The biomechanical performance of locking plate fixation with intramedullary fibular strut graft augmentation in the treatment of unstable fractures of the proximal humerus

We evaluated the biomechanical properties of two different methods of fixation for unstable fractures of the proximal humerus. Biomechanical testing of the two groups, locking plate alone (LP), and locking plate with a fibular strut graft (LPSG), was performed using seven pairs of human cadaveric humeri. Cyclical loads between 10 N and 80 N at 5 Hz were applied for 1,000,000 cycles. Immediately after cycling, an increasing axial load was applied at a rate of displacement of 5 mm/min. The displacement of the construct, maximum failure load, stiffness and mode of failure were compared.

The displacement was significantly less in the LPSG group than in the LP group (p = 0.031). All maximum failure loads and measures of stiffness in the LPSG group were significantly higher than those in the LP group (p = 0.024 and p = 0.035, respectively). In the LP group, varus collapse and plate bending were seen. In the LPSG group, the humeral head cut out and the fibular strut grafts fractured. No broken plates or screws were seen in either group.

We conclude that strut graft augmentation significantly increases both the maximum failure load and the initial stiffness of this construct compared with a locking plate alone.

Fixed-angle locking plates are a relatively new method of fixation for complicated fractures, especially in patients with pathological fractures and osteoporosis.1-5 The use of such plates to treat comminuted fractures of the proximal humerus has theoretical biological and mechanical advantages over conventional techniques. However, complications, including collapse of the fracture and screw penetration of the articular surface, remain a problem.6-10 Gardner et al11 reported a failure rate of 29% (five of 17) for fractures of the proximal humerus after locking plate fixation without medial support. The lack of mechanical support in the inferomedial region of the proximal humerus, and poor bone quality, contribute to this.

Adequate mechanical support of the medial column may be obtained by achieving an anatomical or slightly impacted stable reduction with medial cortical contact, or, in the case of medial comminution, by placing a superiorly directed oblique locking screw in the inferomedial region of the proximal fragment.11,12 Recently, Gardner et al13 claimed that an intramedullary fibular graft combined with a locking plate produces a stronger construct than lateral locking alone. To our knowledge, no biomechanical study has been conducted to investigate the difference in stability between a locking plate alone and a locking plate with strut graft augmentation.

The purpose of this study was to evaluate the biomechanical properties of two different fixation constructs, locking plate fixation alone and locking plate fixation with fibular strut graft augmentation. We hypothesised that the initial fixation strength of a locking plate with a fibular strut graft would be superior to that of a locking plate alone.

Materials and Methods

Specimen preparation. We used 14 undamaged fresh-frozen human cadaveric humeri from patients ranging in age from 43 to 63 years. The soft tissues were completely removed from the specimens, all of which were stored at -20°C and thawed at room temperature for 24 hours before use. Before the specimens were selected the bone mineral densities (BMD) of the ipsilateral proximal tibiae had been determined by dual-energy X-ray absorptiometry (DXA) (Hologic QDR-2000 Whole-Body X-ray Bone Densitometer; Hologic, Bedford, Massachusetts). A previous study had indicated that a BMD > 0.6 g/cm² is acceptable for testing specimens.14 In our study the mean BMD was 0.89 g/cm² (0.72 to 0.93).
An unstable proximal humeral fracture was simulated in each specimen by osteotomy using a microsagittal saw. The first osteotomy was placed in line with the anatomical neck of the humerus, and the second 1 cm distal to the inferomedial aspect of the articular cartilage of the humeral head and perpendicular to the long axis of the humeral shaft. A circumferential segment of bone 0.5 cm thick was removed to simulate bone loss and avoid any contact between the fragments (Fig. 1a).

Study groups. The specimens were divided into two groups, such that an individual's left and right limbs were allocated to different groups. In the locking plate (LP) group the fracture was fixed with a locking plate alone (PHILOS; Synthes, Paoli, Pennsylvania). All the plates were the same length and had the same number of screw holes (six distal and nine proximal). Each plate was applied on the lateral aspect of the proximal humerus and fixed using four locking screws in the diaphysis and seven locking screws in the humeral head (Fig. 1b). In the locking plate and strut graft (LPSG) group the fracture was fixed with a locking plate and an intramedullary fibular strut graft. A 90 mm segment from the diaphysis of the ipsilateral cadaveric fibula was inserted into the medullary cavity of the diaphysis and head of humerus. Approximately 6 cm of the fibular graft was impacted into the diaphysis and held in place with a 2.0 mm Kirschner (K)-wire. A locking plate was then applied in a same way as in the LP group (Fig. 1b). The fibular graft was held in place with two diaphyseal locking screws.

Biomechanical testing. Biomechanical testing was carried out using a servohydraulic materials testing system (Model 8511; Instron, Norwood, Massachusetts). Each specimen was mounted onto the load frame using a custom-designed jig. The humeral head was loaded through a Teflon bar and the load was applied parallel to the long axis of the bone tunnel, all other movements being constrained (Fig. 2). First, uniaxial cyclical loading of between 10 N and 80 N at 5 Hz for 1 000 000 cycles was performed. These loads are the same as those used in a previous study that evaluated the biomechanical performance of locking plate osteosynthesis of the proximal humerus. Load-displacement curves were recorded continuously and stored every 2000 cycles. Displacement of the construct was determined by calculating the differences between the position of the actuator before and after cyclical loading. This represents the amount of collapse. Immediately after cyclical loading, the axial load was increased at a displacement rate of 5 mm/min until the load-displacement curve showed a clear deviation from linearity. Linear elastic stiffness (load divided by displacement) in the low load range and maximum failure load were measured (Fig. 3). The mechanism of failure for each construct was also recorded.

Statistical analysis. A Wilcoxon’s signed-ranks sum test was used to compare the different fixation techniques, calculated using SPSS v.12.0 (SPSS Inc., Chicago, Illinois). Significance was set at p < 0.05.

Results

Dynamic tests under cyclical loading. During dynamic tests under cyclical loading all specimens showed slight initial deformation followed by a plateau until the end of the experiment. The displacement of the construct was significantly less in the LPSG group than in the LP group (Fig. 4, p = 0.031). No specimens failed during the dynamic tests.

Static tests under increasing load. Maximum failure loads and measures of stiffness in the two groups are shown in
Figures 5 and 6 and Table I. These were significantly greater in the LPSG group than in the LP group (p = 0.024 and p = 0.035, respectively). Modes of failure were also seen after static tests. In the LP group, varus collapse and bending of the plate at the osteotomy gap were seen in all specimens (Fig. 7). However, in the LPSG group the humeral head displaced at the proximal osteotomy site in the anatomical neck with fracturing of the fibular strut graft in each case. No plate or screw broke in either group.

Discussion
The purpose of this study was to evaluate the biomechanical properties of locking plate fixation of an unstable fracture of the proximal humerus using intramedullary fibular strut graft augmentation in a cadaveric model. We compared two different fixation constructs: locking plate fixation alone and locking plate fixation with fibular strut graft augmentation. We found that the addition of an intramedullary fibular strut graft resulted in greater primary stability than a locking plate alone. Our results support the concept that restoration of medial support with an intramedullary fibular graft increases the strength of fixation under these circumstances.

Stiffness, represented by the slope of the linear region of the load-displacement curve, is an important factor in fixation. Previous studies have shown that implants that are stiffer at loads below failure also have a higher load to failure, and our study supports this finding. In particular, the intramedullary fibular graft was found to increase both initial stiffness and maximum load to failure, and initial stiffness at the fracture was 2.4 times greater when an intramedullary fibular strut graft was used.
Table I. Maximum failure loads, stiffness and displacement (mean, range)

<table>
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<tr>
<th></th>
<th>LP&lt;sup&gt;p&lt;/sup&gt;</th>
<th>LP&lt;sub&gt;SG&lt;/sub&gt;&lt;sup&gt;†&lt;/sup&gt;</th>
<th>p-value</th>
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<tr>
<td>Maximum failure load (N)</td>
<td>1291.83 (903.43 to 1754.29)</td>
<td>1985.54 (1324.59 to 2569.41)</td>
<td>0.024</td>
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<tr>
<td>Stiffness (N/mm)</td>
<td>292.31 (251.39 to 411.23)</td>
<td>693.52 (551.24 to 862.34)</td>
<td>0.035</td>
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<td>Displacement (mm)</td>
<td>0.63 (0.18 to 0.88)</td>
<td>0.15 (0.02 to 0.27)</td>
<td>0.031</td>
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<sup>p</sup> LP, locking plate alone
<sup>†</sup> LP<sub>SG</sub>, locking plate with fibular strut graft

A locked peri-articular plate has the advantages of being a well-contoured, low-profile plate with several proximal multidirectional screws and locking screw technology that gives angular stability. It is generally believed that these plates provide better fixation for fractures of the proximal humerus, especially in weak bone.<sup>21,22</sup> More recently, several studies have reported that failure of fixation typically occurs because of varus collapse, even though the fracture has been fixed with a locking plate.<sup>6-8,18</sup> If there is no medial buttress in elderly patients with osteoporotic bone, a soft humeral head supported only by rigid hardware tends to settle onto metal, causing varus collapse and screw cutout, which is a frequently reported reason for revision surgery.<sup>7-9,23</sup> In this study all specimens in the LP group collapsed into varus, whereas the LP<sub>SG</sub> group showed no varus collapse or deformity. However, we were unable to replicate the clinical mode of failure whereby the screws pull out or cut out of the humeral head.

Fatigue tests under cyclical loading showed that displacement of the construct in the LP<sub>SG</sub> group was significantly less than in the LP group, although all specimens in both groups survived 1 000 000 cyclic loads. Displacement of the construct represents a combination of subsidence of the humeral head, deformation of the plate and enlargement of the screw hole due to compression of the cancellous bone beneath the screws. Although it was difficult to define the major cause of displacement using our model, in our opinion the greater displacement observed in the LP group was caused by varus collapse and slight plate deformation, because screw hole enlargement was found to be minimal after removing the screws and plates. Furthermore, this finding is consistent with a previous study,<sup>16</sup> in which it was reported that screw hole elongation is minimal when only a locking plate is used for fixation.

In this study the modes of failure after static testing were different between the two groups. Under axial loading at approximately 1300 N, the humeri fixed with a locking plate but without a fibular graft failed by collapsing into varus, with bending of the plate at the osteotomy. This mode of failure is similar to that described in a previous study by Schuermann et al.,<sup>24</sup> who compared the biomechanical properties of a locked plating system using smooth pegs with one using threaded screws for the fixation of a simulated two-part fracture of the proximal humerus with a 10 mm osteotomy gap. They found that plastic deformity of the plate and varus collapse at the osteotomy occurred with a maximum failure load of approximately 1300 N. One interesting finding in our study is that the fracture fixed with a locking plate and fibular graft failed due to fracture of the graft after the humeral head had cut out of the distal fragment at an axial load of approximately 2000 N. This may be due to differences in stiffness between the two constructs, as the locking plates with fibular grafts were stiffer than the locking plates alone, resulting in primary failure with cutout of the humeral head and a broken fibular strut graft, rather than varus collapse with bending of the plate.

Our study has several limitations. First, we did not accurately reproduce a three- or four-part fracture, which are frequently encountered in elderly patients. However, by leaving a 5 mm defect we were able to simulate an unstable fracture with disruption of the medial cortical buttress in a comminuted fracture of the proximal humerus. Secondly, our results apply only to the time of initial fixation and do not reflect the conditions under physiological loading, in vivo biological healing or muscle forces acting around the shoulder joint. We did not apply precise physiological loads during the loading tests even though the amount of
load applied during this study was based on a previous biomechanical study.\textsuperscript{16} If varus collapse or screw cutout occurs at these physiological loads, patients should not be allowed to exercise before the fracture is solidly united. Our data may not be clinically relevant. However, we provide evidence that strut graft augmentation significantly increases both the maximum failure load and the initial stiffness of the construct compared to a locking plate alone. Thirdly, the failure modes in our study were not clinically relevant in either group. Clinically, varus collapse and screw cutout are more often encountered.\textsuperscript{5-10} Bending of a plate and fracture of a strut graft are rarely seen in clinical practice because they occur as a result of supraphysiological loads or high-energy trauma. One possible explanation for this is that the load to failure of the construct was sufficiently large to bend the plate. As noted, the mean maximum load to failure when a locking plate is used alone is about 1300 N. In addition, we placed the screws deeper into the subchondral bone than we would normally do at operation. This was because we chose the length of the screws with the help of a depth gauge and gross observation from the articular surface without C-arm control. There must have been some element of cutting through or pull-out of the head, but in most cases we described the mode of failure as bending of the plate, because that was the most obvious finding. If we had paid more attention to minor changes in the fitting of the plate to the head, or had taken post-failure radiographs of the specimens, we might have found some evidence of screw displacement. Fourthly, the data obtained from our model may not be applicable to complex multifragmented fracture patterns. In particular, it remains to be seen whether locking plate fixation with intramedullary fibular graft augmentation affords any biomechanical advantage for other types of fracture of the proximal humerus.

In conclusion, this biomechanical study shows that fibular graft augmentation significantly increases the maximum failure load and initial stiffness of a construct compared to a locking plate alone. It also supports the humeral head and prevents varus collapse of a fracture of the proximal humerus with comminution of the medial cortex.

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No benefits in any form have been received or will be received from a commercial party related directly or indirectly to the subject of this article.

References


