Biomechanical comparison of the Locking Compression superior anterior clavicle plate with seven and ten hole reconstruction plates in midshaft clavicle fracture stabilisation

Lars Eden · Stefanie Doht · Sönke P. Frey · Dirk Ziegler ·
Jan Stoyhe · Kai Fehske · Torsten Blunk ·
Rainer H. Meffert

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Abstract

Purpose The purpose of this study was to characterise the biomechanical properties of the seven hole superior anterior clavicle LCP (locking compression plate) and to compare these with the properties of commonly applied implants used for the stabilisation of clavicular midshaft fractures such as the locking 7- and ten hole reconstruction plate.

Methods Twenty-four synthetic clavicles were used. A transverse midshaft fracture was induced. The clavicles were fixed with angle stable clavicle LCPs, seven hole and ten hole reconstruction plates ($n=8$ each). Twenty cycles of axial compression and torsion were performed for each sample, which was followed by 1,000 cycles of three point bending and ultimately bending to failure. Axial, torsional and cantilever bending stiffness were calculated from the data recorded.

Results The clavicle LCP showed the highest overall stiffness compared to the seven and ten hole reconstruction plate. Significantly higher stiffness values were found for axial compression and external rotation. In the load-to-failure tests, the ten hole reconstruction plate especially showed early signs of plastic deformation, which might account for early plate insufficiency so frequently observed clinically.

Conclusion The results indicate that the clavicle LCP, as compared to the reconstruction plates, leads to superior biomechanical stability in the treatment of midshaft clavicle fractures.

Introduction

Clavicle fractures are common, especially in young, active men. Midshaft fractures account for 80 % of all clavicle fractures [1]. While non-displaced fractures are still predominantly managed by conservative treatment, displaced midshaft fractures of the clavicle gain more and more importance in the field of traumatology and orthopaedic surgery. A previous study has shown superior functional results with plating when compared to conservative treatment in displaced fractures [2]. Up to 32 % of all patients were dissatisfied after conservative treatment of displaced fractures [3]. It was reported that in the year 2008, 26 % of clavicle fractures diagnosed in Germany were treated surgically, mainly by plating. In the surgical treatment of clavicle fractures, reconstruction plates (Fig. 2b) are the most frequently used implants [4]. Yet, in our clinic, surveys have revealed a relatively high complication rate with this plate, similar to those published by Wijdicks et al. and Houwert et al. [5, 6]. Over a period of two years, five implant failures approximately three months postoperatively were observed (Fig. 1). Consequently, we started using the new LCP superior anterior plate manufactured by Synthes (Fig. 2a). This plate is a precontoured angle-stable plate combining a superior positioning at the lateral end and an anterior positioning at the medial end. Subsequently, no further failures have been observed and we have had very good clinical results [7]. Looking at previous biomechanical studies, the main focus was on the difference between locking versus non-locking plates and superior versus anterior-inferior plate position [8–10]. To our knowledge, only one study has been published comparing a precontoured plate with regular plates.

L. Eden (✉) · S. Doht · S. P. Frey · D. Ziegler · J. Stoyhe ·
K. Fehske · T. Blunk · R. H. Meffert
Department of Trauma-, Hand-, Plastic and Reconstructive
Surgery, Julius-Maximilians-University,
Würzburg, Germany
e-mail: eden.lars@web.de

Fig. 1 X-ray of a broken reconstruction plate three months after surgery

This particular study, however, did not report any differences in mechanical properties between the tested implants [11].

Here, for the first time, we biomechanically characterise the precontoured LCP superior anterior clavicle plate in a standardised setting comparing its properties with regular reconstruction plates.

Methods

Biomechanical testing

Twenty-four synthetic, fourth generation Sawbone® (Sawbones Europe, Malmö, Sweden) clavicles were used for testing. Fourth generation Sawbone has been previously proven to have similar mechanical properties to cadaver bone [12]. Nevertheless, to confirm the comparability of the artificial bone to cadaver bone, load-to-failure tests in three-point bending were performed. To this end, the manufacturer supplied entire Sawbone clavicles, in contrast to the pre-osteotomised models usually offered. Four formalin-fixed cadaver clavicles donated from the local university's anatomy institute were used for comparison. The results showed a very low variance (see Fig. 4), thus we continued with the artificial bones.

A modified three-point cantilever bending procedure was conducted to induce a reproducible transverse midshaft fracture using a special custom-made jig (Fig. 3a, c). The first group of clavicles was reduced anatomically and fixed

with a seven hole titanium LCP superior anterior clavicle plate (Synthes, Tuttlingen, Germany) with three angle-stable, bicortical screws on each side of the fracture. Another group was reduced and fixed with seven hole titanium reconstruction plates (Synthes) bent to shape and three angle-stable, bicortical screws on both sides of the fracture in the superior position. The third group represented a simulated minimally invasive group, a method recently being introduced and performed in an increasing number in Germany [13]. An approximating reposition was performed simulating a closed reduction. A ten hole reconstruction plate (Synthes) was bent and fixed with two angle-stable, bicortical screws on both sides of the fracture. In all groups, eight specimens were tested. All plates, screws, plate benders and drilling equipment were commercially available products provided by Synthes.

For testing axial compression and torsion the ends of the clavicles were embedded in polymethyl methacrylate (Kulzer GmbH, Wehrheim, Germany) and mounted in a Zwick/Roell testing machine (Z020, Zwick/Roell, Ulm, Germany) using a second custom-made jig (Fig. 3b). Twenty cycles of axial compression were applied with a maximum load of 100 N. Afterwards, each clavicle was subjected to 20 cycles of torsion (angular displacement -10° to 10°) at a frequency of 0.25 Hz. Internal rotation was defined as a rotation of the lateral end in anterior, external rotation in the posterior direction to the medial end [9]. The specimens were then dismantled and transferred to the three-point bending test frame (Fig. 3a, c), as previously introduced by Robertson et al. [8]. A total of 1,000 bending cycles with a maximum load of 80 N were performed. The 80 N correspond to 18 % of the average total failure load of the original Sawbone clavicles. Finally, a three-point bending test to failure was conducted. Data were collected using testXpert II V3.0 (Zwick/Roell). The torsional moment and bending stiffness values were calculated at cycle nine from the slope of the torque–angular displacement and load–displacement curves, respectively.

Statistical analysis

Statistical analysis was carried out using a two-tailed Mann–Whitney *U*-test (SPSS 19.0, IBM). The presented box plots represent median, first and third quartiles. The error bars indicate maximum and minimum values.

Results

The data concerning pretesting, comparing cadaver and artificial bone (Sawbone), are summarised in Fig. 4.

Fig. 2 a Superior anterior clavicle locking compression plate (LCP). b Reconstruction plate

Fig. 3 **a** Setup for modified three-point bending test, pre-testing with cadaver bone. **b** Setup for axial compression and torsional testing. **c** Setup for modified three-point bending test; a locking compression plate (LCP) clavicle plate is shown

All 24 specimens were successfully tested for torsion and cantilever bending. In case of axial compression

Fig. 4 Load-to-failure testing in three-point bending comparing Sawbone versus cadaver bone ($p>0.1$)

testing, four specimens failed to produce a regular load–displacement curve. As a result values for axial compression stiffness could not be determined for these four samples (one specimen stabilised with a seven hole reconstruction plate, three with a clavicle LCP).

In axial compression, the seven hole reconstruction plate reached the significantly lowest values compared to the clavicle LCP and the ten hole reconstruction plate (Fig. 5a). The clavicle LCP showed the significantly highest torsional stiffness for external rotation in comparison to the reconstruction plates. For internal rotation, the same trend was apparent, although no statistical difference was seen. The total cantilever bending stiffness was found to differ significantly between the clavicle LCP and the ten hole reconstruction plate and between the seven hole reconstruction plate and the ten hole reconstruction plate (Fig. 5a–d). Analysing the load–displacement curve of cantilever bending, two different linear phases and slopes could be differentiated (Fig. 6a). Statistically, no difference could be determined in phase I, but in phase II the clavicle LCP and the seven hole reconstruction plates were

Fig. 5 Box plots demonstrating axial compression (N/mm) (**a**), torsional stiffness for internal rotation (10°) in Nmm/deg (**b**), torsional stiffness for external rotation (10°) in Nmm/deg (**c**), and total cantilever bending stiffness (N/mm) (**d**); *Indicates statistical significance ($p < 0.05$)

found to be significantly stiffer than the ten hole reconstruction plate (Fig. 6b–c).

All specimens withstood the 1,000 cycles of cantilever bending. None of the specimens showed signs of plate failure or screw loosening after 1,000 cycles of cantilever bending. In the load-to-failure testing (three-point bending) the fixation with the seven hole reconstruction plate failed at an average of 476 N, which is more than values reached for the intact Sawbone clavicle (440 N). The ten hole reconstruction plate reconstructions withstood loads averaging 401 N (91 % of 440 N), and the clavicle LCP failed at average loads of 450 N (102 % of 440 N). A statistical significance between the different groups could not be determined (Fig. 6d).

Comparing the load displacement curves, however, differences between the groups became evident. The clavicle LCP revealed an elastic bending stiffness with a linear slope until failure, whereas the ten-hole reconstruction plate already decreased in slope at loads below 200 N, representing a plastic deformation of the plate. A similar mechanism could be seen for the seven hole reconstruction plate (Fig. 7).

All clavicle LCPs failed by clavicle fracture proximal to the most medially inserted screws. The same failure mechanism was observed for six out of eight of the seven hole reconstruction plates, while two clavicles fractured adjacent to the most lateral screw. The ten hole reconstruction plate revealed a different failure mechanism, as these plates bent above the fracture site until the actuator lost contact with the lateral end of the clavicle (Fig. 8).

Discussion

As the indications for operative treatment of displaced midshaft clavicle fractures increase, a solid and reliable implant is indispensable. For this reason it is important to know the biomechanical characteristics of the available plates.

The goal of this study was to compare three frequently used plates with respect to their biomechanical properties and to gain insight into the mechanism behind the failure noticed in the clinical application of reconstruction plates.

Fig. 6 **a** Biphase curve for cantilever bending. **b** Stiffness of phase I measured between 15 and 30 N. **c** Stiffness of phase II measured between 60 and 75 N. **d** Cantilever bending load to failure. *Indicates statistical significance ($p < 0.05$)

Artificial bone was used since size and shape are easier to standardise, making the mechanical evaluation and comparison more reliable. A transverse fracture was induced because we wanted to gather data on the load to failure of the intact clavicle in comparison to the plate-fixed bone. Our tests also suggested similar properties of the synthetic bone when compared to formalin-fixed cadaver clavicles received from the local anatomy institute. The fracture morphology was reproducible and

in all cases a transverse two-part fracture could be achieved.

As suggested in a previous publication, we tested for torsional and axial compression as well as bending [9]. In our opinion, bending tests are essential, since weights lifted by the abducted arm lead to a multiplication of forces according to the laws of leverage at the fracture site [14], which is well simulated by the three-point bending test and has been established in previous work [8, 10].

Fig. 7 Load to failure curve of load (N) versus displacement (mm). **a** Clavicle locking compression plate (LCP). **b** 7-hole reconstruction plate. **c** 10-hole reconstruction plate

Fig. 8 Implants after load-to-failure testing. **a** Clavicle locking compression plate (LCP), fracture at the medial screw. **b** 7-hole reconstruction plate; fracture at the medial screw. **c** 10-hole reconstruction plate; deformation of the plate

All plates provided stable fixation, reaching on average more than 90 % of load-to-failure values when compared to the intact Sawbone and cadaver clavicle. The failure mechanisms determined here at least partially explain the clinically observed problem of plate breakage. The reconstruction plates showed signs of plastic deformation already at loads below 200 N. It is conceivable that everyday situations lead to an up and down bending of the plates, which might lead to plate failure in the long run. This particularly relates to the ten hole reconstruction plates, where early plastic deformation was observed. Thus, we do not recommend clinical application of this specific plate as a minimally invasive implant in combination with a closed reduction or in case of comminuted fractures lacking fracture support.

The biphasic load–displacement curve noticed in cantilever bending is mostly due to bending of the plate in the first phase and fracture support in the second phase. The second phase was characterised by a considerably higher stiffness than the first phase. In addition to the fact that a compression of the fracture induces improved fracture healing, the authors recommend achieving an anatomical reposition to improve fracture support.

Concerning conditions in cantilever bending tests, a recently published study by Demirhan et al. showed loosening of dynamic compression plates and instability of external fixators after 700 and 300 cycles. This early failure may be due to using non-locking screws and formalin-fixed bones and is thus difficult to compare with our study [15]. In our study, a load of 80 N and the 1,000 cycles of cantilever bending did not challenge the implants up to their maximum

load bearing capacity. In future studies, higher loads and more cycles may be performed.

With regard to axial compression and torsional stiffness, in previous studies, the application of a locking reconstruction plate resulted in values similar to those in our setup [8–10]. Partial et al., for example, used six hole locked reconstruction plates in the superior position and reached an average of 804 N/mm for axial compression, 440 Nmm/deg for external and 430 Nmm/deg for internal rotation [9] (compare Fig. 5).

In all tests, the clavicle LCP provided higher average stiffness in comparison to the seven hole reconstruction plates, reaching statistical significance for axial compression and external rotation. It remains unclear why the ten hole reconstruction plate reached the highest values in axial compression; in all other categories the ten hole reconstruction plate reached the lowest figures.

In conclusion, this study shows mechanical superiority of a precontoured plate compared to a regular contoured plate. The design of the LCP combines an anterior position at the medial part of the plate and a superior position at the lateral end of the clavicle (Fig. 2). Consequently, the plate leads to better mechanical outcomes than those determined in previous tests performed to compare superior or anterior positioning of reconstruction plates [8, 9, 16]. Apparently, the specific design of the plate per se provides a higher strength and stiffness when compared to reconstruction plates.

Even though the extrapolation of results obtained in an in vitro setting to in vivo situations remains difficult, based on our study results and in agreement with our clinical experience, we recommend using the LCP clavicle

plate especially when treating comminuted or multipart fractures.

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