



# Perren's Strain Theory and Fracture Healing

# 2

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## Introduction

Fractured bone behaves differently in biological and mechanical environments. This fact influences the choice and method of treatment by the surgeon. Surgical procedures alter the biological environment, fixation of broken bone alters the mechanical environment; both directly contribute to the course of healing and are determined by the surgeon. The basic knowledge of biology and biomechanics of fracture healing are essential for all trauma surgeons since this knowledge defines the first treatment strategies (Table 2.1) [1].

This chapter serves as a summary for active clinicians rather than a pure scientific review. The primary goal of fracture fixation is to achieve prompt and if possible full function of the injured limb. The functional recovery does not only base on fracture healing but also its mechanics, biomechanics, and biology since these factors define a promising outcome for the patients. During fracture fixation, it is not always possible to achieve full mechanical and optimal biological environment. Strength and stiffness need to be sacrificed if the biological environment is aimed to be as optimal as possible. On the other hand, mechanical requirements may impair the

**Table 2.1** Relationship of fracture morphology, stabilization, and fracture healing [1]

	Simple	Multifragmentary
	Small (<2 mm)	Large (>2 mm)
Relative stability	Bone resorption, healing delay, or nonunion	Secondary bone healing (callus)
Absolute stability	Primary bone healing, osteonal remodeling	Bone resorption, healing delay, or nonunion

biological environment. Osteosynthesis should not aim to permanently replace a broken bone; it should provide a temporary support allowing early functional rehabilitation with healing in a proper anatomical position [1–4]. Further, the type of implant influences the biomechanical environment: Steel with mechanical strength and ductility stands opposed to the electrochemical and biological inertness of titanium. With the treatment decision, the trauma surgeon determines a compromise between mechanical stability and the biological environment as well as the combination of technology and procedure best fit for the patient.

## Bone

The bone supports and protects soft structures while enabling locomotion and mechanical functioning of the limbs. The mechanical characteris-

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tics of the bone are a combination of stiffness (little deformation under load) and strength (tolerate high load without failure). The characteristics of the bone are more similar to glass than to rubber [1]: The strong material breaks under very small deformation. The repeated displacement of fractured elements inhibits the bridging of the fracture gap. Relative stable fixed fracture shifts the balance of mechanical versus biological functions more toward the biological environment. That leads to a sequence of biological events, mainly the formation of soft callus followed by hard callus. That leads to a reduction of strain and the deformation of the less stiff repair tissue. This lower-strain environment promotes the formation of bridging callus which subsequently increases the mechanical stability of the fracture. Full function is restored after the fracture is solidly bridged. Bone remodeling restores the original bone structure [5, 6].

## Fracture

A fracture is an unphysiologic discontinuation of the bony integrity. It is the result of repetitive or a single overload. A traumatic fracture is always combined with a soft tissue damage to certain degree. The rapid separation of fracture surfaces creates a void (cavitation) that also contributes to soft tissue damages.

## Mechanical and Biomechanical Effects

The loss of continuity results in deformation, pain, and impaired supportive function of the bone. Stabilization may restore function and relieve pain. This may lead to pain-free mobility and reduce complications such as complex regional pain syndromes.

With the disruption of the bone, arteries and veins are damaged. That leads to a spontaneous release of biochemical factors helping to induce bone healing. The fresh fractured bone has enough active and effective factors that support and coordinate fracture healing [7]. Biologically,

surgical fracture stabilization should be nothing more than a guidance and a support in this healing process.

**Blood Supply** The pure mechanical process of a fracture triggers biological reactions (callus formation and bone resorption). Equally to other tissue, the healing and remodeling depends on an intact blood supply. Table 2.2 summarizes factors that influence blood supply at the fracture site [1, 8–11].

Necrotic bone induces internal (Haversian) remodeling, allowing the replacement of dead osteocytes with temporary loss of strength (porosis). Large plate-bone contact areas show this effect just beneath the plates. A higher periosteal blood supply (e.g., with the help of a limited-contact dynamic compression plate [LC-DCP]), may reduce the amount of avascular bone. Injury to the bone reduces cortical circulation by nearly 50% [11] that attributes to a vasoconstriction in the periosteal but also the medullary vessels [12]. The healing process, however, increases blood flow in the adjacent soft tissue that nourishes the callus formation [13, 14]. This supports the statement

**Table 2.2** Overview of factors that influence blood supply in a fractured bone [1, 9–11]

Mechanism of injury	Fracture type and its associated soft tissue injury depend on the energy and the direction of the injury
Initial patient management	Motion during rescue leads to additional damage
Patient resuscitation	Fluid resuscitation and oxygen therapy may support healing Late correction of fracture displacements heightens the risk of additional soft tissue damages
Surgical approach	The additional damages through surgical exposure of the fracture should be minimized. Anatomical knowledge is one of the most essential tools of any surgeon [8]
Implant	Contact of the bone and implant may damage bone circulation and depend on the type of implant [9]
Consequence of trauma	Elevated intra-articular pressure and increased hydraulic pressure reduce blood supply and should be addressed early

that the approach to the fracture should damage and strip off as little soft tissue as possible. The essential angiogenesis with subsequent callus perfusion is elementary in the healing process of the fractured bone. This, however, depends on the method of treatment and the induced mechanical conditions (Table 2.3) [15–22].

### Biology of Fracture Healing

Fracture healing is divided either into primary (direct) healing by internal remodeling or secondary (indirect) healing by callus formation.

**Table 2.3** Factors influencing angiogenesis during treatment and healing of fractures

Flexible fixation leads to greater vascular response (larger volume of callus)
Large strain reduces blood supply (instability in great fracture gap) [15]
Surgical exposure alters fracture hematoma and soft tissue blood supply
Extent of reaming influences cortical perfusion [16–18]
Implant-bone contact reduces bone perfusion
Fragment manipulation, minimal invasive approaches, and external or internal fixators may reduce damages to the blood supply [19–22]

The biological process of osteonal bone remodeling is the basis of primary bone healing and occurs only with absolute stability. Relative stability, however, promotes secondary bone healing through flexible fixation methods. The biology behind secondary bone healing is similar to the process of embryological bone development including both intramembranous and endochondral bone formation [23]. This can be seen during the callus formation in the process of fracture healing of diaphyseal fractures (Table 2.4) [1, 24].

### Biomechanics of Bone Healing

#### Methods of Fracture Stabilization

Surgeons interpret stability as the degree of displacement at the fracture site induced by load [25]. This degree defines the course of fracture healing. The stabilized fracture does not displace under physical load. The aim of fracture stabilization is to maintain the achieved reduction, restore stiffness at the fracture site, and minimize pain related to instability at the fracture site [26–28].

**Table 2.4** The four stages of bone healing [1, 24]

Inflammation	<ul style="list-style-type: none"> <li>Until 1 week after fracture</li> <li>Inflammatory exudation from damaged vessels</li> <li>Soft tissue injury and degranulation of platelets release inflammatory mediators</li> <li>Vasodilatation, hyperemia, PMN, macrophages</li> <li>Granulation tissue replaces gradually fracture hematoma</li> <li>Osteoclasts remove necrotic bone</li> </ul>
Soft callus formation	<ul style="list-style-type: none"> <li>2–3 weeks after fracture in adequately stabilized fracture</li> <li>Growing callus can be observed</li> <li>Progenitor cells are stimulated to become osteoblasts</li> <li>Intramembranous bone growth starts from both fracture sites</li> <li>Mesenchymal progenitor cells proliferate and migrate through the callus</li> <li>At the end: stability is adequate to prevent shortening not however angulation</li> </ul>
Hard callus formation	<ul style="list-style-type: none"> <li>3–4 months</li> <li>Starts as soon as soft callus has bridged the fracture gap</li> <li>Soft tissue within the gap undergoes endochondral ossification</li> <li>Callus is converted into calcified tissue (woven bone)</li> <li>At the point of lowest strain (periphery of fracture site), bone callus growth begins</li> <li>Hard callus formation starts peripherally and progressively moves toward the center of the fracture gap</li> <li>Endochondral ossification replaces soft tissue in the gap by woven bone joining original cortex</li> </ul>
Remodeling	<ul style="list-style-type: none"> <li>Months to years</li> <li>Begins after the fracture has solidly united with woven bone</li> <li>The balance of pressure and tensile forces rebuilt the bone to its original morphology</li> </ul>

PMN polymorphonuclear neutrophils

Absolute stability shifts the balance toward neutral mechanical fixation preventing callus formation. Relative stability shifts the balance toward the biological environment that stimulates secondary bone healing. This however can only occur if the motion at the fracture site is not too extensive preventing callus formation and delaying healing [29].

## Conservative Fracture Treatment

This type of treatment requires closed reduction with subsequent stabilization to maintain reduction and reduce fragment motion. Indirect bone healing will be stimulated with a nearly uninterrupted biological environment. Traction or external splinting may achieve stabilization in conservative fracture treatment. A curved cast produces a straight bone, and a straight cast produces a bent bone [1, 30]. The pressure of the surrounding tissue reduces movement of the fragments.

## Relative Stability

Relative stability allows movement of the bone fragments when physiological load is applied. Rigidity of the fixation decreases displacement. If a fixation method is considered flexible, it allows controlled interfragmentary movement under physiological load [2, 24, 31].

**External Fixator** Usually, external fixators provide relative stability. The stiffness of fracture stabilization by external fixation depends on the type of implant (e.g., Schanz screws and bars), the geometrical arrangements of these elements related to one another and the bone (e.g., uniplanar, biplanar, circular), and the coupling of the implant to the bone (e.g., tensioned fine wires) [32]. Important factors that increase the stability of fixation include the following:

- Stiffness of the connecting rods.
- Short distance between the rod and the bone axis.

- Number, spacing and diameter of the Schanz screws/wires, and their tension.
- Unilateral external fixator combines axial, bending, and shearing displacements. The external fixator is the only system that allows the surgeon to modify flexibility by adjusting the implant without additional surgery (dynamization). External fixators provide quick and relative safe stability and are used when the biologic environment and the soft tissue situation allow little manipulation [33–35].

**Intramedullary Nailing** The classic intramedullary nail achieves stability against bending and shear forces perpendicular to its long axis; it however is not immune to torque and is unable to prevent axial shortening. With low torsional stiffness and the loose coupling of intramedullary nail and bone, intramedullary nailing was indicated to simple transverse or short oblique fractures, which cannot shorten and will interdigitate to prevent rotation [36, 37]. The development of locked intramedullary nails and cannulated nails overcame many of these restrictions. Locked nail has the ability to tolerate torsional forces and improved axial loading [38]. The diameter of the nail defines the degree of stability additional to its geometry and the number of interlocking screws as well as their spatial arrangements. The advantages of the locked intramedullary nail come to the price of nonlinear stiffness of the nail-bone construction. To promote insertion of interlocking screws, the locking holes are larger than the diameter of the screws, allowing movement at the coupling, even with little load. Further insertion of interlocking screws may decrease motion as well as the use of angular-stable locking systems (e.g., expert tibial nail) [39, 40].

**Internal Fixators and Bridging Plates** Multifragmented fractures that are stabilized with a plate in the manner of an external fixator provide elastic splinting. The dimensions of the implant as well as the number and the positions of the screws, the coupling between

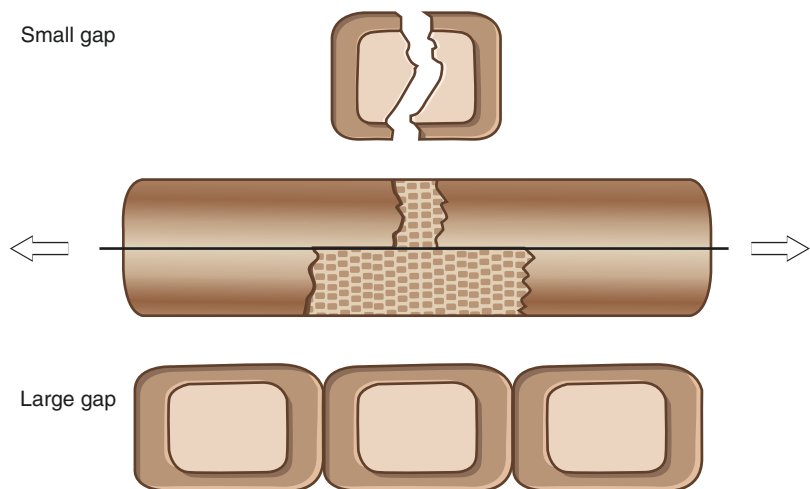
implants, and the implant and the bone define the stiffness of this fixation method. The indication for plating with the goal of relative stability includes multifragmentary fractures. If it is possible, plating with relative stability should be avoided for simple fractures since it increases the risk for delayed union or even nonunion [41].

### Indirect Fracture Healing: Perren's Strain Theory

Acceleration of bone healing is achieved with the stimulation of the formation of callus with interfragmentary movement [42, 43]. The maturing callus stiffens and reduces interfragmentary motion with the possibility of hard bony callus formation. In the early stages of fracture healing, the fracture tolerates greater deformation or higher tissue strain. Later stages when the callus is calcified, the tissue does not tolerate these deformations or strain forces. Figure 2.1 reveals the dynamics of Perren's strain theory. Cell disruption occurs in small gap fractures, whereas in large gap fractures, the strain forces are distributed among cells with each cell experiencing less traction force [2].

Strain is defined as the deformation of material when a given force is applied. Since normal strain is the relative difference in length when a given load is applied, it has no dimension as is expressed by percentage. Before it fractures, intact bone has a normal strain tolerance of 2% before it fractures, compared to the strain tolerance of 100% in granulation tissue [29]. When the movement of fracture ends is too great, the local strain rises over tolerable limit of forming woven bone leading to impaired bridging by hard callus [44]. This leads to an increased volume of the soft callus resulting in a decreased local tissue strain to a level that allows bony bridging. This adaptive mechanism of increasing soft callus volume is impaired in considerable narrow fracture gaps with its movements occurring mostly at the gap leading to high-strain environment. The tolerance decreases after overloading the fracture with too much interfragmentary movement in the healing process [45]. Strain and fluid pressure have an inhomogeneous distribution within the callus. The applied load regulates the callus formation with biophysical stimuli that are sensed by the cells. Different signals are produced with these biophysical stimuli that alter extracellular matrix and tissue properties. After ossification

**Fig. 2.1** Perren's strain theory. Cell disruption occurs in small gap fractures, whereas in large gap fractures, the strain forces are distributed among cells, resulting in each cell experiencing less traction force. (Adapted from AO principles of fracture management [2], with permission from AO Foundation, Duebendorf, Switzerland)



of the callus, these signals reach a steady state and the original cortex regenerates. Excessive interfragmentary strain as well as too wide fracture gaps impair bridging by hard callus leading to the development of hypertrophic nonunions [46]. On the other hand, some mechanical stimulations are needed to form callus. This is impaired in low-strain environments after either too stiff fixation or too wide fracture gaps [44] resulting in delayed healing or nonunions.

### **Absolute Stability**

The only effective method to abolish fracture movement is interfragmentary compression leading to a no-strain environment. This leads to direct bone healing. The fracture heals without visible callus formation. Osteonal remodeling is the consequence of this fixation method (compressive preload and friction).

**Compressive Preload** The compressive preload prevents displacement of the fracture fragments leading to absolute stability if the compression is greater than traction produced by function. The static compression does not produce necrosis, neither in lag screws nor in compression plates, even in overloaded bone [47].

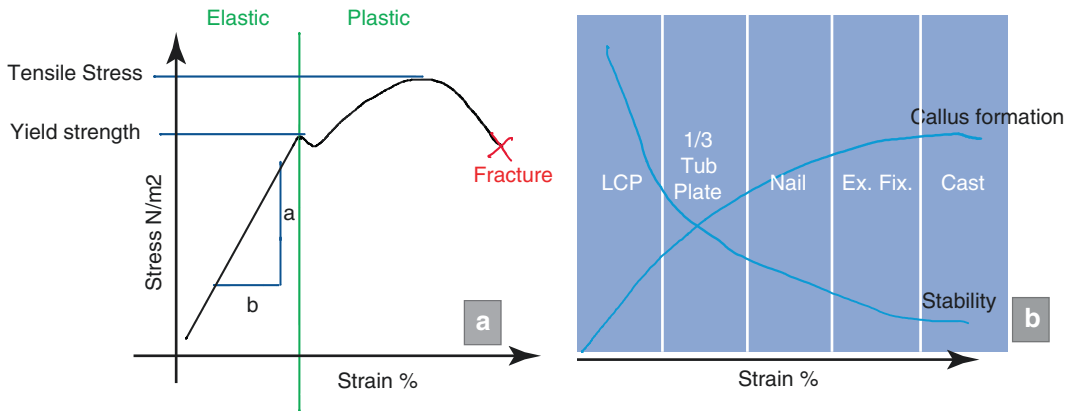
**Friction** Friction counteracts shear forces that act tangentially and thus avoids sliding displacements. The amount of resistance to shear displacements depends on the compression-induced friction and the geometry of the surfaces in contact. Normal smooth bone surfaces produce less than 40% friction [47]. Rough surfaces allow firm fixation with additional counteracting displacements due to shear forces.

**Lag Screws and Plates** The lag screw stabilizes fractures by compression after the approximation between the thread and the head of the screw. These forces exceed the time direct bone healing requires. Lag screws, however, provide small lever arm to resist functional loading.

When viewed from the center of the screw, the area of compression is too small to withstand bending and shearing. This can be overcome with protection plates (neutralization plates) that protect the lag screws from these forces. Thus the plate protects, has ability to compress, and can be used as tension band, bridging of buttress. Simple transverse or short oblique fractures can be treated by a plate that is applied to one side of a fracture and then tensioned (excentric placement of screws). However, this method on a straight plate on a straight bone produces compression underneath the plate with slight tension on the opposite cortex leading to an instable situation. This problem can be overcome by overbending the plate to produce a small gap between the plate and the bone at the level of the fracture. If the plate is placed at the tension side of the bone, it acts as tension band and converts tension into compression at the far cortex producing absolute stability. The buttress is a construct that resists axial load by applying force at 90° to the axis of potential deformity. It is often combined with lag screws.

### **Direct Fracture Healing: Biomechanics**

In the diaphysis, absolute stability is achieved by interfragmentary compression. Early functional treatment is possible within a few days of surgery. Radiological, only minor changes can be observed with minimal or no callus formation [48]. The gradual disappearance of the fracture sign shows progredient fracture healing, whereas a widening of this line may indicate insufficient stability. In the first days after surgery, minimal activity can be observed near the fracture site. The hematoma is resorbed/transformed into repair tissue. After few weeks Haversian systems remodel the bone [49] with simultaneous lamellar filling of fragments. In the following weeks, the osteons reach the fracture and cross it as soon as there is contact [50]. The newly formed osteons crossing the gap provide a micro-bridging or interdigitation.



**Fig. 2.2** (a) Stress-strain diagram with different stages of deformation. Young's modulus is the ability of material to withstand deformation ( $a/b$ ). Tensile stress is the maximal tension material can withstand. At the *yield* strength, elastic (reversible) deformation ends and plastic (irreversible) deformation starts. Here first fibers start to break. (b) Different therapeutic interventions influence

callus formation as well as stability as the function of strain. The most stable (rigid) fixations lead to minimal callus formation. The less flexible the fixation, the more strain is observed that leads to more callus formation. (N = Newton, m = meter, LCP = lateral compression plate, Tub plate = tubular plate, Ex. Fix. = External fixator)

## Summary

Each tissue has elastic and rigid properties. The biomechanical function of tissues depends on the proportion of these properties. Within a tissue, elastic and rigid properties define the amount of stress this tissue can withstand. The bone has the ability to withstand a certain amount of stress as well as strain with reversible deformation (elastic deformation). However, when a certain point is reached (yield strength), single cells or cell compounds start to break and the deformation is irreversible (plastic deformation). If the tissue suffers more strain, after the maximum of stress it can withstand (tensile stress), the tissue will fracture.

Depending on the treatment strategy, as well as the fracture pattern and properties, the degree of rigidity and elasticity within the fracture gap can be defined by the fixation method. For example, the lateral compression plate minimizes due to absolute stability within a fracture gap strain leading to minimal callus formation. Contrary, casting allows more strain leading to more callus formation due to less stable fracture fixation (Fig. 2.2). The treatment strategy depends on the fracture properties as well as the

patients' concomitant injuries. Each treatment should be evaluated and assessed individually.

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