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Pull-out strength of screws from cortical bone in the maxillo-facial region

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The fixation of maxillofacial fractures is an important clinical procedure, which may be achieved by the attachment of plates across the fracture. The stability of the fracture will depend on the stiffness of the fracture fixation plates and the security of the fixation screws to the thin maxillofacial cortical bone. The design of screws, manufactured by Champy and AO were tested from both mini- and micro-fixation systems. Pull-out tests were conducted on cortical bone plates, ranging in thickness from 0.6 to 3.5 mm. No significant differences were observed in the ultimate pull-out forces achieved for both mini-systems of 2 mm outer diameter. However, these pull-out forces were generally greater than those obtained for the micro-screws, even at the lower bone thicknesses. Two models were developed which attempted to predict the behaviour of screw pull-out failure. The failure mechanism was primarily dependent on the thickness of the bone, with secondary influences related to the shear strength of the bone and a geometrical factor of the screw.

1. Introduction

Conventional fixation of mandibular and other maxillofacial fractures is performed either by wiring together the bones or by the attachment of fixation plates to areas of thin cortical bone, using screws, either side of the fracture. The plating devices were developed in a form known as the mini-fixation systems; more recently micro-fixation systems have been marketed and used successfully. Some studies have been performed on the effectiveness of a single fixation system [1–3], while others have compared a small number of fixation methods or designs [4–6].

In a recent study [7], a selection of six mini-plates from five manufactures, were compared and some differences between the plates were observed, although none were statistically significantly different. The mini-plates were generally both stiff in bending and strong in tension. The study indicated that the limitation of the fixation system might involve the attachment of the plates to areas of very thin cortical bone. Of the few appropriate studies, Haug [8] showed that the number of screws rather than the screw length produced statistically significant differences on the overall performance of the fixation system. Other studies [9] have investigated the stripping torque rather than the force to cause pull-out failure, infering the problem to be one of safe insertion and secure fastening of the fixation plates rather than of the loads experienced following fixation.

Eppley and Sadove [10] observed that the maximum torque reached before the screw stripped the bone was largely independent of both screw diameter and pitch. Nevertheless, if screws are inserted into bone of thickness less than one pitch of the screw the holding power will be considerably reduced. Clearly, in clinical practice, if a surgeon is aware of a minimum effective bone thickness, then alternative, appropriate plate positioning or fixation methods can be selected. Determining the screw holding strength of the maxillofacial devices from various thicknesses of bone have not been fully explored in the literature.

The current study investigates the influence of screw design and cortical bone thickness on pull-out strength. Comparisons will be made between the thickness and a model developed for the influence of thickness on screw pull-out strengths.

2. Method

Fresh bovine tibial bone was collected and machined, wet, into parallel-sided plaques of cortical bone. The bone was stored at $-20\,^{\circ}C$ until the day of testing, when the bone was defrosted and soaked in water. The first test was carried out on bone plaques using standard 2 mm diameter Champy self-tapping mini screws. Ten plaque thicknesses were tested, of range 0.4 to 1.0 mm, in intervals of 0.2 mm, and 1.5 to 3.5 mm, in intervals of 0.5 mm. Five Champy mini-screws were tested at each thickness. Holes were drilled in the bone using the drill supplied by the manufacturer. The screws were inserted to a depth such that a full screw pitch protruded through the rear

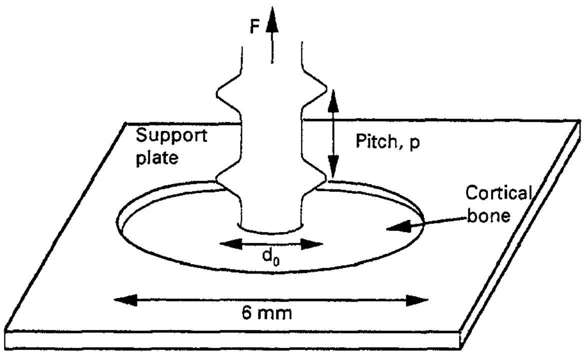

Figure 1 Schematic for the loading arrangement for pull-out tests of screws from bone.

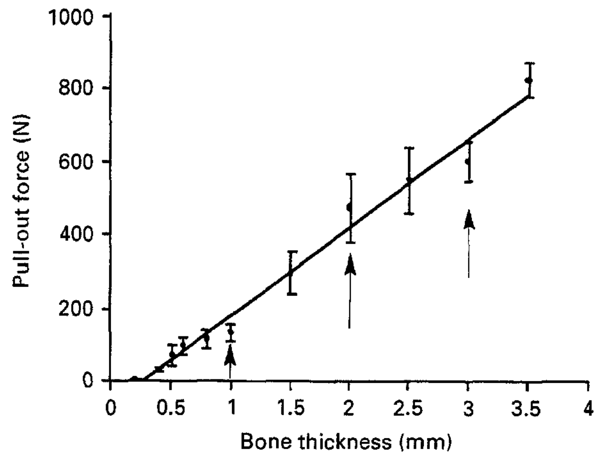

Figure 2 Correlation of 2 mm diameter Champy mini-screw pull-out force (F) with bone thickness (t); the error bars represent standard deviations. The arrows indicate where a complete screw turn has been completed.

bone surface. The bone and screw were placed in a jig, as shown in Fig. 1, and load was applied through the screw head on an Instron 6025 Universal testing machine at rate of 1.667×10^{-2} mm s^{-1}. The bone was constantly irrigated with Ringer's solution throughout the test.

A subsequent series of tests were carried out on a range of titanium mini and micro-screws, to study the influence of diameter and screw pitch on pull-out strength, at four cortical bone thicknesses, namely 0.6, 1, 1.5 and 2 mm. The screws tested were the standard Champy mini, Champy (Lorenz Martin) micro, AO 2.0 mm craniofacial mini and the AO micro-screws, as detailed in Table I; ten screws were tested for each group, at each bone thickness, utilising drills and equipment supplied by the manufacturers.

3. Data analysis

The peak load to failure was recorded and referred to as the pull-out force. Unpaired Student's t-tests were performed on the data.

4. Results

During insertion of the self-tapping, micro AO and Champy screws into thicker bone, of 1.5 to 2 mm, there was a tendancy for the heads to shear off. However, it was found that where minimal force was used and the screwing direction was frequently reversed that it was feasible to insert the screws into these thicknesses.

The pull-out tests produced a consistent pattern of shear failure at the thread-tip–bone interface. This resulted in a retrieved screw with a cylinder of bone material, at its outer diameter, filling the thread profile. The screw–bone interface failed rapidly during the pull-out test, with brittle failure apparent. Once failure had initiated, the screw showed little holding resistance. When the results for all pull-out tests with the Champy mini-screws were combined for different cortical thicknesses, Fig. 2, a linear relationship ($R^2 = 0.943$) was produced of the form

$$F = -55.8 + 243t$$

where F is the pull-out force (N) and t, the bone thickness (mm). It should be noted that this relationship has a dependence upon the pitch of the screw, which was 1 mm for this set of data. Indeed, when the data is examined for tests in bone of low cortical bone thickness, the linear correlation showed a different and lower gradient, Fig. 3. Clearly the pull-out force is highly variable, despite using uniform bone stock.

Comparisons between the four screw types tested are shown in Fig. 4, with the individual relationships for pull-out force against thickness summarized in Table II. Assuming a linear relationship, then the intercept on the y axis provides an indication of the screws performance at low bone thicknesses. The AO micro-screw performs well at low bone thicknesses, however, the increase in gradient, or pull-out strength per unit bone thickness, is low. At bone thicknesses of 0.6 mm the pull-out forces were similar for all screw designs, although the Champy mini-screw's force to pull out was significantly higher, $p < 0.05$, than the Champy micro-screw. At a bone thicknesses of 1.5 and 2 mm the AO mini-system showed a significantly higher holding force than the Champy mini-system, $p < 0.05$, although the two micro-system screws

TABLE I Design details of fixation screws

Manufacturer	Reference	Core diameter (mm)	Outer diameter (mm)	Pitch (mm)	Drill diameter (mm)	Screw catalogue no.
Champy	min	1.6	2	1.0	1.6	25-090-11
Lorenz Martin (Champy)	micro	1.1	1.5	0.5	1.1	25-070-08
AO	mini	1.4	2	0.6	1.5	401.78
AO	micro	0.72	1	0.23	0.76	400.508

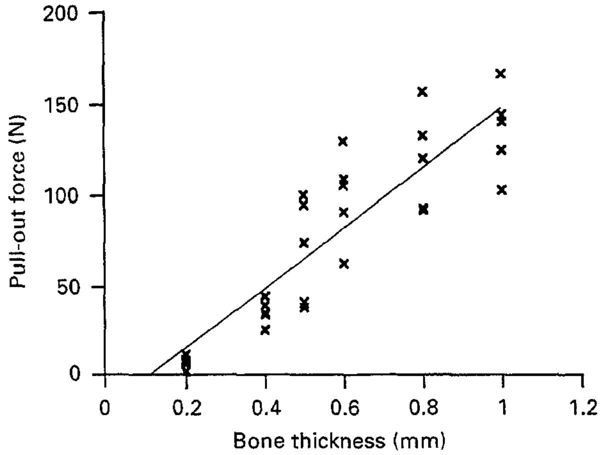

Figure 3 Detail of relationship for pull out force of Champy mini-screws in thin bone plaques. The linear correlation $F = -18.5 + 166t$ was established, $R^2 = 0.783$.

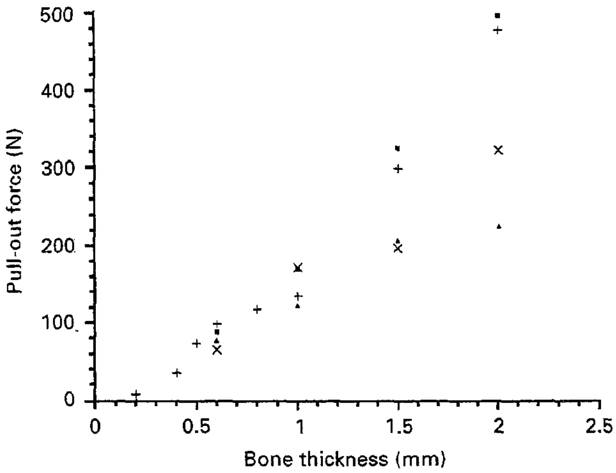

Figure 4 Comparison of the mean values of the pull-out strength of four screw types: Champy mini (+) and micro (×), AO mini (■) and micro (▲), for up to 2 mm cortical bone thicknesses.

TABLE II Constants found in the linear relationship between bone thickness and pull-out force at low (less than 1.5 mm) bone thicknesses for Champy and AO micro-screws, mini-screws.

Screw type	Intercept (N)	Gradient (N/mm)	R^2
Champy mini	− 60	243	0.985
Champy micro	− 26	169	0.941
AO mini	− 107	296	0.99
AO micro	15	113	0.947

showed the same holding resistance. In 2 mm thick bone the Champy (Lorenz Martin) micro-screw was shown to be superior to the AO micro-screw, although neither of the micro-screws would be as suitable as the mini-screw at these bone thicknesses.

5. Model of pull-out failure

The failure of the screws in bone was modelled to predict the factors influencing failure.

5.1. Model 1

When a screw pulls out due to the shear failure of the bone the material failure will occur at the tips of the screw threads. Assuming the screw distributes the load from the head of the screw evenly through the bone then

$$F = \pi d_0 t \tau_{mean} \quad (1)$$

where τ_{mean} is the shear stress on the bone taken as a mean shear force, F, across the whole bone thickness, t, and d_0 is the outside diameter of the screw.

If τ_{mean} is taken as the ultimate shear strength of the bone i.e. τ_{uts}, which varies between 48 and 80 MPa [11], then the ultimate pull-out force by shear failure will then be a function of the outside diameter of the screw and the thickness of the bone.

5.2. Model 2

The analysis for model 1 assumed that the load on the bone is a constant throughout the thickness of the bone, i.e. the threads transmit the same load across all the threads. However, this simple approach can be modified by assuming that the first thread bears the largest percentage of the load and that the load falls off through the thickness. Assuming a continuous linear decrease in the load with distance along the thread, where the total length of the thread in the bone is $\pi d_0 t/p$, given p as the pitch of the thread, then the total load on the screw is the sum of the loads along the screw:

$$F = \frac{f'(\pi d_0 t)p}{2} \quad (2)$$

where f' is the maximum load/unit length occurring at the insertion point of the thread. Therefore the load/unit length one pitch lower than this point, f'' will be

$$f'' = \frac{2Fp^2\left(\frac{t}{p} - 1\right)}{p d_0 t^2} \quad (3)$$

The mean load carried by the first thread, F_1, is given by:

$$F_1 = \pi d_0 \left(\frac{f' + f''}{2}\right) \quad (4)$$

and from Equations 2 and 3

$$F_1 = \frac{Fp(2t - p)}{t^2} \quad (5)$$

Assuming cylindrical pull-out occurs, taking into account the reduction in load over the threads, and assuming that failure initiates over the first screw thread, then the predicted pull-out load will be:

$$F = \frac{\pi \tau_{mean} d_0 t^2}{(2t - p)} \quad (6)$$

These two models are presented in Fig. 5 and are compared with the experimental data for Champy mini-screws. Clearly the simplistic model 1 predicts

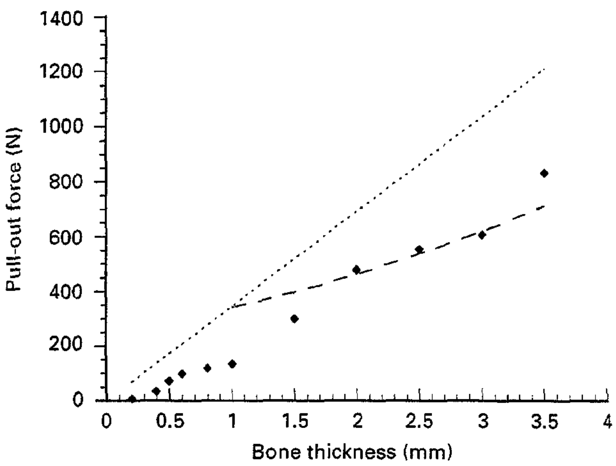

Figure 5 Comparison of the model with experimental data, showing good correlation between bone thicknesses of 2 and 3 mm, for model 2. A value for the shear strength of bone, τ_{mean}, of 58 MPa was used in both models: ◆ experimental; ----- model 1; --- model 2.

too high a value for the pull-out force. Model 2 predicts more accurately the pull-out forces at bone thicknesses greater than 2 mm, although the model also fails to predict pull-out force in bone of thickness less than two screw pitches.

6. Discussion

When standard Champy mini-screws were carefully placed in dense, good quality cortical bone, the forces required to pull them out increased with increasing bone thickness, up to a value of approximately 800 N at 3.5 mm. However, in maxillo-facial surgery it may be difficult to position the screws so that they be inserted into such thick cortical bone. In the mid-face, the range of cortical bone thickness might be expected to be 1–2 mm, where the pull-out forces range from around 100 N to 300 N. Loukota and Shelton [7] found the ultimate load in four-point bending for the standard Champy mini-plate with six holes, to be approximately 115 N; in this case, there would be three screws either side of the fracture to withstand the bending forces and so screws inserted into bone thicknesses as low as 0.5 mm would still be able to withstand the forces applied. However, there would be no safety factors, and probably a bone thickness of 1 mm would be preferable.

In bone thicknesses of over 1 mm it appears that only four screws (two either side of the fracture) are required to adequately fix a mini-plate onto bone. Any extra screws would only cause increased injury to the bone and would often not serve any useful mechanical purpose. There have been a number of studies that have investigated the effectiveness of whole plating systems [8, 12]. Haug [8] found that screw length had no effect on a plate to resist bending forces perpendicular to the long axis of the plate, and, not surprisingly, the screws did not pull out. It was also established that the maximum load that could be withstood used three screws each side of the osteotomy, and that four screws did not increase this load. This confirms that the number of screws used should be restricted to a minimum, between two and three screws either side of any defect. The parameter that was considered to influence the results considerably was the quality of the bone itself – this is clearly a clinical aspect that can only be considered when making a decision, but cannot be changed.

At lower bone thicknesses the situation becomes more complex. As shown in Table I, the pitch of the mini-screws is around 1 mm, while for the micro-screws it is 0.28 mm. Although it has been found previously [10] that screws inserted into bone of thickness less than the pitch of the screw will reduce the holding power considerably, this dramatic effect was not found in the current study. The decrease in the pull-out force, or holding power of the Champy mini-screws at thicknesses of less than 1 mm did not consistently fall beneath the linear regression. Equally, screws of smaller diameter did not perform significantly better at low bone thicknesses than those of larger diameter. Below a bone thickness of 0.6 mm it became very difficult to insert the screws into the bone as the bone was very fragile. In a clinical situation this problem would be even more severe. In the clinical situation it would be more difficult to drill and position the screws as carefully and the quality of the bone itself will be much more variable than the bovine cortex used in the current study.

Comparing the four screw types, the micro-screws did not perform significantly better, even at the thinner bone sections, than the mini-screws despite their smaller pitch. At 1.5 mm and 2 mm the micro-screws were substantially weaker than the mini-screws, with failure occurring as a result of the head deforming. Both the AO and the Champy screws performed in a similar manner. Luhr [13] found the retention of 0.8 mm diameter, non-tapped microscrews to be only slightly below the value of 2 mm diameter screws. In clinical articles, larger mini-plates are recommended in order to provide a greater resistance to displacement.

When a linear model was used to fit the data for the pull-out force versus bone thickness, a good correlation of $R^2 = 0.985$ was found, although it is apparent from the graph that there are other influences, which could relate to the pitch of the screws. Failure occurs around the screw thread tip, and causes a shear failure of the surrounding bone. A previous study [14] described a linear model for pull-out force, F:

$$F = \frac{t}{p} G \tau_{mean}$$

where G was described as a geometrical factor for the screws, which could have included the diameter. The inverse relationship with the pitch of the screw was established, although this was not supported in the current study. This model, however, was developed for thick cortical bone, with larger bone screws than considered in the current study.

In a previous study [12] comparisons were made between the mini- and micro-systems in an animal model, for a bone thickness of approximately 2 mm. Concern was expressed that the micro-screws would not withstand the higher mechanical loads in the regions of the midface. From the evidence of the current work, the micro-screws must be used with great care in bone of thickness greater than 1 mm, to prevent the heads shearing off. However in the thinner bone cross-sections the micro-plates with considerably reduced cross-sectional area, rather than the screws, may be the limiting factor.

There are differences between the bone contact that occurs in the different screw designs. In the AO system the size of the drill hole is greater than the core diameter, indicating an over-drilled hole although the thread depth was greater; this may account for the difference in holding power. In the larger screws there was 0.25 mm (AO) and 0.2 mm (Champy) of bone contact from the drilled core to the screw tip, whereas for the AO micro screws there was just 0.12 mm of bone-screw contact.

The model developed for the screw pull-out indicates that, when there are at least two entire threads engaged in the bone, the model for shear failure of the bone, with the load distributed along the length of the thread, is fairly accurate. However, when the bone thickness drops below this, the model is no longer valid and the pull-out forces are considerably lower. Thus, the pull-out forces from bone are highly dependent on the thickness and material properties of the bone, to a minimum thickness, when other parameters start to dominate.

The study has shown that the maxillofacial cortical bone screws all behave similarly at low bone thicknesses, although different relationships can be established for each of the screw types and designs. The Champy mini-screws appear satisfactory at all bone thicknesses, although the AO mini-system is superior at 1.5 and 2 mm bone thickness. The overall fixation system would only require two screws on either side of the fracture to ensure adequate fixation of the plate to the bone.

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