling the void was investigated in three biomechanical studies, which all utilized injectable synthetic bone substitutes [25–27]. Across the studies, significantly decreased fracture-gap deflection and interfragmentary motion as well as increased axial stiffness and maximum load to failure was observed due to the augmentation. Again, these biomechanical approaches only assess the primary stability. The clinical degradation and remodeling processes of injectable bone grafts and their influence on the constructs stability in the course of time were evaluated in four clinical studies. Three of these studies were case series without a non-augmented control group. In contrast to the biomechanical studies, they also included more complex fracture pattern, such as four-part fractures. In summary, good clinical

outcome values, low rates of loss of reduction and screw perforation were described. The studies neither assessed specific complication due to the injected bone fillers, nor the resorption and remodeling processes. One study retrospectively compared void filling techniques using either calcium phosphate or cancellous bone chips. The authors revealed less loss of fixation and significantly less glenohumeral screw cut-out with calcium phosphate cement compared with no augmentation or with cancellous bone chips [61].

A total of eight studies investigated the significance of allogenic and autologous bone grafts for filling the metaphyseal void [48, 53–57, 61, 62]. Beside the above-mentioned study by Egol et al., all remaining studies are case series reporting good clinical outcomes and stating void filling with bone grafts as a safe-and-reliable procedure. In addition to bone grafting of the metaphyseal void, two studies introduced metallic implants as a potential alternative resulting in similar outcomes and complication rates [43, 62]. Nevertheless, these techniques are currently deemed to be of inferior significance in clinical practice.

The basic principle of screw-tip augmentation with injectable PMMA is to increase the primary stability by enhancing the screw-tip/bone interface. Another advantage of this technique is that it does not substantially change the operative standard procedure of open reduction and internal plate fixation. A total of five biomechanical studies demonstrated that screw-tip augmentation significantly decreases motion between the bone–implant interface and counteracts the varus collapse [28–32]. The most striking effects were detected in specimens with low bone mineral density and unstable fracture patterns, like unstable two-part fractures. On the other hand, comparative analyses in stable fracture patterns and healthy bone specimens did not reveal advantages of screw-tip augmentation. Although this technique has already been widely implemented in clinical practice, there is only one study providing clinical data of a small patient cohort with 12 month follow-up [63]. Especially, the clinical impact of potential adverse events like glenohumeral PMMA leakage, avascular necrosis, or cartilage damage due to exothermic reaction is not fully overseen.

Conclusion

Augmentation of plate fixation for proximal humeral fractures seems to be a reliable and safe procedure. All common techniques mechanically increase the constructs' stability. Clinically evaluated procedures show reduced complication rates and improved patient outcomes. Augmentation techniques seem to have the highest significance in situations of reduced bone mineral density and in high-risk fractures, such as 4-part fractures, fractures with medial comminution, and severe valgus and varus displacement. However, more

high-quality and comparative clinical trials are needed to give evidence-based treatment recommendations.

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Compliance with ethical standards

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