TRAAUA: RESEARCH

A comparison of parallel and diverging screw angles in the stability of locked plate constructs


From the AO Research Institute, Davos, Switzerland

We investigated the static and cyclical strength of parallel and angulated locking plate screws using rigid polyurethane foam (0.32 g/cm³) and bovine cancellous bone blocks. Custom-made stainless steel plates with two conically threaded screw holes with different angulations (parallel, 10° and 20° divergent) and 5 mm self-tapping locking screws underwent pull-out and cyclical pull and bending tests. The bovine cancellous blocks were only subjected to static pull-out testing. We also performed finite element analysis for the static pull-out test of the parallel and 20° configurations. In both the foam model and the bovine cancellous bone we found the significantly highest pull-out force for the parallel constructs. In the finite element analysis there was a 47% more damage in the 20° divergent constructs than in the parallel configuration. Under cyclical loading, the mean number of cycles to failure was significantly higher for the parallel group, followed by the 10° and 20° divergent configurations.

In our laboratory setting we clearly showed the biomechanical disadvantage of a diverging locking screw angle under static and cyclical loading.

One of the greatest unsolved problems in trauma surgery is the stabilisation of osteoporotic fractures. It is reported that 58% of women between 70 and 79 years of age and 84% of women older than 80 years have osteoporosis, which is related to approximately 52% of all fractures. In the treatment of these injuries new implants and techniques have been developed, especially to improve the stability of the bone-implant interface. A recent advance was the internal fixator with angular locking screws, whereby stability is gained by locking the screw head in the plate, in contrast to conventional plate-screw configurations where stability is obtained by compressing the plate to the bone with the screw. Biomechanical and clinical studies showed the mechanical and biological advantages of the new concept. It also appeared intuitive that diverging or converging screws could enhance their purchase, and many of today’s locking implants show non-parallel screw alignment. In a specific case, oblique screw angles might allow the use of longer screws and aim them to regions with superior bone stock. However, the question whether non-parallel screws provide enhanced stability remains unanswered, and hitherto only a few biomechanical studies have addressed this issue by undertaking static pull-out tests. Their relevance is questionable, as physiological loading is complex and can be simulated only marginally by static tensioning of the screw. All of these investigations found that the lowest pull-out strength was with angulated screw configurations.

In this study we investigated the static and cyclical strength of angular stable screw and plate constructs in an artificial bone model and bovine cancellous bone. We performed a static pull-out test to compare our model with earlier studies and undertook cyclical testing to simulate a more clinical example of failure.

Materials and Methods

Specimens and instrumentation. In the first part of the study we used cellular rigid polyurethane foam with a density of 0.32 g/cm³, compression strength of 5.4 MPa and compressive modulus of 137 MPa (Sawbones Europe AB, Malmö, Sweden). The foam contained e-glass fibres and the pore size ranged from 0.5 mm to 1 mm. This model was chosen for its comparability with osteoporotic proximal femoral bone. A total of 48 foam blocks (130 mm × 40 mm × 15 mm) were used and divided into three groups (parallel, 10° and 20°) of eight specimens each for static and cyclical loading.

In the second part we used fresh frozen cancellous bone blocks (30 mm × 40 mm × 15 mm) from bovine distal femurs. Their bone mineral density (BMD) was measured.
using peripheral quantitative CT scans (pQCT, DensiScan 1000; SCANCO Medical AG, Brüttisellen, Switzerland), according to which, pairs of bone blocks were defined. The test specimens were produced by embedding each pair in polymethylmethacrylate (PMMA) (Beracryl; W. Troller Kunststoffe AG, Jegenstorf, Switzerland) using a spacer (Fig. 1) and then randomised by list into three groups of eight specimens each (parallel, 10° and 20° divergent) with equal distribution of density.

We used custom-made stainless steel plates, 80 mm long, 12 mm wide and 6 mm thick, with two conically threaded screw holes located 60 mm apart (Figs 2a to 2c). Each plate was configured to lock two screws at a specific angulation (group 1, parallel (Fig. 2e); group 2, 10° divergent (Fig. 2f); and group 3, 20° divergent (Fig. 2g). The locking screws were self-tapping with a length of 40 mm and diameter of 5 mm (LCP Locking Screw; Synthes, Solothurn, Switzerland).

The specimens were inserted in a custom-made jig to allow standardised instrumentation. Using a mould, the plate was centred and in contact with the foam block. Pilot holes were drilled using an LCP drill guide with a 4.3 mm drill bit (Synthes). The screws were inserted with the drill, then locked by hand with a standardised torque of 4 Nm (Torqueleader; MHH Engineering Ltd, Guildford, United Kingdom). All the screws penetrated the 15 mm thick specimens completely.

**Biomechanical testing.** The plate was connected to a custom-made jig (Figs 2c and 2d), with the specimens rigidly clamped to a counter-bearing.

The static and cyclical pull-out tests were performed with varying load vectors on eight specimens per group and test. The eight bovine cancellous blocks were only tested under static pull-out conditions.

For the pull-out test we used an electromechanical testing machine (INSTRON 4302; Instron GmbH, Pfungstadt, Germany) with a 10 kN load cell. The jig was connected to the load cell using a cardan joint (Fig. 3) and the test performed in displacement control at a crosshead speed of 5 mm/min.

Cyclical testing was performed on a servohydraulic testing machine (MTS Bionix 858; MTS Systems Corp., Eden Prairie, Minnesota). The jig surrounding the plate was connected to the actuator of the machine using a hinge and a steel wire rope (Fig. 4). This resulted in the application of a 30° angulated force, thereby leading not only to pull-out but also to bending moments at the plate-bone interface. Cyclical
testing was performed at 1 Hz, starting at a load of 50 N, which was increased continuously at 0.09 N per cycle. The valley load was kept constant at 20 N. In addition, the actuator rotated cyclically about the vertical axis with an amplitude of 270° at 7.2° per second in order to vary the load vector with every cycle (Fig. 5). Failure was detected using two inductive miniature displacement transducers (WA-T, Hottinger Baldwin Messtechnik GmbH, Darmstadt, Germany) with a displacement range of 5 mm. They were fixed to the jig holding the plate, 42 mm from the insertion point of the screw.

The lower pictures focus on the specimen showing the displacement transducers mounted on plate holding device.

**Finite element analysis.** For the static pull-out test a finite element analysis was performed using Abaqus Software (Abaqus Version 6.8-3; Dassault Systemes Simulia GmbH, Aachen, Germany). In order to represent the experiment as closely as possible, we modelled a solid foam cube and imported the geometry of a 5 mm locking screw (LCP Locking Screw; Synthes). After Boolean operations the foam and screw were meshed with tetrahedral elements of four nodes each, linear displacement behaviour and three degrees of freedom at each node. The model was assumed to be linear, elastic and isotropic, with a Young’s modulus of 137 MPa for the foam and 186 GPa for the screw. The Poisson ratio was 0.3 for both components and the frictional contact (penalty behaviour) between screw and foam was defined as a constant friction coefficient of 0.4. The unidirectional loading (250 N) of the screw was parallel to the foam surface with locked rotation of the screw head. With these boundary conditions we performed an analysis in the two most differing configurations (parallel and 20° divergent).

**Data evaluation and statistical analysis.** The static pull-out force was derived from the load-displacement curves and defined as the first force peak. The tension stiffness was determined from the linear region of the load-displacement curves. For cyclical loading the number of cycles to failure was determined when one of the transducers reached a displacement of > 1.6 mm.

For the finite element analysis we calculated the amount of foam volume stressed (von Mises criteria) above the compression strength limit (5.4 Mpa) in order to evaluate the damage for both simulated conditions. Statistical analyses were performed using SPSS software (SPSS 18; SPSS Inc., Chicago, Illinois). After testing for
normal distribution within each group (Shapiro-Wilk test), significant differences between the groups of artificial bone were detected with the Mann-Whitney test. For the bovine cancellous bone results we used a univariate ANOVA test with BMD as a covariate and a level of significance $p < 0.05$.

Results

**Static pull-out test: artificial bone.** The mean pull-out force for the parallel constructs was a mean of 1.19 kN (SD 0.05). The 10° and 20° divergent constructs revealed pull-out forces of 0.71 kN (SD 0.1) and 0.64 kN (SD 0.09), respectively (Fig. 6). The constructs with a parallel screw alignment showed the significantly highest mean pull-out force ($p < 0.001$). The 10° and 20° divergent constructs reached 60% and 54% of the pull-out force compared with the parallel construct, with no statistically significant difference between the divergent groups ($p = 0.195$). The mode of failure in all groups was stripping of the thread.

The highest mean construct stiffness was for the parallel screws (1.21 kN/mm; SD 0.06) ($p < 0.001$; Fig. 7). The divergent constructs showed a mean axial stiffness of 0.98 kN/mm (SD 0.1) at 10° divagation and 0.83 kN/mm (SD 0.07) at 20°. This was 81% and 69% of the axial stiffness of the parallel screw construct, respectively.

**Static pull-out test: bovine cancellous bone.** The bovine samples showed a mean bone density of 0.512 g/cm$^3$ (SD 0.18) and the mean pull-out force with the parallel screw insertion was 3.68 kN (SD 1.1). For the 10° and 20° constructs the mean pull-out force was 3.68 kN (SD 1.1) and 2.32 kN (SD 0.7), respectively (Fig. 6). There was a statistically significant difference between the parallel and 20° ($p = 0.006$) and 10° and 20° ($p = 0.003$) groups, but no significant difference between the parallel and 10° groups ($p > 0.99$). The 20° divergent constructs reached 63% of the pull-out force of the parallel constructs.

The mean stiffness for the parallel screws was 3.98 kN/mm (SD 0.89), whereas the 10° and 20° divergent constructs showed a mean stiffness of 4.26 kN/mm (SD 0.49) and 2.13 kN/mm (SD 1.13), respectively (Fig. 7). There was a statistically significant difference between the 10° and 20° ($p = 0.006$) and 10° and 20° ($p = 0.003$) groups, but no significant difference between the parallel and 10° groups ($p > 0.99$). The 20° divergent constructs reached 63% of the pull-out force of the parallel constructs.

**Cyclical test.** The mean number of cycles to failure was highest for the parallel group, where the constructs failed at a mean of 2750 cycles (SD 450). The divergent constructs survived a mean of 2154 cycles (SD 287) at 10° and 1354 cycles (SD 310) at 20°. Compared with the parallel screws, the angulated constructs reached 78% and 49% of the number of cycles to failure of the parallel construct, respectively. All these differences were statistically significant ($p < 0.01$; Fig. 8). The mode of failure, stripping of the thread of one of the two screws, was the same for all groups.
Finite element analysis. The amount of damage to the foam in the finite element model was 0.011% compared with 0.016% for the parallel and 20° divergent set-ups, respectively. This represents a damage reduction of 47.4% for the parallel configuration compared with the 20° divergent set-up, and is in accordance with the results of the pull-out tests. Contour plots of the von Mises stress\(^\text{15}\) reveal an asymmetric stress distribution, with one-sided stress concentrations for the 20° configuration (Fig. 9).

Discussion

With decreasing bone quality the weak point of a locking screw construct shifts from the screw-plate interface to the bone-screw interface.\(^\text{16}\) In order to enhance stability, further changes in the screw configuration were introduced, and although angulated screw configurations might seem to offer enhanced stability,\(^\text{17}\) this belief was never proved.

Some studies have investigated the biomechanical effects of screw angulation in conventional and locked plate constructs. Robert et al.\(^\text{10}\) tested angulated screws in conventional plates in a range from parallel to 40° divergence, using rigid polyurethane foam blocks. They showed a significantly higher pull-out force for the parallel constructs and no significant decrease above 20°. Bekler et al.\(^\text{18}\) investigated different insertion angles of locking screws using an artificial osteoporotic bone model. They also found the highest pull-out force with parallel screws, and the divergent screws showed no difference between 15° and 30°. However, the axial stiffness showed an inverse behaviour and was highest for the divergent constructs.\(^\text{8}\) In another study, Perren et al.\(^\text{9}\) investigated the biomechanical behaviour of locked parallel and angulated screws. They found that the pull-out force was highest for the constructs with 40° angulated screws, but for the 10° and 20° angulated constructs the pull-out force was significantly lower than with parallel screws. Dipaola et al.\(^\text{18}\) investigated the influence of screw orientation in anterior cervical plate constructs and also found that the highest pull-out force was with parallel screws. As these studies support our findings of lower pull-out forces with screws angulated up to 30° compared with parallel configurations, we could not support the conclusion of Bekler et al.\(^\text{8}\) that angulated screws provide higher construct strength.

The common limitation of these studies is the use of a static pull-out model. Physiological loading is complex, and it is predominantly alterations in cyclical loading that are believed to cause failure of osteosynthesis, especially cut-out.\(^\text{19,20}\) We therefore performed alternating loading with a tension and bending component to simulate the clinical situation. All these tests showed a clear tendency for superior construct stability and stiffness with parallel screw configurations, and the finite element analysis allowed a better understanding of the underlying mechanics. A higher proportion of loaded elements exceeding the yield stress of the material was found in the simulated bone structure for the 20° divergent model. The loading stress concentrated on the divergent side of the screw (upper side), whereas unloading of the elements was seen on the other side of the screw thread. Conversely, in a parallel screw arrangement bone stress was found to be distributed evenly around the screw, resulting in a biomechanically superior condition.

Notwithstanding our efforts to simulate the clinical condition, our investigation still represents an abstract experimental setting. To what extent the findings apply to clinical practice cannot be fully answered here. It may be possible to increase the screw length with an angulated locking hole, and it is reported that longer screws, when tested individually, have a higher failure strength, with a gain of about
16 N/mm. Moreover, local differences in bone density may be compensated for by targeting angulated screws to regions of superior bone stock. This advantage applies particularly to porotic bone, but requires anatomical knowledge. Our study intended to draw an overall picture of the performance of diverging locking screws without regard to a specific application. The performance of a construct under particular conditions depends strongly on local physiology and must be investigated individually.

We used a homogeneous cancellous bone model and did not consider the influence of cortical bone. In relation to the study of Singh et al., who reported values of approximately 0.2 g/cm³ for the osteoporotic human femoral head, bovine bone shows a 2.6-fold higher BMD and therefore only marginally reflects the human situation. Axial stiffness and pull-out force were similar for the parallel and 10° divergent constructs in bovine bone, and it may be possible that the comparatively high BMD rules out the weakening influence of the angulated screws. Although cyclical testing approximates physiological conditions there are still major differences, such as a predominant pull-out component. Physiological loading does not exclude pull-out but, for example, plates are mainly loaded in axial compression with superimposed bending.

Our experiments showed that increasing the insertion angle of two locked screws from a parallel to a diverging configuration impairs the static pull-out resistance and fatigue performance under cyclical loading. Also, with the application of a periodically varying load vector, the mean number of cycles to failure decreases continuously as the angle of insertion of the screw increases. Our finite element model was in agreement with these results, and all tests suggest that angulated screws in locked plate constructs do not provide better stability than parallel screws.

References