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The static and dynamic behaviour of tibial fractures due to unlocking external fixators

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Abstract

Objective. To determine how the mechanical environment of a tibial fracture is influenced by unlocking an external fixator frame.
Design. A clinical study examined 10 consecutive patients fixed with the Orthofix DAF.
Background. It has been claimed that the healing of diaphyseal tibial fractures is assisted by unlocking external fixators to allow free axial movement, but the influence on the mechanical environment at the fracture has not been established.
Methods. A transducer attached to bone screws measured dynamic interfragmentary displacement during walking both before and immediately after unlocking the fixator at 6 weeks in 10 subjects. Four subjects were monitored over the first hour after unlocking to measure interfragmentary gap shortening.
Results. Mean peak amplitudes of cyclical axial and angular displacement before unlocking were 0.46 mm (SD 0.27) and 0.37° (SD 0.30), and after were 0.42 mm (SD 0.19) and 0.34° (SD 0.28). Mean peak torsional and transverse shear displacements were 0.21° (SD 0.11) and 0.30 mm (SD 0.17) before unlocking, and after were 0.42° (SD 0.39) and 0.51 mm (SD 0.60). Gaps shortened permanently by unrecoverable axial translations of between 0.2 and 1.4 mm; the mean was 0.69 mm.
Conclusions. Unlocking was found more often to reduce both axial and angular motion, but to increase shear. Overall, this may reduce maximum longitudinal strains in the external callus. The reduced motion may arise from gap shortening.

Relevance

Reduced longitudinal strains in external callus may reduce the risk of re-fracture. Gap shortening brings the fragment ends into closer proximity, this should aid the stages of bone formation and remodelling. Therefore, strain reduction and gap shortening may be responsible for the benefit to healing claimed for the unlocking procedure. Copyright © 1996 Elsevier Science Ltd.

Key words: External fixator, displacement, fracture, tibia

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Introduction

It has been shown that fractures may heal by the indirect process that induces external callus and that the progress of healing is influenced by the degree of interfragmentary strain[1–6]. The healing process in stable fractures is therefore greatly dependent upon the mechanical environment provided by the fixation device and the loads applied during patient activity. The magnitudes of interfragmentary displacement required to produce rapid healing are unknown; it is known, however, that too great a displacement may cause a hypertrophic non-union, and too little may delay healing[7–10].

Interfragmentary loading may be induced with the patient either active or passive. Active induction can be through walking, producing cyclic axial motion (CAM)[11,12], while passive induction can be mechanically driven (CAM)[5,11]. Since fractures typically

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respond to the mechanical environment imposed by active loading, it is necessary to examine motion during routine activity. The motion to be examined should arise from common treatment regimes imposed by typical fixation systems. In the past, methods of measuring interfragmentary displacements involved measurement of the deformation of the external fixator frame[13,14]. Such measurements were not performed in each of the six degrees of freedom required for monitoring three dimensional movement. Also, the single degree of freedom devices used were capable of measuring only constrained axial motion arising from axial load. They could not be used to measure, for example, the axial motion that occurs during a routine patient activity, because this would have induced random bending and compressive motion and loading at the fracture site. Recently a new device has been developed which can measure dynamic interfragmentary motion accurately in three dimensions[12] during active movements arising from a three dimensional system of forces and moments. This device was used for the present study.

Fracture treatment methods have progressed away from the earliest external fixators, which attempted to reproduce the rigidity seen with internal compression plates and screws. This practice ceased when the advantages of healing by external callus formation were recognized, giving rise to widespread acceptance of the more flexible external fixators[8,10]. It was said that unlocking the column of a unilateral external fixator, allowing it to move freely axially, converted a more rigid external fixator into a dynamizing fixator. The term 'dynamization' may cause misunderstanding since it has been used to describe two different functions. It has been used to describe micromovement of the fracture due to cyclic interfragmentary movement of the unlocked fixator[15], and it has been used to describe the transfer of greater tibial load across the fracture to initiate 'dynamic compression' of the gap[17,18]. To avoid confusion, the terms 'locked' and 'unlocked' will be used here rather than dynamizing and non-dynamizing. It is maintained that the unlocked fixator allows only 'dynamic' axial movement to occur at the fracture site, implying that shear and angulation is prevented[17,18]; it is further maintained that unlocking assists fracture healing. Laboratory tests on externally fixated fracture models and previous studies on fracture movements in patients, have since indicated that external fixation frames allow significant angular and torsional interfragmentary displacement in both the locked and then unlocked mode[12,15]. Also, there is evidence from laboratory modelling that unlocking a fixator reduces angular displacement at the fracture but increases shear (torsional and transverse) displacement[15]. If this is found to be the case with patients, the reduced angular displacement may be beneficial for healing since it alters the longitudinal strains in the tissue at the periphery of the collar of callus where the strains are likely to be closest to yield and to refracture. However, small increases in shear displacement may cause substantial increases in strain and it has been shown that substantial shear movement may be deleterious to healing[19].

To date there have been no reported studies in human fractures that measure accurately in three dimensions the change in interfragmentary movements that arise from the common practice of unlocking external fixators. This has been done in the present study during walking activity as fractures typically heal under the mechanical regime imposed by routine weight-bearing. The fixators were unlocked at 6 weeks, which was within the period advocated by De Bastiani (4–6 weeks)[18]. As the size of the interfragmentary gap influences healing[20], the change in the passive gap size caused by non-recoverable translation was also monitored.

Materials and methods

Patient selection

Ten consecutive patients treated with an Orthofix® DAF External Fixator (Verona, Italy), were prospectively studied. Nine of the 10 subjects involved in the study were male. Their mean age was 29.3 years (range 16–57). Fracture patterns varied in structure from simple transverse fractures to spirally oblique, and soft tissue injury varied in severity. The fixators were unlocked at 6 weeks after fracture and before tests commenced it was confirmed clinically that all fixators were free to telescope during walking. At the time of unlocking all subjects required two crutches as a walking aid.

Measuring the interfragmentary motion (recoverable displacement) at the fracture

Interfragmentary motion was monitored continuously as the patient walked over a floor-mounted force plate, before and immediately after unlocking the fixator for the first time at 6 weeks (SD 0.3 weeks). The motion was monitored by the Oxford Micromovement Transducer (OMT)[21] shown in Figure 1, fixed to bone screws across the fracture site close to the bone. This used six magnetic field Hall Effect Devices (HED) (Honeywell 9206, Motherwell, Scotland) to measure displacements in six degrees of freedom, three linear and three rotational. The three-dimensional displacement of the base of the transducer in relation to the top was then translated trigonometrically to provide the displacement of the distal fragment in relation to the proximal at the centre of the fracture. This translation assumed that the bone screws, from the transducer clamp to the bone (5 mm), and the bone, from screw insertion to fracture (50 mm), were rigid. As the screw–bone interface is also assumed to be rigid, data arising from a non-rigid interface is discarded. The presence of loose screws may be detected from the transducer output, since displacement increases abruptly to a maximum during gradual loading because of loosening. By simulating a fracture monitoring situation using a purpose-built calibration jig, movements were applied

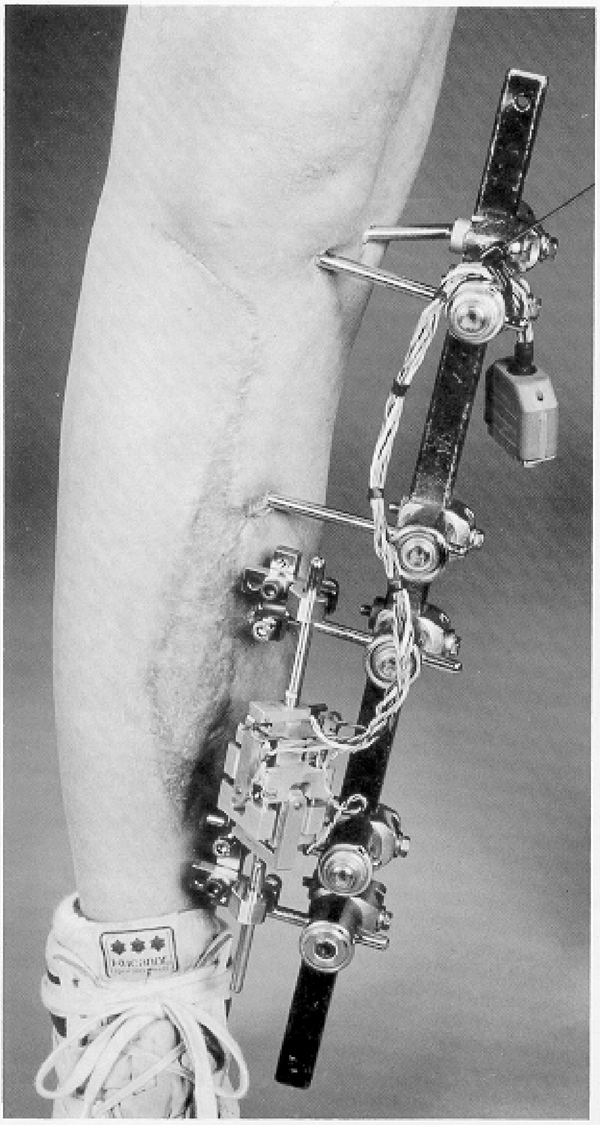

Figure 1. The Oxford Micromovement Transducer (OMT) attached to the bone screws of an external fixator. Dynamic interfragmentary displacement is monitored continuously in six degrees of freedom at the centre of a tibial fracture site.

in the six degrees of freedom using Vernier scales, and agreement was found with the transducer to within 0.025 mm and 0.025°. The positive sign convention for the transducer shown in Figure 2, had the 'y' axis at 35° from the pins towards the anterior border of the tibia. The maximum axial displacement while walking over the load cell was compared to the maximum load achieved during that step.

Measuring the interfragmentary gap shortening (non-recoverable translation)

In four of the 10 subjects, non-recoverable interfragmentary displacement was measured continuously with the OMT over the first hour after unlocking the fixators. The subjects were required to walk for 10 steps at 10-minute intervals during the following hour, to provide nominal patient activity.

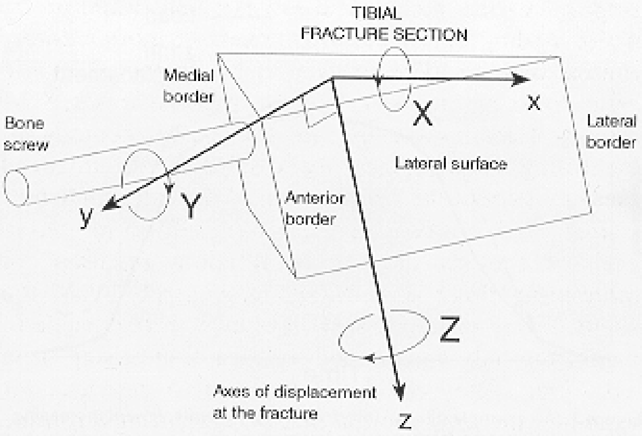

Figure 2. The positive sign convention for displacements measured by the transducer in six degrees of freedom. There are three linear and three angular orientations of displacement of the distal fragment in relation to the proximal at the fracture centre.

Visual assessment

Two radiographs (medial and anterior) were taken before unlocking and 2 weeks after, to examine any gap shortening arising from the unlocking procedure.

Results

Walking tests: interfragmentary motion (recoverable 'elastic' displacement)

No loosening of the bone screws was present in any of the 10 subjects at the time of testing. For all fractures, the change in ability to weight-bear before and after unlocking was variable (Table 1). The mean loads before and after unlocking were 373.2 N (SD 200.28) and 347.3 N (SD 199.6) and no significant difference statistically was found between the two groups ($P<0.05$, paired t test, $n = 10$). During loading axial displacement increased proportionately with the ground reaction force in all subjects (as the example shown in Figure 3).

Examination of the radiographs prior to unlocking indicated that gaps were 1.00 mm ±0.5 error bounds. From examination of radiographs at 2 weeks after unlocking all 10 fractures indicated some reduction in gap size.

Table 1. Load during walking and maximum axial displacement in 10 tibial fractures before and after unlocking fixators

Maximum load (N) Before/after unlocking	*Maximum axial displacement (mm) Before/after unlocking*	*Maximum transverse displacement (mm) Before/after unlocking*
621/567	0.95/0.58	−0.47/−0.51
143/184	0.47/0.68	+0.18/+0.20
565/488	0.15/0.25	−0.15/−0.31
192/147	0.55/0.46	−0.24/−0.27
379/438	0.09/0.13	−0.11/−0.16
295/147	0.67/0.57	+0.43/+0.41
659/667	0.29/0.28	−0.34/−0.37
283/379	0.22/0.21	+0.65/+2.19
111/80	0.61/0.51	+0.17/+0.42
484/376	0.57/0.49	−0.21/−0.25

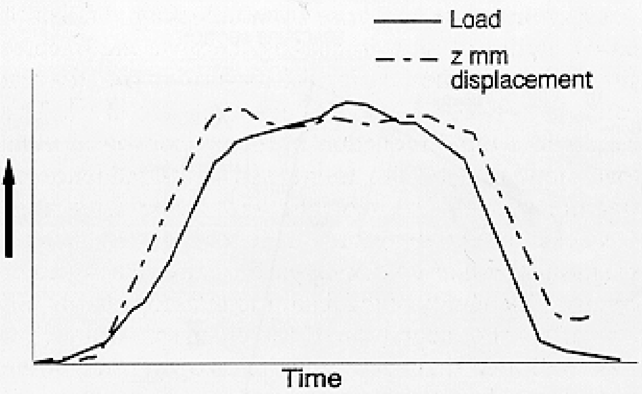

Figure 3. An example of axial interfragmentary displacement increasing with ground reaction force.

The amplitude of axial displacement during walking (z in Figure 2) increased in three subjects, remained unchanged for two, and decreased for five following unlocking (Table 1). The range of amplitudes was 0.09–0.95 mm with a mean displacement before unlocking of 0.46 mm (SD 0.27) and a mean displacement after unlocking of 0.42 mm (SD 0.19). There was no statistically significant difference between measurements taken before and after unlocking ($P<0.05$, paired t test, $n = 10$).

Examining the angular displacement of the distal fragment in relation to the proximal in the plane of the pins, displacements were found to be reduced in four subjects, were unchanged in three subjects, and increased in three subjects after unlocking (Table 2). The range of amplitudes of angulation was 0.03–0.87°. Two subjects reversed the direction of angulation in the plane of the pins after unlocking. These subjects had transverse fractures in which the fragments were 'hinged' at the lateral border, due to an intragap prominence on the lateral side of the fracture. Mean pin plate angulation before unlocking was 0.37° (SD 0.30) and after unlocking it was 0.34° (SD 0.28). There was no statistically significant difference between measurements before and after unlocking ($P<0.05$, paired t test, $n = 10$). It was apparent that subjects with large fracture gaps or comminution could initiate greater amplitudes of CAM.

The amplitudes of transverse shear (x, y in Figure 2) also increased in seven subjects and remained largely unchanged for three following unlocking (Table 1). The range of amplitudes of displacement was initially 0.11–0.65 mm and mean displacement before unlocking was 0.30 mm (SD 0.17) and after was 0.51 mm (SD 0.60). The amplitudes of torsional shear displacement during walking (Z in Figure 2) increased in seven subjects and remained largely unchanged for three following unlocking (Table 2). The range of amplitudes of displacement was initially 0.02–0.40° and mean displacement before unlocking was 0.21° (SD 0.11) and after was 0.42° (SD 0.39). The differences in shear caused by unlocking were statistically significant ($P<0.05$, paired t test, $n = 10$).

Table 2. Load and maximum pin plane angulation in 10 tibial fractures before and after unlocking fixators. A change to a positive sign suggests an axis of reversed rotation at the cortex furthest from the site of pin entry

Load at maximum pin plane angulation (N) Before/after unlocking	*Maximum pin plane (deg) Before/after unlocking*	*Maximum torsion (deg) Before/after unlocking fixator*
614/562	+0.87/+1.00	−0.32/−0.57
86/79	−0.41/−0.44	+0.16/+0.16
260/462	−0.03/+0.47	+0.21/+0.58
87/75	−0.36/−0.31	−0.20/−0.22
379/303	−0.05/−0.07	−0.02/−0.04
295/147	−0.56/−0.44	−0.21/+0.18
207/180	−0.05/+0.13	−0.33/−0.32
102/115	−0.13/−0.13	+0.40/+1.41
101/79	−0.58/−0.09	+0.11/+0.44
446/317	−0.69/−0.34	−0.14/−0.25

Table 3. Non-recoverable interfragmentary translations in four fractures after the first hour following unlocking of fixators

Axial (mm)	*Transverse shear (mm)*	*Angular (deg)*	*Torsion (deg)*
−0.17	0.12	0.28	−0.14
−0.88	0.11	0.26	−0.04
−0.28	0.46	0.42	−0.26
−1.44	1.32	0.25	0.98

Interfragmentary gap shortening (non-recoverable translation)

Table 3 gives the non-recoverable axial, angular, and shear translations measured in the four subjects during the first hour after unlocking. The range of axial collapse of the gaps was 0.2–1.4 mm, and the mean was 0.69 mm. In three of the four subjects translation was not predominantly axial, but angular, and shear movements were also large.

Discussion

When the fixator is locked, CAM is induced by walking. Since displacement at the fracture gap during weight-bearing is proportional to the load applied, axial displacement and pin-plane bending may be controlled by regulating weight-bearing. The effect of unlocking on the amplitude of cyclic axial displacement was found to be unpredictable, but contrary to general opinion neither mean axial displacement nor mean weight-bearing changed significantly. Five of the subjects had reduced amplitudes of displacement, and generally these could not be wholly accounted for by a change in displacement in proportion to a reduced weight-bearing. Reductions in amplitude, probably occur in fractures where the fixator has previously maintained a substantial gap (of more than 1 mm) during the locked period. This is because the fixator frame is able to respond as an elastic spring when operating in the locked mode, and it is this spring which brings about the recovery of the initial gap size during the unloaded sequences of dynamic weight-bearing[16]. Conversely the frame in the unlocked mode cannot restore gap size quite so forcefully and so the gap shortens over time, further restricting the range of cyclical displacement and probably initiating a reduction in CAM. This may not be true of perfectly reduced transverse fractures with no compressible gap material, and also for the less well healed cases in which the callus does not resist stretching. For the less well healed fractures, small tensile forces exerted by the weight of the limb below the fracture were sufficient to cause tensile displacement during the raised leg sequences of walking. These increased after unlocking the frame, and possibly contributed to those increases in CAM observed in three of the 10 subjects.

Although patient numbers were insufficient to provide a statistically significant difference in pin plane angulation, laboratory tests suggest that angular displacement would reduce[16]. This is a consequence of the reduced axial tibial load supported by the frame after unlocking, which reduces the bending moment exerted by the tibial load about the fixator column. The relevance for bone healing is that the reduced lateral load supported by the pins, leads to reduced pin bending and reduced peak stresses at the pin–bone interface[22]. This preserves intact the pin sites, and reduces the risk of asepctic loosening through repeated pin bending during CAM.

The shear displacements appear small, but in conjunction with a shortened interfragmentary gap they may produce large strains in the intragap tissue. The shear movement may be due to the shape of the fracture interface, since axial tibial loads acting on oblique fractures should induce transverse shear displacement and on spiral fractures they should also induce torsional shear displacement. Additional shear occurs at the fracture because of rotational looseness in the telescoping mechanism of the fixator when it is unlocked, as seen in fracture simulations in the laboratory[15]. Both transverse and torsional shear may inhibit the progress of healing[19].

The structural change at the fracture site brought about by the shortening of the gap may be a contributory influence on healing. A permanent reduction of the fracture gap brings the bone ends into closer proximity, which may assist the later stages of bone formation and remodelling[20], and may help resist shear. Therefore, gap shortening is likely to be the cause of the improved healing result claimed for the unlocking procedure rather than changes in elastic interfragmentary motion or load. It is unlikely that healing will be influenced by a change in the load supported at the fracture, since the increase due to unlocking is expected to be less than 10% during full weight-bearing in an adult of average weight with a stable fracture and a 1 mm gap[15]. Therefore, the proportion of tibial load supported at the fracture and also the mean weight-bearing on the tibia are not expected to change greatly.

Limitations of the study

The measured changes in elastic and non-recoverable interfragmentary movement are relevant only to unlocking the frame at the 6-week point in healing. A different result may arise from unlocking the fixator either earlier or later in healing, because the fracture site begins to stiffen during calcification of the external callus at between 4 and 6 weeks after fracture[23]. This results in a rapid reduction in the proportion of tibial load supported by the frame and in its influence on fracture motion[15]. Unlocking the frame later than 6 weeks should therefore cause changes of smaller magnitude, while unlocking earlier may cause greater change. The ability of the fixator to telescope freely will also affect the magnitude of the changes. Although it was confirmed that each frame telescoped prior to the test, slip stick restriction to telescoping movement may be possible in those fixators without bearing mechanisms to assist sliding. However, the findings of this study are clinically relevant since the fixators currently in use are predominantly those without bearings.

In conclusion, weight-bearing and recoverable (elastic) axial gap displacement during walking did not change greatly as a result of unlocking the frame, but transverse and torsional shear displacement increased by 70% and 100%, possibly due to rotational looseness in the unlocked fixator column. Therefore the benefit to healing claimed for unlocking frames may arise from non-recoverable gap shortening, which in this study was found to be between 0.2 and 1.4 mm, and not the change in load or elastic motion at the fracture.

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