Biomechanics Of Musculoskeletal Injury

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Dedication

To our Wives and Children

Preface

Virtually all of the members of the Orthopaedic Faculty at the University of Toronto have contributed in some way to this text, as most of the concepts are those which were transmitted through rounds, seminars, or informal discussions at the various teaching hospitals. Under the leadership of Professor Robert B. Salter, the basic philosophy of orthopaedic training at the University of Toronto has been that important concepts must be conveyed in a systematic and simplistic manner. We hope this textbook complies with that basic philosophy.

It was to Professor Donald R. Wilson that we originally presented the idea of a biomechanics textbook written by two orthopaedic surgeons who were originally trained as professional engineers. Had it not been for his encouragement and support, it is unlikely that the present book would have become a reality. Doctor Wilson continues to be an inspiration to those surgeons who have trained under him.

Dr. Dennis Evans's chapter on spinal injuries represents a career-long interest in this subject. This dates to his involvement in the Spinal Injuries Unit in Manchester, England, where he worked with Doctor Holdsworth. We are grateful to Dr. Evans for contributing this valuable chapter to our text; no engineer could have done it with greater clarity and few surgeons with a greater wealth of experience.

Miss Margot Mackay, B.Sc., A.A.M., the Department of Art as Applied to Medicine, University of Toronto, has been primarily responsible for the illustrations in this text. She is a very talented artist who has the ability to convey complex concepts using illustrations that are elegant in their simplicity. Miss Mackay was assisted by Mr. Frederick Lammerich.

We wish to thank Ms. Barbara Tansill and the staff at Williams & Wilkins for the excellent job they have done in preparing this text. We also wish to thank Drs. John, Godin, Moriarity and the editorial staff of MediEdit, Toronto, as well as the Department of Photography of Toronto East General and Orthopaedic Hospital for their valuable contribution to this text.

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CHAPTER 1

Biomechanics of Long Bone Injuries

Eric R. Gozna

It is essential for the orthopedic surgeon to have a clear understanding of the biomechanics of long bone injuries, as these are the most common major injuries that he will be required to treat. Following careful clinical assessment of the patient, the accurate interpretation of the radiographic fracture pattern is the single most important step in planning a treatment protocol.

Though most musculoskeletal injuries occur in a predictable manner, as dictated by the forces involved and the structure of the region, there are always certain fractures that are unique to each injury. These fractures constitute the "personality" of that injury and distinguish it from all others. The purpose of this chapter is to describe a few of the underlying biomechanical principles that contribute to the unique characteristics of long bone injuries and to describe a systematic biomechanical approach for anticipating any long bone fracture pattern.

When confronted with the radiographs of a long bone fracture, the surgeon should remember the five factors responsible for any bony injury, three of which depend upon the characteristics of the *load* and two upon the characteristics of the *bone*:

Load characteristics

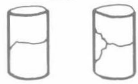
1. Type of load
2. Magnitude of load
3. Load rate

Bone characteristics

1. Material properties of bone
2. Structural properties of bone

Through systematic analysis of the radiographs and individual consideration of these factors, the surgeon can derive a great deal of information about the injury, such as the type of load involved, the amount of energy expended, the location of remaining soft tissue and periosteal hinges, and an estimate of the degree of associated soft tissue injury (anticipating

Table 1.1. Fracture Patterns Resulting from Combinations of Compression, Bending, Torsion

Fracture Pattern	Load	Appearance	Common Sites
Diaphyseal impaction	Axial compression		Intercondylar humerus, femur, tibial plafond
Transverse	Bending		Any long bone diaphysis
Spiral	Torsion		Any long bone diaphysis; frequently tibia, humerus
Oblique transverse (or butter-fly)	Axial compression + bending		Femur, tibia, humerus
Oblique	Axial compression + bending + torsion		Tibia-fibula, forearm

potential complications). In this manner the surgeon can fully define the personality of the particular injury.

The following sections will describe in detail the five factors listed above and the role that they play in the biomechanics of long bone fractures.

TYPE OF LOAD

Engineers refer to the application of a force to an object as *loading*. An object can be loaded in four ways: tension (traction or pulling apart), compression (pressing together), bending (angulation), and torsion (twisting). In medieval times the rack provided an ideal experimental model for pure traction injuries. As history books will attest, the major injuries resulting from this form of torture were to joints and ligaments and not to long bones. Hence, pure tension loading rarely produces injury to long bones. The clinically important ways in which long bones can be loaded are therefore combinations of compression, bending, and torsion. Table 1.1 summarizes the types of fractures which result from the various combinations of loads. The five basic injury patterns which result from combinations of compression, bending, and torsional loads are: diaphyseal impaction, transverse, oblique transverse, spiral, and oblique fractures.

Diaphyseal Impaction Fractures

If a short cylinder of homogeneous material is subjected to a compressive load applied through its center (i.e., axially), the fracture will propagate at an angle of approximately 45° with the center line, because this is the angle along which maximum stresses develop.[2,8] Theoretically the material would fail along this plane, producing an oblique fracture pattern. In practice, however, it is difficult to apply a compressive load exactly through the middle of a cylinder, and, as a result, one portion is subjected to greater compressive loads than others.[11] If a cylinder is long enough, e.g., a human long bone, bending movements are created and a phenomenon known as "column buckling" occurs. In this response, the material tends to bend and collapse rather than to sheer at an oblique angle.

Fortunately, in dealing with long bone compression fractures, the orthopedist rarely needs to consider column buckling or pure oblique fracture configurations because, in long bones, an axially applied load

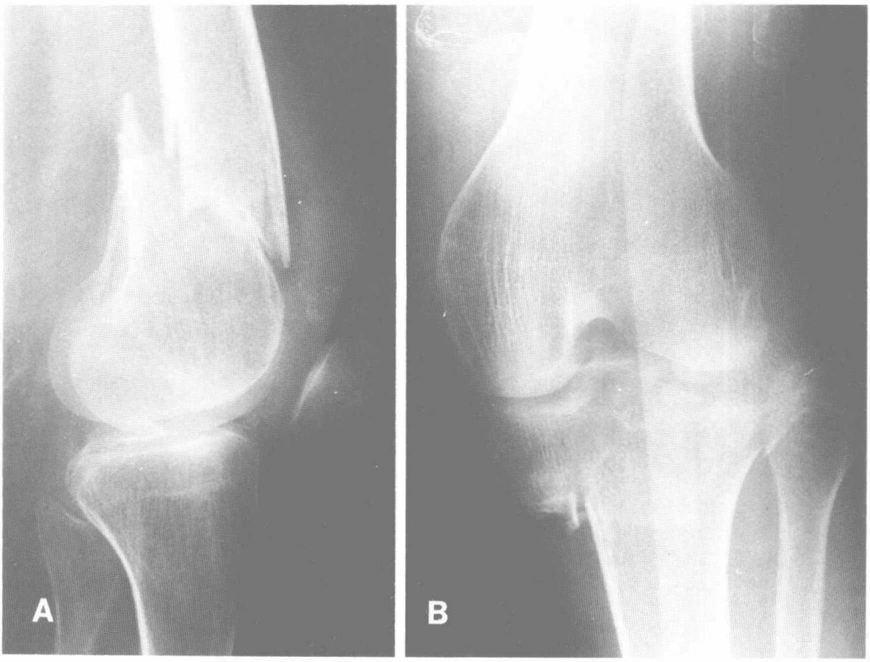


Figure 1.1. Two examples of diaphyseal impaction fractures resulting from longitudinal compression loads are the "Y" type supracondylar fracture of the femur (*A*) and the comminuted tibial plateau fracture (*B*).

usually drives the diaphyseal bone, with its thick rigid cortex, into the thin metaphyseal bone like a battering ram.[16] The resultant diaphyseal impaction fraction is the most common fracture pattern stemming from axial loading of long bone. Examples of this fracture pattern are supracondylar femoral fractures (Fig. 1.1*A*), tibial "plafond" and comminuted tibial plateau fractures (Fig. 1.1*B*).

Transverse Fractures

A bending load applied to a long bone subjects that portion of the cortex on the concavity of the bone to compression forces while it subjects that on the convexity to tension forces (Fig. 1.2). Cortical bone is weaker in tension than in compression[2,3,11,13]; hence, it generally will fail in tension before it fails in compression. The crack begins on the tensile side of the cortex, and when the outer layers of bone fail, the layers immediately under this are subjected to maximum stress and fail. As successive layers fail, the crack propagates at right angles to the long axis of the cylinder and produces a transverse fracture line.

As half of the cylinder is under compression and the other half is under tension, there is a point between these two regions ("the neutral axis")

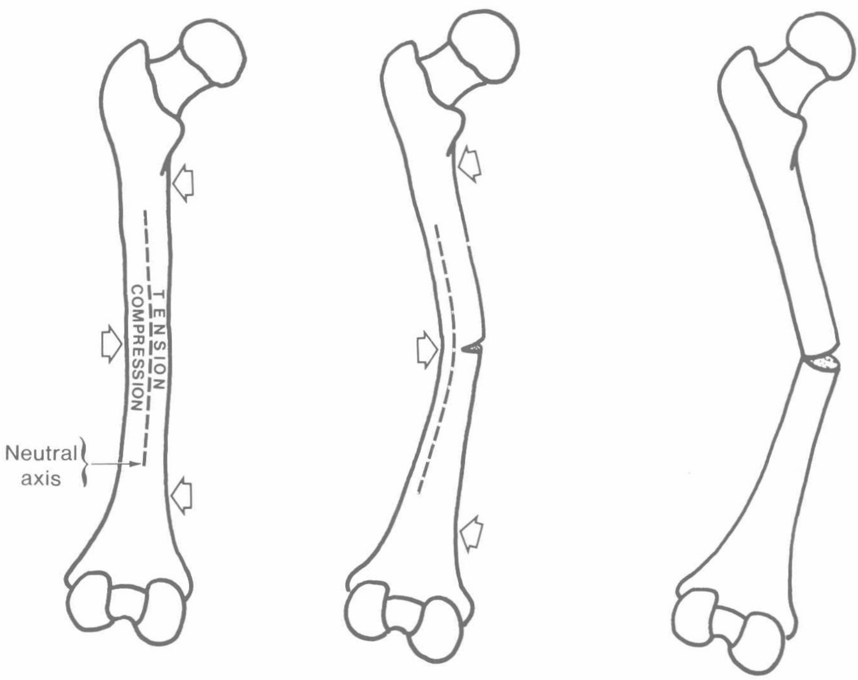


Figure 1.2. Transverse fracture—bending load.

where there are no tension or compression forces. As the crack propagates across the bone, the neutral axis moves from the midline towards the cortex on the concave side of the bone (Fig. 1.2).

Oblique Transverse and Butterfly Fractures

These fracture patterns result from a combination of axial compression and bending (Fig. 1.3). As described earlier, pure axial loading should produce a uniform compression force throughout the bone, whereas bending produces compression forces on one side and tension forces on the other. When these two loads are combined, the net effect is to add to the compressive forces on the concavity and to subtract from the tension forces on the convexity. As a result of the combined axial compression and bending loads, several modes of failure can occur.

1. If the compressive forces are sufficiently large relative to the bending forces, the bone fails in compression, producing an oblique fracture.
2. If, on the other hand, the bending forces are sufficiently large, the stress will produce a pure transverse fracture.
3. Most commonly a combination of the two produces an injury known clinically as the oblique transverse fracture.[2] As the name implies, this fracture pattern is partially oblique (representing failure in compression) and partially transverse (tension failure).

Radiologically this pattern looks like a transverse fracture with one fragment containing a protuberance or "beak" (representing the oblique component).

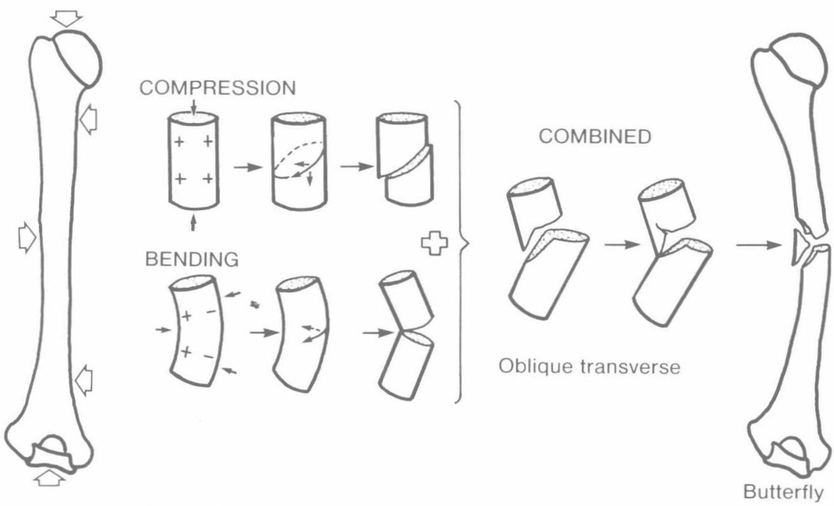


Figure 1.3. Butterfly and oblique transverse fractures—combined axial compression plus bending loads.

The butterfly fracture is a variation of the oblique transverse pattern. As the fragments continue to angulate, owing to the bending load, the fragment containing the oblique segment (beak) is impacted against the other fragment. Consequently the beak is sheared off, producing the classical butterfly fracture (Fig. 1.3).

Oblique transverse and butterfly fractures are commonly seen in the lower extremities when the thigh or calf receives a lateral blow during weight bearing; this fracture is common among pedestrians injured by automobiles (Fig. 1.4).

Spiral Fractures

There is controversy as to whether bone, when subjected to torsional loads, fails as a result of shearing—one portion sliding over another—or tension—pulling apart of intermolecular bonds.[3, 4, 13, 27] In any event, the

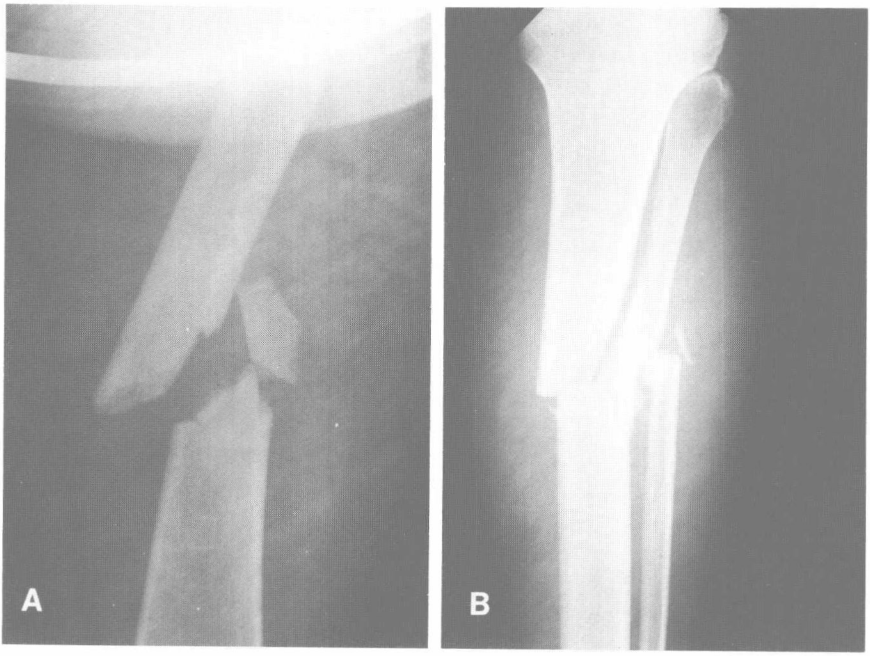


Figure 1.4. The butterfly fragment is always located on the compression side of the bone. These x-rays are from pedestrian accidents and give a great deal of information about the mechanism of injury. The x-ray on the left (*A*) shows a femoral fracture resulting from a direct blow to the lateral side of the thigh by the bumper of a transport truck. The butterfly fragment is located on the lateral (compression) side of the femur. The radiograph on the right (*B*) is that of another patient struck on the anterolateral aspect of the calf by a sports car. As would be anticipated, the butterfly fragment is situated anterolaterally.

resulting fracture takes the form of a spiral propagating around the shaft at an angle of 40–45° with the long axes of the bone.[3, 4, 27, 28]

The mechanics of a torsional spiral fracture can be illustrated by drawing a square on the side of a rubber tubing (such as an operating room suction hose) and then twisting the tube. The square then changes to a rectangle, a change which implies that the long sides of the rectangle are under tension (i.e., stretched) and the other sides are compressed. If, as experimental data indicate,[2, 3, 4, 11, 13] adult cortical bone usually fails in tension before compression, the crack should propagate at right angles to the long sides of the rectangle (that portion under tension). Hence, the spiral should curve around the shaft in a direction that would allow the portion of bone under tension to open up. This is what happens. The spiral usually continues until the proximal and distal cracks are approximately one above the other and then a longitudinal crack appears to

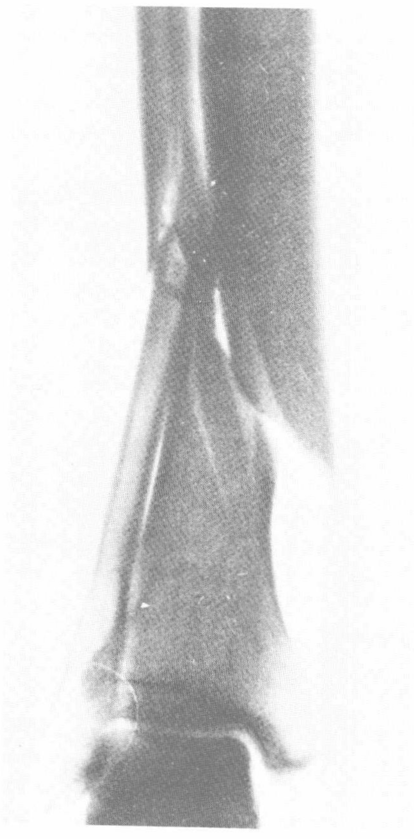


Figure 1.5. Spiral fracture as the result of skiing injury. The ski tip caught in the snow, producing external rotation force through the calf. The direction of the spiral tibial fracture is that which would be expected from the history of the injury.

join these two points, producing the vertical segment of the spiral fragment.

The direction of the spiral indicates the direction of the torsional force producing the fracture. Figure 1.5 shows a spiral fracture of the tibia resulting from an external rotation injury. The direction of the spiral could have been predicted from the history of the injury. As will be elaborated upon later, this information is important in understanding the location of the soft tissue hinges and hence in planning a closed reduction of the fracture.

The Oblique Fracture

Clinical[2, 24, 25] and available experimental data[15] indicate that the oblique fracture is the result of a combination of compression, bending, and torsional loads, the two most important components probably being compression and torsion. The summation of these three forces is equivalent to a bending load about an oblique axis.

In his book *Ruminations of an Orthopaedic Surgeon*, Dr. George Perkins[25] emphasized that it is important to distinguish between the oblique and spiral fracture patterns. Not only are they produced by different loads but they also have different prognoses: the spiral fracture usually heals uneventfully, whereas the oblique fracture often ends in nonunion.

On superficial examination the oblique fracture has a radiological appearance quite like that of the spiral fracture (Fig. 1.6); however, on closer examination the difference becomes apparent. In the oblique fracture the ends are short and blunt and there is no vertical segment, whereas the spiral fracture has long, sharp, pointed ends and a vertical segment is always present. Dr. Perkins compared the radiological picture of the oblique fracture to a garden trowel, that of the spiral fracture to a fountain pen nib. He felt that the higher incidence of nonunion in the oblique fracture was due to the lack of stability of the fracture fragments. Stability is, of course, a function of both fracture configuration and the presence of soft tissue support, which can be used to maintain a reduction. As the next two sections will demonstrate, from a biomechanical viewpoint the oblique fracture represents a higher energy injury than does the simple spiral fracture and, hence, more soft tissue injury and consequently delays in healing could be anticipated.

MAGNITUDE OF LOAD

In dealing with long bone fractures, not only must the type of force be considered but also its magnitude. The energy which produces the fracture is dissipated in a number of ways. Some is lost in the process of deforming (straining) the bone, some through the actual breaking apart of the intermolecular bonds within the bone, i.e., producing the fracture, and the rest is dissipated in the soft tissues surrounding the bone. Obviously the greater the magnitude of the force, the higher its energy content and, hence, the more tissue destruction. Conversely, the more complex the fracture pattern (oblique, oblique transverse, butterfly, and

Figure 1.6. Comparison of oblique and spiral fractures of the tibia. The spiral fracture (*right*) has a tip like a fountain pen nib and a vertical segment, whereas the oblique fracture (*left*) is shaped like a garden trowel and has no identifiable vertical segment.[25] The distinction is important because oblique fractures are higher energy injuries and hence associated with a greater incidence of delayed union.

comminuted) the greater the energy needed to produce the fracture.[27] The fractures which result from these complex load configurations represent high energy injuries.

LOAD RATE

In recent years, students of fracture biomechanics have recognized the necessity of specifying the rate at which the force was applied (load rate) when discussing the results of biomaterials testing.[12, 18, 20, 22, 26, 28] This information is needed because bone and most other biological materials possess *viscoelastic* properties. A viscoelastic material is one whose mechanical properties vary according to how rapidly the forces are applied. For example, Sammarco et al.[28] showed experimentally that it requires approximately 43% more torsional energy to break diaphyseal bone in 50 msec than to break it in 150 msec. Not only is more energy required to produce the fracture but the energy imparted to the bone is not dissipated in an orderly manner.[16, 26, 28] Numerous secondary fracture lines are created by minor discontinuities, and the bone literally explodes. The radiological appearance is that of a comminuted fracture (Fig. 1.7).

MATERIAL PROPERTIES OF BONE

The orthopedist needs to understand the properties of bone as a material for the same reason that an architect needs to understand the characteristics of wood or concrete. A craftsman cannot appreciate the mechanical properties of the overall structure unless he has first acquired an intimate knowledge of the physical properties of the basic material. Because bone is the fundamental structural material of the skeleton, the orthopedist must understand both its strength and its inherent weakness if he is to deal logically with musculoskeletal injuries.

It is important to distinguish between the *material* and *structural* properties of bone. When talking about the material properties of bone, the physical properties of the bone itself are described, whereas when discussing the structural properties of bone, how size, shape, and configuration (i.e., structure) affect strength is described. Both of these concepts are important to the understanding of why a particular fracture pattern occurs.

A great deal of engineering effort has been expended in the study of the material properties of bone. The reader is encouraged to examine this important subject in the comprehensive review provided by Reilly and Burstein.[27] Although a detailed review is outside the scope of this book, this section will point out a few of the properties which distinguish bone from other structural materials. An engineer might define adult bone

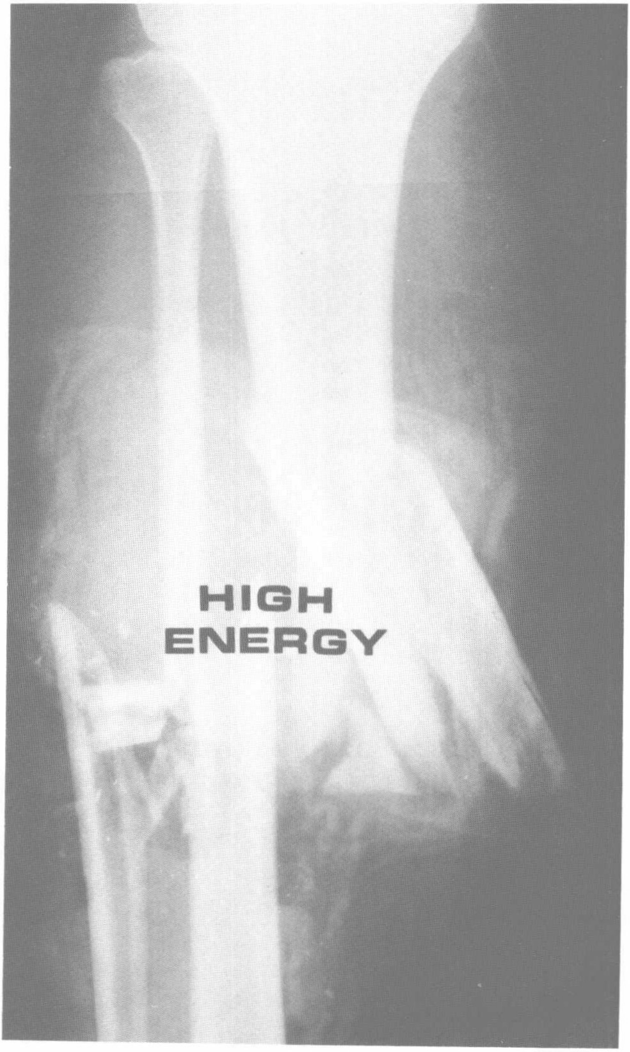


Figure 1.7. Comminuted tibia and fibular fracture as the result of a motorcycle accident. This high energy fracture with its associated soft tissue injuries eventually required amputation.

cortex as a nonhomogeneous, anisotropic, viscoelastic, brittle material which is weakest when loaded in tension. This definition, although somewhat overpowering, is seen to be quite straightforward when it is broken down into its components.