CAST-BRACING FOR FRACTURES OF THE FEMORAL SHAFT
A BIOMECHANICAL AND CLINICAL STUDY

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A study was made of the mechanics of load-bearing in a series of patients treated with a cast-brace for fracture of the distal femur. Knee hinges incorporating strain-gauges, a simple force-plate on the floor and a standardised weight-bearing test were used to record axial loads through the cast-brace itself and through the fracture during the phases of healing. The cast-brace carried loads of only 10 to 20 per cent of body weight and functioned mainly as an antibuckling hinged tube. Patterns of weight-bearing recovery showed that the fracture itself limited loads to safe levels. A measure of the recovery of strength at the fracture was determined and termed the "fracture load index". Graphs obtained in this way demonstrated four biomechanical phases of bony union which correlated well with the stages of clinical healing. The clinical application of these results have lead to improvements in the design of braces and the use of a cylinder cast-brace for fractures of the proximal femoral shaft and of a new type of brace with a hinge at the hip attached to the thigh cast for fractures of the proximal shaft. A simple clinical test is described by which it is possible to monitor the healing of fractures in cast-braces.

The long-leg cast-brace with hinges at the knee has become accepted in the treatment of fractures of the distal femoral shaft since the work of Mooney et al. (1970). The clinical advantages of combining non-operative treatment with early mobilisation of the patient and of the fractured limb were shown, and these were confirmed in further reports by Connolly, Dehne, and Lafollette (1973), Brown and Preston (1975) and others. There has been very little published work on the biomechanical function of the cast-brace in relation to the healing of femoral fractures. Meggitt, Broom and Ross (1975) reported preliminary findings in a prospective study of the clinical value and mechanical function of the cast-brace. A method was described by which it was possible to measure simultaneously the load on the cast-brace using strain-gauges mounted on the hinges, and the total load on the leg using a force-plate. By subtraction, the load taken by the femoral fracture could be assessed during a standardised "10-second steady standing test". The present paper reports the full results and was postponed until the results from patients with delayed union in the cast-brace could be used to provide evidence for theories on the recovery of load-bearing capacity.

The objectives of the study were to investigate, first, the load-relieving function of the cast-brace and the significance of weight-bearing in the upper thigh; and secondly, the mechanics of loading on the healing femoral fracture. These biomechanical results were applied clinically to improve the design of cast-braces for distal femoral fractures, to develop a new design of brace for fractures of the proximal femoral shaft and to assess a simple clinical test of bony union.

MATERIAL AND METHODS

Cast-brace. The design used throughout the series consisted of a quadrilateral polythene brim at the thigh with a long-leg plaster open at the knee to accommodate a pair of stable metal hinges. This was applied over stockinet, an elastic knee-support and one layer of plaster wool.

Load-measuring devices. During weight-bearing in the brace, axial loads pass both up the lower leg, across the knee and through the fractured femur, and also up the cast-brace through the knee hinges to the thigh cast and then to the upper thigh. The load on the cast-brace and the total load on the leg were measured during a standard test; the load on the fracture was then obtainable by subtraction (Fig. 1).

Cast-brace load. This was measured as an axial thrust through each hinge using a cylinder transducer incorporated in the shank of the hinge. At first strain-gauges were also positioned to assess bending moment and shear stress but the results were not significant compared with the high axial thrust produced by vertical loading and these measurements were not continued (Figs 2 and 3).

Total leg load. This was measured on the floor using a portable force-plate designed on a beam-bending principle with a strain-gauge transducer. This measured vertical loads only. The hinge and force-plate loads were measured simultaneously using a Wheatstone bridge type of detector circuit and were displayed digitally and also recorded on an oscillograph.

Fracture load. This was estimated by subtracting the hinge load from the total leg load during the standard weight-bearing test.

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Weight-bearing test. A standard weight-bearing test was necessary to allow repeated and comparable measurement of the loads at intervals during the healing of a fracture. At first conventional gait analysis was used with a walk-way and two force-plates to record maximal weight-bearing on each leg during the stance phase with minimal crutch support for the fractured limb. This method proved difficult and time-consuming. A simpler test was developed and termed the '10-second steady standing test'. For this test the patient stood erect with the fractured leg in its cast on the force-plate and transferred as much weight as possible through the limb. A frame or crutches were allowed to help the patient to balance. A 10-second load recording was then obtained from the force-plate and the hinge transducers simultaneously (Fig. 4). By requiring the maximal weight to be held for 10 seconds steadier results were obtained, and the higher thrust which was possible for very short periods was eliminated. When the braced limb was hanging vertically the strain gauges on the hinges registered a negative value and very variable recordings were obtained when the limb was in a horizontal position. A baseline for the hinge transducers was therefore obtained by using the weight of the cast-brace. This was initially estimated from the weight of the plaster and other components of the brace and later by weighing the patient before and after application of the brace. The patient then loaded the force-plate with this known cast-brace weight as indicated by a separate digital read-out. The two hinge transducers were then set to zero. The established brace weight was later subtracted from the force-plate load. The total body weight was also recorded. The 10-second test was repeated at each review until consistent load recordings from the hinges and from the force-plate were obtained, usually within five or six tests. The average of the highest three recordings was used.

The results of the 10-second test correlated closely with the mid-stance gait loads recorded at the same session (Fig. 5) in three patients throughout the healing of their fractures and was therefore used as the standard test for this series. The compact force-plate enabled load testing to be undertaken rapidly in limited space. The cast-brace load, the total leg load and indirectly the fracture load were
Recordings taken for one patient at the same session, to demonstrate that the 10-second test gives results which agree with those provided by a gait-analysis recording.

An example of experimental recording of the force-plate and hinge loads with the calculation of fracture load as a percentage of normal body weight.
all expressed as a percentage of body weight throughout the study after appropriate correction for the weight of the cast-brace itself (Fig. 6).

**Patient management.** Twenty-two patients with fractures of the distal two-thirds of the femur, uncomplicated by any other injury which could interfere with rehabilitation, were treated by manipulative reduction and balanced skeletal traction using a pin through the tibial tubercle and a Thomas' splint. Traction was removed when the fracture had reached a "sticky" stage in that it could be angulated but not displaced on clinical examination and radiographs showed early callus formation. A long leg cast-brace was then applied with knee hinges incorporating the strain-guages. This stage was usually reached five to seven weeks after fracture. The patient was then allowed to stand and walk supported by crutches or a frame. The hinges were kept in extension until stable balancing was achieved and then freed by removal of the locking screws. At this stage the first 10-second steady standing test was carried out. The patient was then allowed to leave hospital and instructed to take the maximal possible weight on the leg in its cast-brace. Load-bearing tests and measurement of knee flexion were made at two-week intervals and radiographs were taken at four-week intervals. The cast-brace was removed when full weight-bearing for 10 seconds could be achieved. Further tests on the unsupported leg were carried out immediately after removal of the brace and then at weekly intervals until it could be shown that full body weight was supported for 10 seconds.

**RESULTS**

Twenty-two patients with fractures of the distal two-thirds of the femoral shaft were studied throughout their treatment. Fifteen of these patients united soundly without complication. Two patients suffered delayed union. Five patients had special adjustments to their cast-braces but also achieved complete bony union.

Three examples are presented of results from patients recovering without complication after fracture at different levels in the femur.

The first patient (Fig. 7) had the application of a cast-brace 7.5 weeks after he sustained an oblique mid-shaft fracture of the femur. The graph shows axial brace-loading of 10 to 20 per cent of body weight throughout, with a steady increase in the leg load from 36 per cent to full body weight by 16 weeks, at which time the brace was removed. The fracture load thus increased from 30 per cent at 7.5 weeks to 50 per cent at 12 weeks, and to 80 per cent at 16 weeks before the brace was removed. There was little difference at 16 weeks between the unsupported fracture load measured directly and the indirectly calculated load in the brace. Full body weight could be supported on the limb two weeks later.

In the second patient, who had sustained an oblique fracture of the distal third of the femur (Fig. 8), brace-loading varied from 10 to 17.5 per cent throughout. The leg load was 53 per cent at seven weeks rising to 100 per cent at 14 weeks. The fracture load increased from 50 per cent at 10 weeks to 83 per cent at 14 weeks, when the brace was removed, and reached 100 per cent at 15 weeks. Again there was little difference between the indirectly calculated fracture load in the brace and the directly measured load out of the brace.

Figure 9 shows the graph from the patient who achieved the most rapid healing. The fracture was oblique and supracondylar. Brace-loading varied between 5 and 10 per cent, with leg load increasing from 50 per cent at five weeks to full body weight at eight weeks, at which stage the brace was removed. Four days later the patient could stand for 10 seconds with his full weight on the limb. There is the suggestion of a plateau in some of these fracture load curves and this will be discussed later.

The results from 15 patients without complications

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**Graphs showing total leg-load, brace-hinge load, and by subtraction, the fracture load in three patients who had sustained fractures of the shaft of the femur. Clinical details concerning the patients and a discussion of the results are included in the text.**
are given in Table I. Fractures in the middle and lower third of the femoral shaft showed similar behaviour. All fractures reached the “sticky” callus phase and had application of the brace between five and seven weeks and all achieved 100 per cent leg-loading between 14 and 16.5 weeks. Figure 10 collates the results for 10 shaft fractures in a single graph. Axial brace-loads range from 8 to 22 per cent with a mean of 15 per cent and the fracture load improves from 50 per cent between 8.5 and 11 weeks to 100 per cent between 15 and 18 weeks.

![Graph showing mean fracture-loads and mean brace-loads ± 1 standard deviation averaged in 10 patients with fracture of the distal shaft of the femur. Transverse arrows indicate the range of times at which fracture load-bearing reached 50 per cent of body weight and 100 per cent of body weight.](image)

The five supracondylar fractures showed earlier callus stability and bony union than the shaft fractures but the brace-loading was similar with a 7 to 18 per cent range.

Two patients suffered delay in bony union, and failed to achieve full weight-bearing in the cast by 20 weeks after fracture. Figure 11 is the record of a 21-year-old man who sustained a transverse fracture of the mid-shaft of the femur in a high-speed motor-cycle accident. The fracture showed little callus or stability until the ninth week, when the brace was applied. The graph shows that fracture-loading was little changed until 13 weeks, after which steady recovery occurred. At 21 weeks the brace required changing. On removal of the brace the fracture was clinically united with no pain on stressing. The patient, however, could only support 77 per cent of body weight. Radiographs showed a large posterolateral bone mass and the patient was advised to take only partial weight on the limb. One week later the 10-second test showed 78 per cent body-loading with no pain and 110 degrees of knee flexion. While the patient was leaning across a bed one week later, refracture occurred. At operation, the distal fragment was covered in fibrotic muscle and only end-to-side healing had occurred. The weight-bearing test had provided a fairly accurate index of the mechanical weakness of the fracture. Rapid and complete bony union followed intermedullary nailing and bone grafting.

Figure 12 is the graph for a 72-year-old lady who sustained a displaced supracondylar fracture. The graph shows that at application of the brace seven weeks after injury, the fracture load was 45 per cent but after a fall on the knee at eight weeks the fracture load fell to 35 per cent within nine weeks. There was slow recovery of load-bearing, reaching 60 per cent at 18 weeks and 100 per cent at 26 weeks. The further injury had caused mechanical interference to the healing fracture and produced a delay in bony union, thus confirming the validity of the load test. This patient had some pain during the standing tests for four weeks after her fall, but no other patient suffered pain during tests throughout the series.

In an attempt to seat the cast firmly on the ischial tuberosity three young adult male patients with fractures
of the lower femur had their cast-braces modified. A padded polythene brim was firmly opposed to the ischial tuberosity with the hip flexed to 30 degrees. A loose below-knee cast with a thick lining was used. Two patients showed mean cast-brace loads of 52 and 63 per cent at six weeks. However, they were unable to extend the hip fully because of pain caused by pressure on the tuberosity, and the thigh cast had to be changed within one week. A third patient tolerated a less tight ischial-bearing cast-brace. Figure 13 shows that cast-brace loads increased from 25 per cent at six weeks to 47 per cent at 11 weeks when 100 per cent leg-loading was possible. The fracture load was therefore only 53 per cent, and out of the cast-brace the directly measured load on the leg was a little less at 48 per cent. The fracture was solid to clinical examination but pain was experienced on forced bending. The patient refused further casts and walked with crutches taking the maximal comfortable weight on the limb. A steady recovery followed with full weight-bearing at 17 weeks.

Tightening of the thigh cast was tried on two other patients 10 weeks after fracture of the lower femoral shaft. A one-inch strip of the cast was removed from the front and the cast split vertically at the back. The thigh section was then firmly tightened and replastered. Loading tests before and after this adjustment showed no significant difference in either patient.

**DISCUSSION**

**Cast-brace function.** The results show that the thigh section of the cast-brace carries an average of 10 to 20 per cent of the body weight during the healing of the fracture, and does not function as a weight-relieving caliper. It can with difficulty be made to take higher loads with seating on the ischial tuberosity, but significant increase in brace-loading cannot be obtained by tightening the thigh section. The brace load remains constant and the maximal possible leg load steadily increases throughout healing. It is therefore the fracture itself which controls this loading. The main deforming force is lateral angulation produced by the recovering adductor and abductor muscles, as in the known complication of late varus bowing in traction. Axial load-bearing was generally found to be greater in the medial hinge during the period when the fracture was more plastic. The cast-brace seems to have a bend-controlling function and thus to allow safe intermittent compression of the fracture during walking. The three-point fixation principle applies, with the upper thigh cast above and the shin cast below providing medial supports, while the lower thigh cast and hinges give lateral support (Fig. 14). Anteroposterior stresses are less because the muscles are balanced and there is a free fulcrum at the knee. The cast-brace therefore functions mainly as an "antibuckling hinged tube". Hydraulic muscle-support to the fracture is unlikely to contribute once telescoping of the thigh has ceased. The elastic lining and thigh cast may, however, reduce tissue oedema and allow the muscle pump to contribute to vascular return. The quadrilateral shape of the upper thigh cast adds to the support surfaces and also provides
improved protection against torsion of the fracture. 

**Mechanics of fracture repair.** Axial forces through the intact femoral shaft during a 10-second steady standing test or at the mid-stance of gait result from the load of body weight plus the compression load from contracting muscles. These forces are inhibited after a shaft fracture, but as repair occurs they slowly recover. Muscle loads cannot be measured but the weight-bearing loads have been demonstrated. The graphs show that for a given femoral fracture at a specific time in healing, there is a consistent maximal load which can be taken on the limb. This load steadily increases and is a mechanical index of fracture repair, providing a physiological measure of the recovery of strength in the healing limb.

![Diagrams to illustrate the deforming forces in fracture of the shaft of the femur and the mechanism of three-point pressure in resisting these forces. The antibuckling function of the cast-brace is evident.](Fig. 14)

This mechanical recovery occurs parallel to the clinical and radiological signs of fracture healing. Fracture load levels of 25 to 35 per cent of body weight are found at the phase of "sticky" callus from five to seven weeks, after the injury, and this increases to 100 per cent by 15 to 18 weeks in keeping with the observed clinical picture of sound union. The clinical and radiological determination of union is empirical but the use of the "fracture load index" gave a functional measure of recovery of strength. The validity of this crude but practical healing index is confirmed by results from the patients with delayed union. One showed a sharp decrease in load index after further injury, and in the second patient the load index remained at 78 per cent before refracture occurred (Figs 11 and 12).

The fracture itself controls the safe load level in or out of the cast-brace during progress to union. The fracture site appears to exhibit a biological feedback system and it is postulated that there are mechano-receptor units which inhibit damaging load-bearing through the limb by inactivation of muscles and joints.

During their standing tests patients did not complain of pain but of feelings of "unsteadiness", "weakness", "giving way" or "looseness". Pain is not part of the mechanism of inhibition. As callus becomes more rigid, the mechano-receptors allow higher but safe limb-loading levels. No previous report can be found concerning this mechanical feedback in human fracture repair but it is suggested that the signal from stressed callus is mediated through osseous bio-electrical potentials.

Fracture loads during healing show a plateau in the middle of the recovery curve with steeper slopes before and after it (Figs 7, 8, 9, and 10). Four mechanical repair phases can be identified. The period before early stability allows application of the cast-brace may be termed Phase 1. The first steep curve of recovery is Phase 2, the plateau is Phase 3 and the final steep slope rising to full weight-bearing may be called Phase 4 (Fig. 15). These phases of mechanical recovery correlate closely with the clinical, histological and radiological repair sequences observed in the human femoral fracture.

The period when the fracture is mobile and displaceable during the organisation of haematoma and granulation tissue (unstable—Phase 1) is followed by "sticky" bendable callus and rapid increase in strength resulting from the calcification of the callus (plastic—Phase 2). Vascular resorption of the calcified callus and early endochondral ossification corresponds with slower axial recovery during the "plateau" period, when the
fracture is springy but cannot be bent (elastic—Phase 3). With final remodelling of trabecular and osteonal bone solid bony union is completed (rigid—Phase 4). This pattern may not always be discernable, because different phases may occur in different sites at the same time in a large volume of callus.

The best criterion of fracture healing is probably ultimate breaking strength. This can only be applied in experimental fracture models and has been used to identify four stages of healing: unstable, plastic, rigid and clinical union (Laurin, Sison and Roque 1963; Clark, Goodship and Lanyon 1975). White, Panjabi and Southwick (1977) also described four biomechanical stages of healing based on the stiffness of the callus. Little work has been done on the mechanics of human fracture healing. It is postulated that the functional strength shown by the fracture load index increases parallel to the ultimate breaking strength in a healing fracture of the femoral shaft.

CLINICAL APPLICATION

Brace design for distal femoral fracture. The cast-brace working as an antibuckling hinged tube, provides resistance to lateral bending in the early plastic phase. Medial pressure at the knee is required to provide stability, and strong metal polycentric hinges are used (Fig. 14). This is important in preventing varus angulation especially in distal fractures, while in fractures of the middle shaft or for later application hinge stability is less important. The lockable metal hinge permits early standing and walking without fear of collapse of the knee, especially in the older patient. Locking screws are removed once stable balance has been attained, usually within three days.

The standard cast-brace has been shown to provide support to the femoral fracture through the thigh cast, knee hinges and upper shin cast amounting to between 10 and 20 per cent of body weight. The ankle and foot section of the plaster acts only as a static support for the brace above; it immobilises the foot, ankle and calf and adds to the weight. Removal of the lower cast section to leave a free ankle and foot would provide better function. A modified "knee-hinge cylinder brace" was designed, using a suspension system from the waist (Fig. 16). A waist belt supported the upper cast with adjustable straps, two of leather in front and one of elastic at the back to allow for sitting. This cylinder brace has been used clinically since 1976, but the weight of the plaster-of-Paris cast often caused slipping. The introduction of Crystona lightweight plaster in 1978, allowed reduction of the weight of the long-leg cast-brace to 70 per cent and that of the knee-hinge cylinder brace to 50 per cent compared with conventional plaster casts. A long-leg cast-brace is used for obese patients with no waist and flabby thighs, and the cylinder brace for most other patients. The combination of the lightweight plaster and the cylinder design has improved the functional quality of femoral fracture bracing (Vaughan-Lane and Meggitt 1980).

Brace design for proximal femoral fracture. The knee-hinge cast-brace provides inadequate support for fractures of the proximal third of the femoral shaft until bony union is well advanced (Fig. 17). Mooney et al. (1970) stated that "fractures in the proximal third of the femur cannot be controlled by the cast-brace" while...
Diagram to illustrate the deforming forces in fracture of the proximal shaft of the femur and to show the principle of three-point fixation as provided by the hip-hinge thigh-cast brace.

Use of the hip-hinge thigh-cast in a 51-year-old man who had sustained a subtrochanteric fracture of the femur. Figure 19—Lateral view of the patient wearing his cast-brace. Figure 20—Anteroposterior radiograph of the same patient.

Connolly et al. (1973) and Brown and Preston (1975) also commented on the difficulty of controlling a fracture of the upper femoral shaft.

The concept that the cast-brace functions as an antibuckling tube in resisting the main deforming forces was applied to fractures of the upper femoral shaft. The main deforming forces at this level stem from the lateral bending moment of abductor and adductor muscles. Resistance to this varus angulation force on the three-point fixation principle necessitated lateral support at the fracture site with medial support for the distal femur below and for the pelvis above, with a hinge at the hip to give stability (Fig. 18). For fractures in the proximal half of the femoral shaft, the distal lever arm on the medial side was provided by a thigh cast extending to just above the knee. The knee hinges and lower leg cast
were mechanically unnecessary. Proximal lever support was provided by a rigid metal band applied firmly to the pelvis by a belt, and linked to the thigh cast by a metal hinge and flange placed laterally and in a position of 20 degrees of abduction. A new “hip-hinge thigh-cast brace” was therefore designed with a quadrilateral torsion-resisting thigh cast attached by a uniplanar metal hinge to a rigid pelvic band. An adjustable waist belt and shoulder strap suspension were provided (Figs 19 and 20).

This hip-hinge cast-brace was used very rarely with conventional plaster of Paris as the weight and subsequent slipping produced problems. The introduction of Crystona lightweight plaster in 1978, enabled weight reduction by 30 per cent. Early mobilisation of 24 patients with fractures of the proximal half of the femoral shaft in the hip-hinge thigh cast has been undertaken. It has been used on its own for traumatic fractures, some occurring distal to the prosthetic hip (Figs 21 and 22), and on occasions as external support for precarious internal fixation of fractures in the trochanteric region and shaft (Meggitt and Vaughan-Lane 1980). Application of the thigh brace was reasonably easy. The edges of the Crystona cast were protected with felt and the hinge axis was set at the level of the tip of the greater trochanter in a position of 20 degrees abduction at the hip. Varus angulation was not a problem and bony union occurred in all the traumatic fractures between 11 and 18 weeks.

**Test of union.** The study shows that there is good correlation between clinical recovery and the load-bearing strength of the healing limb in a cast-brace. The brace carried a constant 10 to 20 per cent of body weight, and the fracture itself determined the safe load level. A crude but practical test for use in the fracture clinic was developed to quantify the mechanical healing of femoral fractures and to determine the safe time for removal of the brace. The test requires the patient to stand erect with the foot of the braced limb on a bathroom scale and the normal foot supported at the same level on blocks (Fig. 23). While using a frame or crutches to retain balance, the patient slowly transfers as much weight as possible to the fractured leg and a steady
standing weight for 10 seconds is obtained. The patient rests and the test is repeated until a consistent highest recording can be obtained. From the known body weight a "fracture load-bearing index" is calculated as a percentage of body weight. This index is recorded in the clinical notes at each attendance at the clinic. Steady increase in this index provides an indication of satisfactory healing. When full weight-bearing is possible on the limb, the cast-brace can be removed with the

knowledge that the true fracture load is greater than 80 per cent of body weight. Testing immediately after removal of the brace usually shows this degree of fall in the index and occasionally a greater one in apprehensive patients. Further tests show rapid recovery to 100 per cent of body weight in one to three weeks. To obtain a more accurate load-bearing index in the long-leg cast-brace, subtraction of 20 per cent of body weight may be undertaken at each test. In patients with the knee-hinge cylinder brace and the hip-hinge thigh brace, the 10-second steady weight-bearing load can be recorded directly as only axial force-plate loads are involved in the absence of the foot section of the cast. Examples of the use of the simple test are given.

The load-bearing recovery curve for a cylinder-braced fracture of the distal femur is shown in Figure 24: 100 per cent load was achieved at 14 weeks. The brace was left on for a further two weeks, and when it was removed only an eight per cent reduction occurred; this recovered fully within seven days. Figure 25 shows a mid-shaft transverse fracture which proved slow to stabilise. A long-leg brace was applied at 12 weeks since the patient refused internal fixation. Little callus developed but at 19 weeks the fracture appeared to be united and the brace was removed. The leg-load index was 85 per cent in the brace and 67 per cent after removal. This rose to 70 per cent over three weeks when refraction occurred suddenly when the patient was going down a step using crutches. At operation for nailing, very little callus was seen at the fracture site, thus explaining the mechanical weakness and delayed recovery.

Figures 26 and 27 show the load curves for two patients with fractures of the proximal femoral shaft who were treated in the hip-hinge thigh brace. Fracture stability allowed brace application at six weeks and full weight-loading at 11 weeks.

The mechanical index of fracture union has been used to monitor the healing of femoral shaft fractures in 50 patients in the fracture clinic at Addenbrooke’s Hospital, Cambridge, from 1977 to 1980. It proved to be a practical method of assessment of healing of the fracture and gave an accurate indication of progress. A variety of different repair curves was obtained but in adults for all levels of shaft fracture a 10-second steady
standing test showed full weight-bearing out of the brace by 20 weeks. The test provides an indication for the safe timing of brace removal. Failure to show an increase in steady load-bearing to full body weight within 20 weeks, is an indication of delayed or deficient bony union with a danger of refracture.

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