Techniques for improving stability in oblique fractures treated by circular fixation with particular reference to the sagittal plane

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Biomechanical studies involving all-wire and hybrid types of circular frame have shown that oblique tibial fractures remain unstable when they are loaded. We have assessed a range of techniques for enhancing the fixation of these fractures. Eight models were constructed using Sawbones tibiae and standard Sheffield ring fixators, to which six additional fixation techniques were applied sequentially.

The major component of displacement was shear along the obliquity of the fracture. This was the most sensitive to any change in the method of fixation. All additional fixation systems were found to reduce shear movement significantly, the most effective being push-pull wires and arched wires with a three-hole bend. Less effective systems included an additional half pin and arched wires with a shallower arc. Angled pins were more effective at reducing shear than transverse pins.

The choice of additional fixation should be made after consideration of both the amount of stability required and the practicalities of applying the method to a particular fracture.

Tibial fractures are common and complications such as delayed union or nonunion may lead to considerable long-term morbidity.1-3 The aim of surgical stabilisation of fractures is to achieve the optimum mechanical conditions for healing while avoiding complications and allowing the best conditions for early rehabilitation. Limited compressive movement is considered to stimulate union, whereas excessive shear movement is thought to be detrimental.4-12

Excessive shear is seen particularly in oblique fractures and has been thought to be a cause of their delayed union and nonunion.4,5,9 The unstable nature of oblique fractures, especially those occurring at the metaphyseal-diaphyseal junctions of the tibia,13-15 makes them difficult to manage effectively by either conservative or operative techniques. Various configurations and adaptations of circular fixators have been developed in an attempt to improve their mechanical attributes, their biological interface and their ease of application.16-20

Biomechanical studies involving both all-wire and hybrid types of circular fixation have found that oblique tibial fractures remain unstable under loading, leading to large shear movements at the site of the fracture21,22 To solve this problem, various authors have recommended the use of additional olive wires to supplement fixation.19,21,22

However, anatomical constraints prevent the use of olive wires when the plane of obliquity is sagittal, which is best seen on an anteroposterior (AP) radiograph.23 Our aim was to test a range of techniques for dealing with unstable oblique fractures which were not amenable to the use of olive wires.

Materials and Methods

Testing model. Eight testing models were constructed using synthetic tibiae (type 1104; Sawbones Europe AB, Krossverksgatan, Sweden). A jig was developed which contained cutting and drilling guides to ensure that the models were constructed identically in terms of the angle of obliquity, the plane of the fracture and the build of the fixation devices. The tibiae were fixed in the jig and oblique fractures in the sagittal plane were created using a hand-saw. Holes were pre-drilled for wires and screws. The osteotomies were made around the distal metaphyseal-diaphyseal junction with their centre 10 cm from the joint line. An obliquity of 70° to the horizontal was chosen since that was the most common in a clinical review of 36 oblique tibial fractures treated by the Sheffield ring fixator (Orthofix SRL, Verona, Italy). The two surfaces of the osteotomy were sanded using 80-grit sandpaper to reduce roughness in order to achieve consistent
friction at the site of the osteotomy. The fractures were then stabilised using the ring fixator. Four metaphyseal wires, with a crossing angle of 70°, were placed on one distal ring and tensioned to 1400 N using the same tensioner. Two diaphyseal screws were placed in the Sheffield clamp and a further screw was placed anterolaterally at 67.5° to the other two screws, which corresponded to the holes in the ring. All screws used were stainless-steel tapered (Orthofix) 130 mm long and 6 mm in diameter with a 40-mm threaded section.

The fracture was reduced fully. The condyles were then removed and a plate was fitted to the proximal tibia for fixation to the testing machine.

Methods of additional fixation. Six different methods for providing additional fixation were identified after a preliminary study had been carried out using 15 different techniques. The methods were chosen on the basis of practicability and mechanical performance in the preliminary studies using a single bone-fixator model. They were:

1) Arched wires (Fig. 1a). These consisted of two straight Kirschner wires inserted parallel to the plane of the fracture, one on either side of the line of the fracture. The wires were then arched and tensioned to 1000 N, compressing the site of the fracture. They were bent to the same degree in our study by moving each wire clamp by one hole round the ring. This corresponded to a movement of 7.5° for each clamp.

2) Arched wires in which the clamps were moved by three holes around the ring. This corresponded to a movement of 22.5° for each clamp.

3) Push-pull wires (Fig. 1b) which were developed as a technique for achieving compression across the site of the fracture. A wire with a short threaded segment at its tip was inserted across the site so that its thread engaged in the posterior cortex only. A pushing olive wire, as described by Atkins, Sudhakar and Porteous,24 was used to provide an opposing force on the anterior cortex. In our model the threads of the pulling wire were unable to achieve sufficient hold in the soft plastic bone and therefore an olive wire was used to test the concept. After insertion of the two wires, the pushing olive wire was tightened first against the bone and the pulling wire was then tensioned to 400 N.

4) Steerage pins (Fig. 1c) with an angle of 25° to the ring plate. This was the steepest that we could achieve using the equipment available, although for maximal effect the pins should be placed parallel to the plane of the fracture. The proximal steerage pin replaced the anterior supplementary screw and the distal pin was placed in an equivalent position to a transverse half pin. The steerage pins were tested against an additional control fixator in which the Sheffield clamp and supplementary screw sat above the proximal ring and a transverse distal half pin was inserted in its normal position. The steerage pins were inserted with identical pin spacing allowing a direct comparison of the influence of changing the angle of the pins (Fig. 2).

5) Transverse compression screws (Fig. 1d). These used the same technique as above (4) but, before testing, the distal screw was placed under tension in order to create a compressive force across the site of the fracture.

6) A transverse half pin (Fig. 1e). This was inserted in the distal fragment to improve the bending stiffness.

Testing procedure. The bone was fitted with an interfragmentary movement device which had been developed in-house and measured linear displacements in three dimensions. The device consisted of two parts, one of which had
three strain gauge sensors and the other a square metal block (Fig. 3). The sensors were connected to strain-gauge amplifiers linked to a PC data acquisition system (DASH 300, Amplicon Liveline Ltd, Brighton, UK). The sensors were individually calibrated to a resolution of 0.007 mm and an accuracy of within 5% using a universal materials testing machine (Autograph ASG10kN; Shimadzu Corporation, Kyoto, Japan). The movement device was mounted across the centre of the line of the fracture on the medial surface of the tibia. A template was used to fit it to the bone, ensuring an initial compression of the sensors. Care was taken to align the block and sensors parallel to the line of the osteotomy.

Cyclical compression tests were performed with a preload of 10 N and a maximum load of 200 N which was maintained for 1 sec. The loading rate was 10 mm/min. The loads were applied at five different locations on the compression plate by means of a steel ball, resulting in five different loading conditions, one axial and four off-axis compressions. In each loading condition three cycles were performed for conditioning followed by three cycles of actual testing. The analogue signals from the materials testing machine and the movement device were sampled at 20 Hz and stored in a personal computer for later analysis.

For each of the eight models, a standard fixator was tested before any method of additional fixation was applied to the bone. The bone was then fitted with the six additional systems and the test was repeated. The fixator was tested in its standard configuration before and after each additional method of fixation was tested in order to rule out any possibility of deterioration of the testing models throughout the repeated loading.

The methods of non-standard fixation were tested in the following order: push-pull wires, arched wires (one-hole then three-hole arch), transverse half pin, steerage pin, additional control for steerage pin and transverse compression screw. There was no indication that the presence of the holes from the previous methods of fixation altered the placement or performance of methods which were tested later in the process.

Processing of the data was performed using Microsoft Excel 2000 (Microsoft Corp., Bedmond, Washington). Each test consisted of three load cycles. A mean was calculated for each interfragmentary displacement component from the data points when forces were at 200 ± 5 N giving a single value every time a frame was tested.

**Statistical analysis.** This was performed with SPSS (SPSS Inc, Chicago, Illinois). The data for all the standard frames were subjected to repeated-measures analysis of variance (ANOVA) to test for changes in the mechanical properties of the frame after repeated loading. The statistical significance of the additional techniques was assessed using a paired t-test in order to compare each method of additional fixation with the standard fixator which directly preceded it in the testing process. The Bonferroni correction was used to account for repeated testing. In order to examine the relative merits of the additional fixation techniques, the differences between the methods of additional fixation and the control were subjected to repeated-measures ANOVA with Bonferroni adjustment for pair-wise comparison of the estimated marginal means. An arbitrary level of 5% was chosen to indicate statistical significance.

**Results**
Table I contains the mean (SEM 1.96) interfragmentary displacements in three dimensions under axial loading for the standard frames. It can be seen that AP shear was the major component of movement in these fractures and was the most sensitive measure to a change in fixation in our study. For this reason only the mean AP shear displacement for all five loading modes is presented (Table II).

There was no significant deterioration in mechanical performance throughout the loading of each model. The difference between the mean AP shear for the first test of each standard frame and the last test before the model was dis-
The null hypothesis that there was no difference between the standard frames tested at different stages in the testing process was accepted (repeated-measures ANOVA, $p = 0.18$).

Figure 4 shows box-plots of AP shear displacement under axial loading for each additional method of fixation. The paired $t$-test showed that all the additional fixation systems tested had significantly lower shear displacement than the standard frame ($p < 0.01$ for all null hypotheses examined). The mean differences were as follows: push-pull 2.11 mm; small-bend arched wires 0.82 mm; large-bend arched wires 2.00 mm; additional half-pin 1.22 mm; steerage 1.46 mm; compression pins 1.73 mm.

Repeated-measured ANOVA of AP shear displacement under all loading conditions showed that the additional fixation, loading modes and their interaction significantly affected the AP displacement ($p < 0.05$). However, the additional fixation was the most significant factor ($F$ statistics = 88) followed by loading modes and the interaction (both $F$ statistics = 2). The pair-wise comparison between the steerage pins and the additional control fixator (fitted with transverse pins in an otherwise identical configuration) was significant ($p < 0.05$, mean difference 0.53 mm). The most powerful methods for reducing shear were the push-pull wires and the arched wires with a greater bend, which were not significantly different from each other ($p = 0.563$), but were both significantly more effective than the other methods tested ($p < 0.01$ in each case). The arched wires with a greater bend were not significantly more effective than the transverse compression screws ($p = 0.342$). These and the steerage pins were the next most effective techniques ($p < 0.01$ compared with the additional distal half pin and the low-bend arch wire, $p = 0.084$ between them), followed by the additional distal half pin ($p < 0.01$ for all pair-wise comparisons). The low-bend arch wire was least effective ($p < 0.01$ for all pair-wise comparisons). The differences for the paired $t$-tests were approximately normally distributed, as were the residuals for the ANOVA analyses.

### Discussion
All the different methods of fixation were effective in reducing movement in this typically unstable fracture. Excessive shear movement in oblique fractures has been implicated in the literature as a cause of delayed union and nonunion although the amount of shear which may be acceptable is unclear.$^{4,5,9,10,12}$ In a study of 50 coronal-plane oblique fractures in our unit the use of additional fixation in the form of olive wires appeared to decrease healing times.$^{25}$ In a preceding study of such fractures,$^{22}$ olive wires were

<table>
<thead>
<tr>
<th>Loading mode</th>
<th>Standard</th>
<th>Push-pull</th>
<th>1-hole arch</th>
<th>3-hole arch</th>
<th>Additional half pin</th>
<th>Transverse compression</th>
<th>25$^\circ$ steerage</th>
<th>Additional control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Axial</td>
<td>2.19 (0.30)</td>
<td>0.07 (0.08)</td>
<td>1.25 (0.21)</td>
<td>0.13 (0.24)</td>
<td>1.06 (0.31)</td>
<td>0.40 (0.33)</td>
<td>0.80 (0.16)</td>
<td>1.33 (0.27)</td>
</tr>
<tr>
<td>Anterior</td>
<td>2.08 (0.23)</td>
<td>0.25 (0.14)</td>
<td>1.50 (0.18)</td>
<td>0.41 (0.31)</td>
<td>0.79 (0.21)</td>
<td>0.48 (0.37)</td>
<td>0.65 (0.13)</td>
<td>1.21 (0.45)</td>
</tr>
<tr>
<td>Posterior</td>
<td>2.59 (0.61)</td>
<td>0.29 (0.19)</td>
<td>1.49 (0.39)</td>
<td>0.49 (0.68)</td>
<td>1.59 (0.77)</td>
<td>0.81 (0.43)</td>
<td>1.12 (0.27)</td>
<td>1.65 (0.45)</td>
</tr>
<tr>
<td>Medial</td>
<td>1.94 (0.23)</td>
<td>0.29 (0.15)</td>
<td>1.17 (0.28)</td>
<td>0.40 (0.35)</td>
<td>0.85 (0.18)</td>
<td>0.43 (0.34)</td>
<td>0.75 (0.12)</td>
<td>1.19 (0.26)</td>
</tr>
<tr>
<td>Lateral</td>
<td>2.74 (0.38)</td>
<td>0.37 (0.09)</td>
<td>1.89 (0.22)</td>
<td>0.65 (0.55)</td>
<td>1.31 (0.65)</td>
<td>0.96 (0.25)</td>
<td>1.09 (0.20)</td>
<td>1.67 (0.28)</td>
</tr>
</tbody>
</table>

Table I. Mean (SEM 1.96) AP shear, mediolateral shear and compressive displacements measured under axial loading

<table>
<thead>
<tr>
<th>Method of fixation</th>
<th>AP shear (mm)</th>
<th>ML shear (mm)</th>
<th>Compression (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard</td>
<td>2.19 (0.29)</td>
<td>0.07 (0.08)</td>
<td>0.02 (0.10)</td>
</tr>
<tr>
<td>Push-pull 1-hole arch</td>
<td>1.25 (0.21)</td>
<td>-0.11 (0.06)</td>
<td>-0.02 (0.04)</td>
</tr>
<tr>
<td>3-hole arch</td>
<td>0.13 (0.24)</td>
<td>-0.02 (0.02)</td>
<td>0.02 (0.03)</td>
</tr>
<tr>
<td>Additional half pin</td>
<td>1.06 (0.31)</td>
<td>-0.12 (0.09)</td>
<td>-0.14 (0.33)</td>
</tr>
<tr>
<td>Transverse compression</td>
<td>0.40 (0.33)</td>
<td>0.02 (0.10)</td>
<td>0.02 (0.04)</td>
</tr>
<tr>
<td>25$^\circ$ steerage</td>
<td>0.80 (0.16)</td>
<td>-0.04 (0.16)</td>
<td>0.02 (0.11)</td>
</tr>
<tr>
<td>Additional control</td>
<td>1.33 (0.27)</td>
<td>-0.03 (0.07)</td>
<td>0.01 (0.12)</td>
</tr>
</tbody>
</table>

Table II. Mean AP shear (SEM 1.96) displacement under the five different loading modes

Carded was 0.02 mm. The null hypothesis that there was no difference between the standard frames tested at different stages in the testing process was accepted (repeated-measures ANOVA, $p = 0.18$).

Figure 4 shows box-plots of AP shear displacement under axial loading of 200 N for each of the different methods of fixation. The methods of fixation are as follows: 1, standard; 2, one-hole arched wire; 3, three-hole arched wire; 4, push-pull wire; 5, additional transverse half pin; 6, transverse compression pin; 7, 25$^\circ$ steerage pins; and 8, additional control fixator.

Box plots of peak AP shear measured under axial loading of 200 N for each of the different methods of fixation. The methods of fixation are as follows: 1, standard; 2, one-hole arched wire; 3, three-hole arched wire; 4, push-pull wire; 5, additional transverse half pin; 6, transverse compression pin; 7, 25$^\circ$ steerage pins; and 8, additional control fixator.
shown to reduce shear by a similar amount to the techniques demonstrated here.

Arched wires, a technique described by Ilizarov and Green,19 were effective in reducing shear. They are perhaps the most invasive of the techniques in our study, involving the anterolateral muscle compartment in a way which is familiar to users of all-wire frames. This, however, may be less popular with those who choose to use hybrid frames in which diaphyseal fixation is limited to the subcutaneous surfaces of the tibia. The greater bend of wire was clearly more effective at reducing shear movement, but we are concerned that the soft tissues are placed under excessive pressure by arching the wire to such a degree.

The push-pull technique, modelled using an olive wire instead of a true pulling wire, appeared to control movement at the fracture very successfully, allowing only very small amounts of shear. The limiting factor is likely to be the amount of tension that the thread of the pulling wire can withstand. We believe that the results of our study justify further investigation into developing a pulling wire which would be effective clinically. As with the arched wires and the transverse compression screw, this technique would have the added advantage of allowing the surgeon to improve the reduction of the fracture intra-operatively while maintaining a minimally invasive approach.

The additional half pin successfully reduced shear in these fractures, although to a lesser degree than many of the other techniques examined in this study. The advantages of this method are that it is the least disruptive, it is a simple procedure, the equipment is readily available and it is easy to remove in the outpatient clinic. The fracture would need to be central enough to leave a gap between the metaphyseal wires and the fracture line, allowing a corridor for insertion of the screw. Equally, half pins could not be used in fractures with intra-articular extensions, as the pin could not cross the fracture line.

Low levels of shear were achieved using the transverse compression pins, and this method could be applied with relative ease in simple oblique fractures. It was interesting to see that simply angling the half pins closest to the fracture site while discouraging length, but allowing small degrees of motion perpendicular to their shear performance. By resisting motion along their surfaces of the tibia. The greater bend of wire was clearly more effective at reducing shear movement, but we are concerned that the soft tissues are placed under excessive pressure by arching the wire to such a degree.

We are very grateful to Dr C. Taylor and Dr J. J. Hutson Jr, who developed the steerable pin and transverse compression pin, respectively. We would also like to thank Mr Milan Oleksak and Mr Tony Branfoot for the advice given to develop the techniques studied. The first author (AJM) wishes to acknowledge a scholarship from the Arthritis Research Campaign. 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