# FEMORAL FRACTURES INDICATIONS AND BIOMECHANICS OF EXTERNAL FIXATION

## Externe fixatie van femurfrakturen Indicaties en biomechanisch onderzoek

ACADEMISCH ZIEKENHUIS

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# FEMORAL FRACTURES

# INDICATIONS AN BIOMECHANICS OF EXTERNAL FIXATION

# EXTERNE FIXATIE VAN FEMURFRAKTUREN

# INDICATIES EN BIOMECHANISCH ONDERZOEK

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More rational and more humane use of technologies is likely to result if there were a more consistent strategy for assessment, and a more systematic attempt to apply the result to clinical practice.

Bryan Jennett 1987

To Henny, our parents,
Lysette and Thomas

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# FEMORAL FRACTURES, INDICATIONS AND BIOMECHANICS OF EXTERNAL FIXATION

## A GENERAL PART

## INTRODUCTION

In our modern society, serious injuries, which sometimes result in disablement, are not uncommon. The increased intensity of traffic and the number of people participating in high risk sports also plays a part. High velocity injuries are a typical example and the combination of comminuted fractures with extensive soft tissue injuries, which can result, demand optimal treatment.

For an accident victim, the correct choice of treatment from the various alternatives available, is of overriding importance if the best possible results are to be achieved (1). This choice has become more difficult due to technical progress, particularly from a biomechanical point of view, which has led to new therapeutic possibilities. The development of new surgical techniques is illustrated by the various treatment methods which can be employed to treat femoral fractures. The present treatment arsenal offers a range of options, from conservative treatment, using plaster of Paris or traction techniques, to various forms of internal osteosynthesis and extensive external fixation systems which can be mounted on the upper leg.

Although in some cases conservative treatment can form the best approach (2,3,4), at present many surgeons prefer to use internal fixation. When a fracture has been sufficiently stabilized by osteosynthesis to allow the patient to undergo a training programme or even to burden the leg, functional treatment is possible (5).

Internal fixation can be carried out in various ways. For femoral shaft fractures, an (interlocking) nail is becoming increasingly popular, instead of open realignment of the fracture. External fixation, which has become a generally accepted method of treating fractures of the lower leg, has been used infrequently on the upper leg. During the last 100 years, several different types of external fixation have been tested on femoral shaft fractures on a limited scale in various parts of the world.*

It is clear that external fixation offers good prospects for treating serious, (possibly) comminuted, compound femoral shaft fractures (often in combination with blood vessel and nerve injuries). Only a few authors elect to use external fixation on all femoral shaft fractures, including those in children (6,7). Various views exist on the indications, treatment schemes and adjunct therapy. The search for similarities and background information was one of the first objectives of this study. The biomechanical aspects play a central part in this.

An overview of the literature on the treatment of femoral fractures is given and the relationship between the anatomy of the upper leg and external fixation is investigated. Experimental models have been used to answer the question of what forces act upon the femur and how they are neutralized by external fixation.

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* External fixation: the fixation of skeletal parts using immobilizing material, in which pins are inserted into the bone and are held together by means of an external support structure.

The histological aspects of fracture healing during stable and unstable (external) fixation are discussed briefly together with their clinical consequences.
A large proportion of this thesis is taken up by biomechanical research, in which the rigidity and elastic deformation of 12 different external fixation frames (applied to the femur) were analyzed. To illustrate the clinical prospects (and the relationship with biomechanical studies) representative case histories of patients have been added.

The question addressed in this thesis can be split up into a number of parts:

**(A)** What consequences do the various external fixation devices have on the anatomical relationships and the function of the leg when applied to the femur?

**(B)** How much movement do the fixation devices tested in this study allow and which of them (preferably easy and quick to assemble) offers the most stability?

**(C)** What is the course of fracture consolidation using external fixation and are there any clinical problems? If external fixation is applied, which is the most suitable frame?

Additional aims of this study are to give a valid representation of the present state of affairs and to render a number of practical conclusions which will be of use to treatment teams when a patient with a femoral shaft fracture enters the hospital.

| Main diagnosis (SIG-code: 821.0) | No. of pats | Days in hosp. | Sex | Age | Treatment | Deceased |
|---|---|---|---|---|---|---|
| 1983 | 2071 | 79280 (mean 38.3 days) | M 1253<br>F 819 | 0 - 14 Yrs:767<br>15 - 64 Yrs:837<br>≥ 65 Yrs:467 | Operative 61%<br>Closed 39% | 63 pats (3%) |
| 1984 | 1982 | 76238 (mean 38.5 days) | M 1220<br>F 762 | 0 - 14 Yrs:741<br>15 - 64 Yrs:806<br>≥ 65 Yrs:435 | Operative 62%<br>Closed 38% | 41 pats (2%) |
| 1985 | 1930 | 68192 (mean 35.6 days) | M 1123<br>F 790 | 0 - 14 Yrs:709<br>15 - 64 Yrs:745<br>≥ 65 Yrs:477 | Operative 63%<br>Closed 37% | 50 pats (2.6%) |

Table 1.1 Epidemiological data femoral shaft fractures 1983 - 1985; Non Specified, closed (source SIG, Information Centre for the Health Service)

| | No. of patients |
|---|---|
| 1983 | Closed :2557 (821.0)<br>Open : 213 (821.1) |
| 1984 | Closed :2425<br>Open : 208 |
| 1985 | Closed :2328<br>Open : 177 |

Table 1.3 Epidemiological data femoral shaft fractures 1983 - 1985;

| Main diagnosis (SIG-code: 821.1) | No. of pats | Days in hosp. | Sex | Age | Treatment | Deceased |
|---|---|---|---|---|---|---|
| 1983 | 151 | 5851 (mean 38.3 days) | M 103<br>F 48 | 0 - 14 Yrs: 44<br>15 - 64 Yrs: 42<br>≥ 65 Yrs: 65 | Operative 79%<br>Closed 21% | 4 pats (2.6%) |
| 1984 | 153 | 6252 (mean 40.9 days) | M 106<br>F 47 | 0 - 14 Yrs: 29<br>15 - 64 Yrs: 98<br>≥ 65 Yrs: 26 | Operative 86%<br>Closed 14% | 4 pats (2.6%) |
| 1985 | 121 | 4514 (mean 37.3 days) | M 93<br>F 28 | 0 - 14 Yrs: 21<br>15 - 64 Yrs: 86<br>≥ 65 Yrs: 14 | Operative 84%<br>Closed 16% | 2 pats (1.7%) |

Table 1.2 Epidemiological data femoral shaft fractures 1983 - 1985; Non Specified, open (source SIG, Information Centre for the Health Service)

| | (821.0) | | (821.1) | |
|---|---|---|---|---|
| | percentage | patients | percentage | patients |
| 0-14 Jrs | 21 % | 445 | 46 % | 42 |
| 15-64 Jrs | 89 % | 2095 | 95 % | 256 |
| ≥ 65 Jrs | 82 % | 1114 | 87 % | 52 |

Table 1.4 Percentage of patients treated surgically with main diagnosis femoral shaft fracture, divided into age groups. Non-specified, closed (821.0) and open (821.1)
Source SIG 1983-1985, total number of patients 6,388 of whom 4,004 underwent surgery

# CHAPTER 1 FEMORAL SHAFT FRACTURES

## 1.1 Epidemiological data

Epidemiological data are concerned with: the number of victims, mortality rate, type of injury, choice of treatment, duration of hospitalization, sex and age distribution. In the Netherlands (14.4 million inhabitants) the SIG (Information Centre for the Health Service) keeps records on more than 97% of all hospital admissions. These data are extrapolated to 100% by means of a correction factor. It is possible to register the reason for admission via code numbers for the main diagnosis or for any secondary diagnoses. For example, if a femoral shaft fracture has been registered as a secondary diagnosis, there must also have been an accompanying injury which, as the principal diagnosis, will have been more prominent.
SIG data recorded during the last few years (from 1983 to 1985) are summarized in Tables 1.1, 1.2, 1.3 and 1.4. These data concern femoral shaft fractures "not specified, closed, code 821.0" and "not specified, compound, code 821.1" (8).

In 1983, 97.5% of all hospital admissions were registered. These data show that, on average, over 2130 patients per year with a principal diagnosis of "femoral shaft fracture" (open and closed) were treated. The period of hospitalization was nearly 40 days. Six out of ten patients were male, the proportion in the youngest age group (0-14 years) was high. In this age group open repositioning and fixation is carried out less frequently (20%) due to the danger of surgical damage to epiphyseal plates and subsequent growth disturbances.
Research in 1973 (9) has shown that in that period, 1 out of 7 femoral fractures was a compound fracture. Over the last 10 years this figure has been halved to only 1 out of over 14 patients. The modernization of the road system, car designs and law enforcement (e.g. the compulsory wearing of seat belts) may explain this decrease. There has also been a sharp decrease in the number of moped accidents. Mopeds lost a great deal of their popularity when it became compulsory to wear a crash helmet. In contrast to the death rate of over 3000 victims on the roads in the 1960s, the death rate in 1984, with much more intensive traffic, was 1600 (10).

SIG data have shown that 60% of closed femoral shaft fractures and over 80% of open fractures are treated surgically. The mortality rate is 1.7 to 3%. It is not possible to establish from the data whether accompanying (brain) injuries are partly responsible for the ultimate mortality. The mean total number of femoral shaft fractures per year (main or secondary diagnosis, Table 1.3) in the period 1983 to 1985 was 2636. This means an incidence of 1 patient with a femoral shaft fracture to every 5460 Dutch inhabitants, per year.
Statistical research during the period 1978 to 1981 (the most recent data available) in the framework of the Dutch Health Law, provides information on the choice of treatment (11). Data on 568 femoral fractures (shaft plus supracondylar) show that

external fixation was very seldom chosen as the primary treatment method (<1%: 5 patients). Three patients (from a group of 36) had compound fractures. In 74 patients it was shown that a second form of treatment had to be selected at a later stage; in two the choice was external fixation.

## 1.2 Mechanism of origination

If a structure is exposed to a known amount of stress and the resulting degree of distortion is measured, a relationship can be found between stress and distortion and, subsequently, the strength and rigidity of the structure can be established. In order to determine the strength and toughness of bone directly connected with bone fractures, three parameters are of importance for the stress distortion curve:
**(A)** the amount of stress which can be applied before it breaks: the breaking point,
**(B)** the amount of distortion which can take place before the breaking point is reached,
**(C)** the amount of energy which can be absorbed before the breaking point is reached: the material form changing energy.

The moment a femur breaks, the permitted level of material stress has been exceeded. This stress is related to the form and size of the bone diameter and the amount of stress to which it has been exposed (12)
Five types of stress can be distinguished: traction, pressure, flexure, slide and twist. Combinations of these form compound stress. In order to study the mechanical behaviour of bone, experiments were carried out on pieces of bone of standardized form and dimensions.
Major differences have been found between cortical and cancellous bone. Although a combination of these two types of bone can be considered as one material, the porosity varies considerably. Cortical bone is much denser than cancellous bone. It can withstand more stress before it breaks, but it is less flexible. Cancellous bone is able to absorb a great deal of distortion stress due to its more porous structure.
The strength of a bone varies with the direction of the force acting upon it. The strength and rigidity are greatest in the direction in which the bone is burdened most often (13). During normal activities, only a small amount of the energy absorbing capacity of a bone is utilized. A bone's ability to absorb energy depends on the speed at which the forces act upon it. The greater the speed, the greater the amount of energy which will be absorbed before the bone breaks. When a bone finally breaks, the energy it has absorbed is freed at the moment the fracture occurs. With high stress speeds, the absorbed energy will not be able to escape quickly enough via a single tear, so more comminuted fractures occur, which can cause extensive damage to the surrounding soft tissue. At lower stress speeds, a single tear is usually sufficient to discharge the energy. Little or no dislocation takes place and the soft tissue is hardly affected.
The characteristics of many types of material have been established through biomechanical research, including the greater resistance of adult cortical bone to

pressure than to traction and transverse forces. A decrease in the strength of a bone due to immobilization or old age and a decrease in resistance to frequently changing stress can eventually lead to fractures due to bone fatigue.

## Biomechanical research

Biomechanical research (14,15) has shown that the type of fracture can be analyzed by means of the elasticity theory, in which the relationships between external stress and internal material resistance can be explained.
From this it can be deduced that transverse fractures are caused by bending forces (Figure 1.1). A combination of transverse forces and pressure causes butterfly fragments. The fracture starts as a transverse tear on the traction side and a triangular butterfly fragment results.
Solitary pressure causes the bone to bend at one or more locations. The fracture will occur at the site where the bone is bent the most.
If a bone is subjected to tortional stress, a spiral fracture will result at the weakest point. Osteoporotic bone has a poor resistance to tortional stress, thus spiral fractures are particularly likely to occur (9).
The results of studies on human and animal cadaver material have been compared with clinical findings (16). Owing to the fact that laboratory experiments are an oversimplification of what takes place in reality, there is still some uncertainty about the effect of various combinations of stress. Also the extent to which soft tissue or adjacent joints contribute to energy absorption and the role of muscle activity on the energy dis- tribution in bone is not yet fully clear.

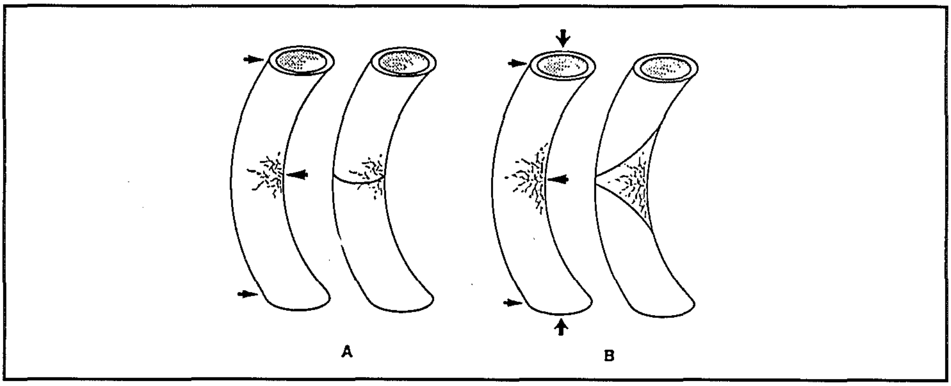


*Figure 1.1 Schematic representation of the origination of fractures under the influence of pressure and transverse forces.*

## Biomechanics of femoral shaft fractures

Certain types of accident can give rise to characteristic fractures. The way in which the wrist of an elderly person is broken (falling with the hand extended) can be deduced from the nature of the trauma.

Various factors play a part in the case of femoral shaft fractures. An important aspect is that the femur is the strongest bone in the human body which only fractures when it is exposed to a considerable amount of stress. Traffic accidents are a major source of femoral fractures. These fractures are cause by a combination of pressure and bending forces (14). A car having a head on collision is a good example of this and can lead to typical shattering of the femur if the shaft becomes wedged between the dashboard and the acetabulum (17). The knee absorbs the first impact; the extent to which the knee becomes injured depends on the force of the impact and the position of the knee (18,19). The impact subsequently affects the femoral shaft and neck, in quick succession. The neck of the femur is more likely to break than the shaft (15). Motorcyclists form another high-risk group. As a result of a collision or a fall, the knee and upper leg are exposed to enormous forces. In more than half of the patients with knee injuries from a head on motorcycle accident, permanent loss of mobility of the hip or knee joint results.

## Miscellaneous injuries

Occupational accidents have diverse natures. Accidents involving the femur which take place in or around the home or on the playing field, do not usually involve much violence. Tortional stress can lead to long or short spiral fractures. Shot wounds can cause serious comminuted fractures in combination with soft tissue injuries. This type of serious injury is rarely seen in the Netherlands.

## 1.3 Evolution of the treatment

A number of conditions must be fulfilled to achieve good results in fracture treatment. The choice of treatment depends on the magnitude of the injuries and the fracture type. It is not only the experience of the treatment team in utilising the various types of treatment which determines the treatment method, but also the organization, technical possibilities and the design of the clinic.

Since about the turn of the century, surgeons have been able to choose between surgical and non surgical procedures, both of which have their own specific advantages and disadvantages. During the last few years femoral fractures have been treated using open (plate) fixation but there is also a distinct preference for closed realignment if possible. This can be achieved by inserting a (intramedullary) nail into the marrow cavity, if necessary clamping it on to the middle third, or by using an interlocking mechanism.

## Consolidation and immobilization

Fractures always consolidate, even if they are not immobilized. Rib, clavicle and vertebral fractures are good examples. Nevertheless, goal orientated treatment is usually necessary to make sure that consolidation takes place with the bone fragments correctly aligned. It is possible to start functional treatment at an early stage if a fracture has been sufficiently stabilized using osteosynthesis to withstand a training or weight bearing programme. The many disadvantages associated with long term immobilization are avoided in this way.

## History from 400 BC up to the Second World War

As early as 400 years BC, Hippocrates held the opinion that immobilization should be the aim following realignment. If necessary and in relatively few cases, he performed open surgery to set the fractures (20).

Great progress has been made in the treatment of fractures since 1900 and improved techniques have been developed. Before the turn of the century, a femoral fracture nearly always led to disability owing to shortening of the leg or angulation of the broken bone. Surgeons had to guess the nature of the fracture because there was no X-ray equipment available at that time to help with the diagnosis. The first radiographs did not appear until 1896.

In the second half of the last century, developments started which ultimately led to a series of improvements in the treatment of fractures and wounds, for example, anesthetics, the prevention of shock, plaster of Paris and splint immobilization and particularly the discovery of X-rays. Hygienic measures (washing hands prior to surgery, wearing masks and caps) were introduced together with other antiseptic proceedings.

Before that time, open fractures usually led to the amputation of the affected arm or leg. Due to these anti septic measures, they subsequently formed the basis for developments in the surgical treatment of fractures.

This evolution led to a survey of the literature on treatment possibilities for femoral shaft fractures in 1983 (5) in which therapies such as the intramedullary nailing procedure (possibly in combination with cerclage), plate osteosynthesis and interlocking nails were mentioned. It is striking that no room was left for more conservative forms of treatment, not even for external fixation.

Before the Second World War, femoral shaft fractures were not often treated surgically. Shortly afterwards osteosynthetic techniques developed so rapidly that surgical stabilization soon became the treatment of choice. Large collections of statistics have made it clear that osteosynthesis of the femur produces better functional results than conservative treatment (21).

## The risk of infection

In the Netherlands, research has shown that the total infection rate following internal osteosynthesis of long bones is fairly high: 2.9% for the surgical treatment of closed fractures and 15% for open fractures (11). In an annotation (22) it was stated that the high percentage of infections after AO ASIF osteosynthesis of various fractures, including open shaft fractures, is unacceptable and that primary internal fixation of open fractures should no longer be considered as the treatment of choice. In this series, patients treated surgically did not have any advantages with regard to better functional recovery, but they did display better anatomical reconstruction than the patients treated conservatively. These are conclusions drawn from a retrospective heterogeneously compiled study group, but data on the osteosynthesis technique applied, the circumstances under which it took place and the level of experience are lacking.

### Considerations in the choice of technique

Conservative techniques, such as Perkins' traction, are sometimes employed out of sheer necessity. For example in the developing countries (23), where osteosynthesis material is extremely expensive, its application requires experience and sufficient sterility cannot always be guaranteed.
The extra trauma of osteosynthesis and the chance of infection are contributing factors to the use of the Perkins' traction technique as the treatment of choice in some British clinics. In the Netherlands, the Thomas' splint is applied infrequently as the therapy of choice.

## 1.3.1 Closed treatment

### Evolution

Over the centuries, repositioning and maintaining the correct set of a fracture has been a major problem. The invention of plaster of Paris bandages by Mathyssen in 1852, was revolutionary. But the anatomical relationships of the pelvis and upper leg have never really lent themselves to treatment using plaster of Paris. Traction techniques, based on the notion that pull in a longitudinal direction would bring both fracture fragments into alignment, formed a better alternative. Steinmann and Kirschner developed a method of continuous weight traction, in which wires were drilled through the bone fragments. In the conservative treatment method developed by Perkins, in which traction is applied by means of a tibial pin, training programmes can be started at an early stage despite the compulsory bed rest. The broken leg can be exercised in traction on a special bed (from which part of the mattress has been removed) in order to prevent muscle atrophy and the joints from becoming stiff.

### Complications

The wire extensions used for traction sometimes cause osteitis at the point of insertion and occasionally tear through the bone. Long term femoral traction, via wires inserted into the lower leg, are thought to be responsible for the ensuing knee complaints, through overstretching of the knee ligaments and the joint capsule. If Perkins' traction is applied, nearly half of the patients suffer from problems with knee flexion. Another disadvantage is contracture of the hip joint, caused by long term nursing in a (half) sitting position.

### The Thomas splint

In 1910, Thomas, an English surgeon, invented a splint, which became known as the Thomas splint. The broken leg was placed in an open splint and the foot was fixed to it. By means of a frame fixed to the os ischii, traction was exerted on the upper leg via the splint and the foot. Particularly excessive shortening of femoral fractures could be prevented in this way. Although this was a simple and safe method of treating femoral fractures which produced satisfactory results (24), it was only suitable for femoral shaft fractures in the distal third. Decubitus occurs frequently at the site of the support ring. The obligatory period of bed rest is a great disadvantage, especially for elderly patients.

### Closed versus surgical techniques

It is particularly through the influence of Sarmiento (25) that early functional, closed fracture treatment has received attention over the last few years. With the aid of tubular, synthetic splints specially made to fit the patient, possibly in combination with a frame, an effective training programme could be started at an early stage. Functional treatment is very suitable for fractures of the lower leg but can give rise to many problems in the case of proximal and midshaft femoral fractures. The problems associated with applying plaster bandages to the upper leg, also apply to the application of the tube splints, thus it is very difficult to achieve adequate stabilization. Although the procedure was easier at more distal sites, the results remained unsatisfactory. The method is no longer being applied to femoral fractures by Sarmiento himself.

Böhler, active at the time of the Second World War, was an advocate of strict conservative policies, although he did apply intramedullary nail osteosynthesis in some cases. In 1963 Dencker also still held the opinion that a conservative approach was the treatment of choice (26). It is particularly the major technical innovations in the field of osteosynthesis material during the last 35 years (especially by the AO ASIF group) which have contributed to the fact that conservative treatment of femoral shaft fractures in adults has faded into the background.

## 1.3.2 Surgical treatment

### History

The history of surgical femoral shaft fracture treatment is two centuries old. There have always been clear supporters and adversaries of conservative and surgical treatment methods. In 1775 Lapuyade and Sicre were sentenced to life long imprisonment because one of their patients had died after open fracture fixation with the aid of wire (27). At the turn of the last century, reports appeared on the use of ivory pins on the tibia and femur (Felix Lejars). In the same period, Hansmann, Lambotte, Nicolaysen, Delbet and Hey Groves were employing intramedullary nails and plate osteosynthesis. Experiments have also been conducted using nails made of human and animal bone, besides ivory and iron. The latter gave rise to problems due to rust formation. Bone grafts were resorbed far too quickly, therefore the fractures were liable to redislocate.

## Intramedullary nailing

In 1940, Kuntscher gave the starting shot for further development of the intramedullary nail. About twenty years later, nails became available which were resultant to rotation. Their special four leaf clover form meant that they could be clamped into the marrow cavity and increase stability.

In order to be able to set fractures at a more proximal or distal location, Kuntscher developed an intramedullary nail which could be used to fix the proximal fracture fragment to the distal fragment with the aid of screws, straight through the pin. This interlocking nail principle was perfected by Grosse and Kempf (28). With the presently available interlocking nails it is possible to achieve adequate fixation, even in the case of comminuted fractures. The fracture haematoma remains intact and there is no extra tissue damage at the site of the fracture. This interlocking technique has proved to be practicable (with practice) and it provides adequate stability.

## Ender and Rushpins

Enderpins have also been used to treat femoral shaft fractures. Their stabilizing effect leaves a lot to be desired, as do Rush pins. Rotation of the fracture occurs frequently; protruding pins cause pain and limit the function of the knee (29). Quite often, additional plaster of Paris immobilization or traction is necessary. Nevertheless, a field of indication appears to exist for this osteosynthetic technique in experienced hands (30, 31).

## Internal fixation

The development of internal fixation using plates and screws has undergone particular evaluation since 1910 (Lane). Lambotte was the first to suggest fixing comminuted fractures using a combination of plates and screws. Later on, he hardly performed any internal fixation operations and gave preference to external fixation. Internal osteosynthetic techniques have been further developed by the Swiss AO ASIF group. In particular, the application of plate osteosynthesis was stimulated by this (21,32,33,34,35).
Intensive research in the field of biology, biomechanics and metallurgy has produced a great many implants, with carefully adapted tools to mount the pins,

nails and plates quickly and easily. Nevertheless, plate osteosynthesis of the femur and tibia have formed points of discussion for some time. Application of a plate gives rise to a considerable amount of extra soft tissue injury and the remaining periosteal blood supply can become damaged. Another disadvantage is the risk of infection (22).

The AO ASIF group recommends the compression plate for comminuted fractures and a drilled out medullary nail for midshaft fractures. Since the appearance of an AO ASIF interlocking nail a short time ago, they appear to be having a change of opinion and regard this as the treatment of choice.

Although osteosynthesis can be complicated by infection, it has been shown that if the procedure is carried out with the utmost care (in accordance with AO ASIF guide lines), osteosynthesis produces better results than the conservative therapy propagated by Dencker in 1963.

### External fixation

Since the turn of the century, experience has also been gained with external fixation of the femur. It has never been the treatment of choice. If external fixation is applied to the upper leg, depending on the type of frame, skin and muscle have to be pierced at a number of places, which is considered to be a great disadvantage. The resulting adhesions are thought to be responsible for the limited knee function during and after external fixation (14). The soft tissue injuries caused by the fracture and the subsequent scar formation may also adversely influence the knee joint. In our experience, the range of movement of the knee recovers completely, even if long term external fixation (more than 12 months) has been applied.

## 1.4 External fixation, historical overview

The development of fracture treatment in general and that with the aid of external fixation in particular, form a fascinating subject for many people. This may be because it is a good example of how a medical innovation can gain territory step by step. New (technical and biomechanical) insights have made steady improvements and refinements possible.

The external fixation device invented by Lambotte in 1902 is generally thought to be the first "real fixator". However, Jean Francois Malgaigne had devised a patellar clamp in 1843 which was a primitive form of external fixation (28,36,37,38,39). In America it was Clayton Parkhill, in 1897, with his "bone clamp" who started the process. Both Parkhill and Lambotte observed that metal pins inserted into bone were tolerated extremely well by the body. Mainly on the basis of their research findings, a great many external fixation devices have been and are being developed.

In the period that erysipelas was still considered to be a scourge of the times, Malgaigne's patellar clamp was a risky undertaking because, during the mounting procedure, it was necessary to perforate the skin. The resulting skin wounds increased the chance of the patient contracting a fatal infection. With varying degrees of success, Malgaigne treated four patients using his clamp. Rigaud produced an improved model in 1850. The fixation pins were not pushed against the patella with this version, but were inserted into it. The modified model was still being used 50 years after its invention.

In 1840 Malgaigne was using a different form of external fixation. A screw which was fixed to a splint with the aid of belt, was screwed through the skin into the bone to keep the fracture fragments in place. If extra screws were necessary they were joined together using wire. The screw system was applied particularly in cases where bone fragments threatened to pierce the skin and remained in situ for an average of 30 days.

Von Heine (1878), professor of surgery in Prague, used an adapted version of Malgaigne's screw technique, but also developed his own methods. One of these involved drilling a hole through the cortical layers of the bone fragments near to the fractured ends, perpendicular to the longitudinal axis. Ivory pins (± 15 cm long) were then pushed through the holes and fixed in plaster of Paris by means of a tube and clamps. In this way the first form of external fixation (Figure 1.2) was developed and used on a small number of patients.

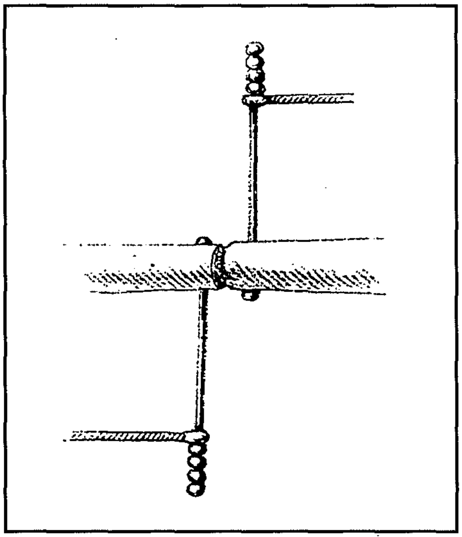


*Figure 1.2 An early form of external fixation applied by Von Heine in 1878. After open reduction, the fracture fragments were held in position using ivory pins.*

In London in 1893, Keetley also designed a primitive form of external femur fixation (Figure 1.3). Iron pins were inserted percutaneously, at locations proximal and distal to the fracture, in one or both bone cortex layers and fixed together outside the skin. This fixation device was used on at least two patients but was not a great success. When the pins were removed from one patient after 43 days, they showed signs of rust and the bone refractured after a fall.

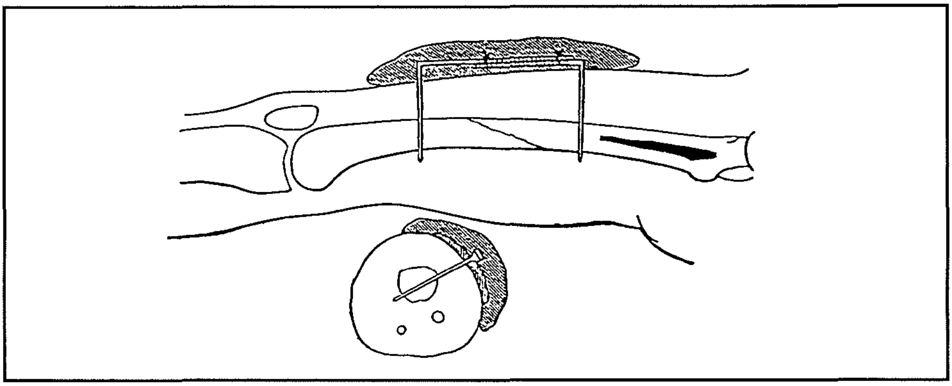


*Figure 1.3 External fixation applied by Keetley in 1893. The iron pins showed signs of rust.*

The fixation device invented by Parkhill in America in 1898 was made of silver plated steel and was used to treat a case of pseudarthrosis of the femur and two malunions. Plaster of Paris immobilization was used in combination with the fixation device. It remained in situ for an average of six weeks.

In the early stages, the development of fixation apparatus in Europe and America took place separately. Albin Lambotte (1866-1955), who worked in Antwerp, was one of the most important propagandists in Europe. If necessary, he performed open reduction and predrilled the pin holes. The sharp ended pins were only fixed to the cortex (Figure 1.4). They had to be inserted parallel to each other (two proximal and two distal to the fracture, 2 cm away from the fracture). Cerclage was sometimes added in the case of oblique fractures.

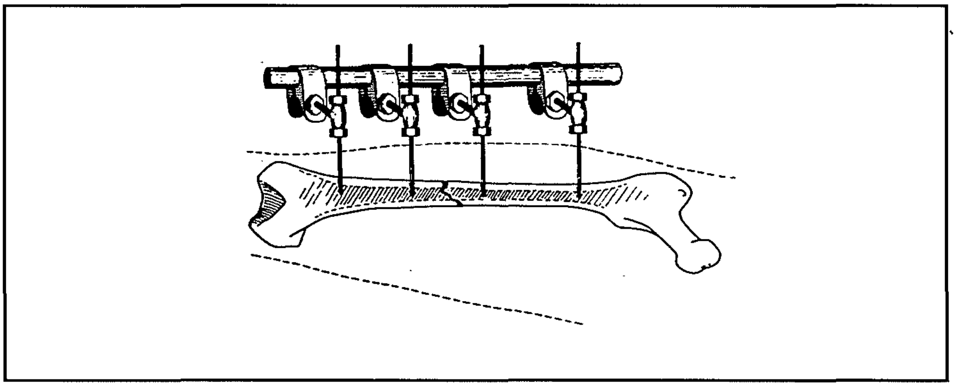


*Figure 1.4 Schematic representation of the external fixation device used on the femur by Lambotte in 1902. The ends of the pins (with screw thread) were only inserted into the lateral cortex.*

## External fixation in combination with distraction

In order to prevent shortening of the leg, Lambret modified the device in 1910 with transfixation pins to make distraction possible. In England in 1914, Hey Groves underlined the advantages of distraction equipment and developed his own model without knowledge of Lambret's design.

Hey Groves considered his fixation device to be most suitable for treating comminuted open fractures, particularly of the lower leg. He removed the device after three to six weeks. Transfixation of the humerus, femur and lower leg proved to be pretty well impossible. His experiments with unilateral fixation of the femur in cats were a failure, probably because the extremity was fully burdened and it was not possible to achieve sufficient stability. At other locations, fractures consolidated with minimal callus formation, according to Hey Groves because the bone ends could be fixed rigidly. His fixation material was probably strong enough for cats, but with modern fixation material it is seldom possible to immobilize the fragments sufficiently to produce primary fracture healing.

## Other developments

In 1930, Juvara, a surgeon in Budapest, reported on his experience with femoral fixators, which remained in situ for three months. The Frenchman, Ombrédanne (1871-1956), particularly concerned himself with treating diverse fractures in children. If he considered that external fixation was indicated, it was not left in situ for more than two weeks. A pliable aluminum connecting piece was used which was not strong enough for use on adults. Of the various other models, the frame developed by De Boever was used by many surgeons. It was the first device to be made of stainless steel; repositioning was possible with the fixator still in the bone. Both Judet and Massart emphasized the importance of external fixation for the treatment of open fractures in 1932. One year later, Joly from Brussels, introduced a connection piece, which also allowed repositioning (in two directions) after it had been mounted. This basic principle was elaborated on by Raoul Hoffmann, a Swiss, some while later. It was already being applied by Conn in 1931.

The first publications by Hoffmann on his own frame appeared in 1941. He was the one who ultimately combined all the advantages of other fixators. In principle, his frame was suitable for use on all parts of the body. Closed repositioning of a fracture after the frame had been applied was no problem. The Hoffmann frame has been and is still being employed extensively in Europe.

## The United States of America

There was less interest in treating fractures with external fixation in America. Even the Hoffmann system hardly received any attention. Although Lilienthal from New York had already formed the opinion that infected fractures formed a field of application for external fixation in 1912, a feeling of disappointment with these treatment methods dominated in America. The Anderson and Haynes apparatus

(1939) was applied occasionally. One of Haynes' designs, specially for the femur, made use of transfixation pins in the distal part of the bone.

## War-time influence

The First World War had very little influence on the development of external fixation in Europe and America. In 1919 Crile described the application of a fixation device on a war casualty with a compound fracture. The device still gives a robust impression (Figure 1.5).

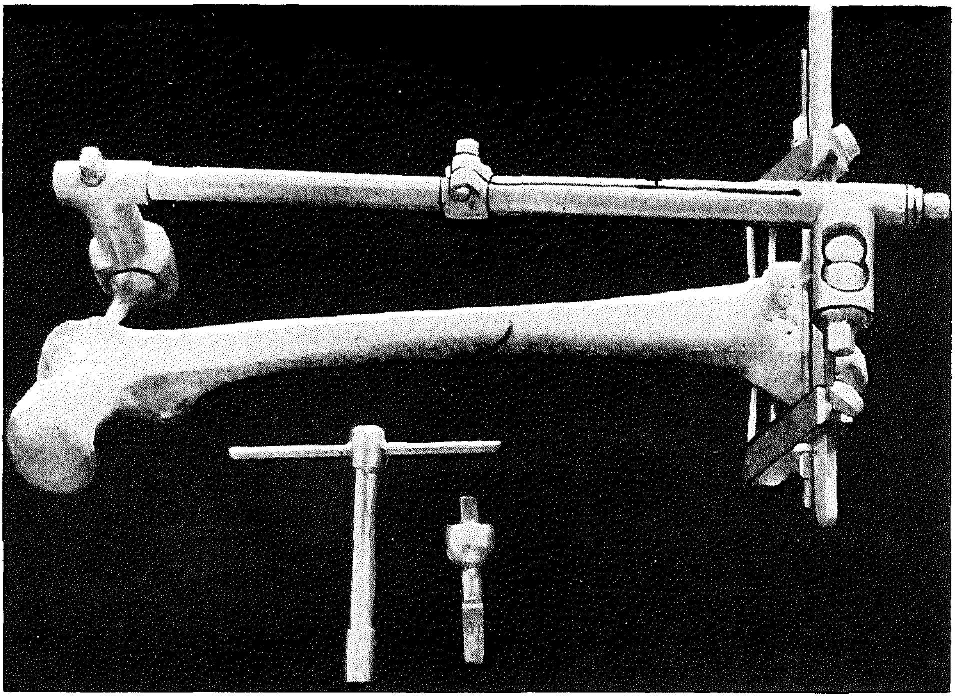


*Figure 1.5 Crile's external fixation device (1919).*

The influence of the Second World War and the post war period was much greater, especially under the influence of the Hoffmann system. However, due to the large number of complications and disappointing treatment results, the use of external fixation for the treatment of fractures was ultimately forbidden in America in 1944. This prohibition delayed new developments for many years.

In the post war period in England, Charnley particularly concentrated on applying his fixation system to achieve compression arthrodesis. It is probably the only form of external fixation which is capable of producing primary fracture healing.

## Post war period

Using Charnley's frame as a basis, the AO ASIF group from Switzerland developed an external fixator which was introduced in 1952. It was not a success and appeared to be very unstable. In 1976 a more stable version became available; the connecting bars which had formerly had a screw thread had been replaced by stronger, hollow connection pipes.

Vidal also emphasized the importance of rigid fixation in 1960. With the aid of components from the Hoffmann system, he too developed a transfixation device with double connecting bars (quadrilateral frame) which he applied in cases of infected non-unions. Adrey subjected the frame to biomechanical tests (40).

During the last 20 years, it is once again the Belgians who have been paying a great deal of attention to the development of external fixation. Burny, particularly, has analyzed the clinical applicability of the Hoffmann system in accordance with statistical norms (41). His dedication and enthusiasm for external fixation go so far that he 'only wishes to work at a clinic without plaster of Paris.'

In the meantime, various new types of fixation have been developed. De Bastiani (6,7), from Italy, designed a fixator with a telescopic connection piece and two ball and socket joints. By means of the telescope mechanism, it is very simple to convert the system from a rigid frame into one which allows controlled axial movements. This fixator can also be used in leg lengthening procedures, in common with the Wagner apparatus which had been developed earlier.

In the Soviet Union, ring fixation devices have always been the centre of interest (42). Ilizarov developed a device which Kronner, an American, later modified (43). He applied plastic components to the frame in order to make it lighter and easier to handle. His compatriot, Fischer, developed a fixation system in which the bulky closed rings were replaced by (horseshoe shaped) half rings.

## Further developments

There seems to be no end to the stream of adaptions and improvements which can be made. It can be expected that, on the basis of experience gained so far the systems which are already available will be perfected before too long.

## 1.5 Fields of indication for external fixation

External fixation has established a firm place among modern fracture treatments. Although until recently, it was only considered for application on cases of compound fractures, it has become clear that the potential infection risk involved with internal fixation of closed fractures can form a reason for choosing external fixation.

In general, external fixation is used on fractures with accompanying soft tissue injuries, if the anatomical relationships allow the application of an external fixation device.

With every type of osteosynthesis, surgeons always try to make sure that the broken arm or leg remains a usable extremity (44). In the case of one or more serious fractures, the bone should preferably be stabilized, because this creates favorable circumstances for healing (45). Movement of the fracture extremities causes tissue damage which increases the risk of infection (46). Life threatening complications, such as the Adult Respiratory Distress Syndrome (ARDS), including fat embolism and the Multi-Organ Failure Syndrome (MOF) can also be prevented (47,48,49,50,51). Stable (internal or external) osteosynthesis is a necessity for undisturbed healing of both the fracture and the adjacent soft tissue injuries (45,46,55,56,57). In contrast to internal fixation, fracture stabilization by means of external fixation can be performed quickly, which is a great advantage in the case of multi trauma patients. It has also proved to be a successful way of treating fractures with accompanying nerve and blood vessel injuries, burns and infected fractures, thanks to the technical improvements (44,52).

External fixation devices in various forms find large scale clinical application. Most experience has been gained in the treatment of tibial fractures. A clear field of indication has not yet been defined; personal insights and experience play a part. Some surgeons only apply external fixation as a temporary measure (44,53), others choose it for every type of fracture until full consolidation has taken place (6,41). The general opinion is that in the case of serious compound fractures, stabilization with the aid of external fixation should be chosen instead of internal osteosynthesis because the infection risk is smaller (54).

Elastic external fixation seems to be more suitable for stimulating fracture healing in the phase following recovery of the soft tissue. The field of application of dynamic (axial) fixation lies somewhere between that of elastic and rigid fixation. Therefore, in the first few weeks after the accident, it is aimed to treat the fracture with a frame construction which is as rigid as possible. Several weeks later, the frame construction is revised to supply more elastic fixation. This "dynamization" of a fixator shows biomechanical similarities to intramedullary nail fixation. A vibration mechanism has been developed which can be mounted on an external fixation device. It gives rise to carefully controlled, minimal axial movements (from 0.5 to 2.0 mm) daily, at the fracture site, but it is presently still at the experimental stage (58).

The first clinical experience with 102 patients with serious tibial fractures has shown that daily axial micromovements of 1 mm (for 500 cycles for 15 minutes) meant that fewer secondary operations were necessary on account of delayed union than when rigid fixation was applied. Also, a steeper gradient of stiffness was seen in the group subjected to axial movement and the time between the injury and full weight bearing was significantly shorter in this group (59).

## Advantages and disadvantages

Despite various basic philosophies, external fixation has become an indispensable appliance. If external fixation is used in the correct manner, it has few disadvantages. Most bone infection around the fixation pins can be avoided and it does not form a clinical problem. Fixation pins which penetrate certain muscles (such as is the case with the femur), can lead to limited joint movement. External fixation applied in the vicinity of a joint makes functional treatment rather difficult. Some fixation systems are very bulky, heavy and entail a complicated mounting procedure.

## External fixation of femoral fractures

Although more clinical experience has been gained during the last few years with the application of external fixation to the femur, treatment results have only been published on a very limited scale. Whether or not this form of therapy is chosen is a strongly individual matter, it depends on many factors and is often considered to be exceptional (60). External fixation is usually looked upon as a valuable temporary emergency measure for 'untreatable fractures' (61). It forms an additional therapeutic possibility (69). In the case of multi trauma patients who are in shock or have cranio cerebral injuries, femoral fractures can be treated quickly and adequately with little operation risk. If necessary, it is possible to adjust the set of the bone fragments later on and exert compression (62) or distraction (60) on the fracture.
External fixation of the femur has been applied for a variety of reasons on account of traumatological and orthopaedic abnormalities in children and adults (38,63,64,65,66,67,68,69,70,71,72,73, 74,75,76). Only retrospective analyses of the treatment results have been conducted, for example in the form of case histories or the incidental application of various types of fixators (77,78,79,80). Most experience has been gained using the Orthofix frame (6,7,81,82,83,84). De Bastiani applied this frame consistently on all fresh femoral fractures and has published the results of more than 100 patients (85). Closed fractures healed after an average of 4.4 months, open fractures after an average of 6.5 months.
Several variations of the Hoffmann frame have also been applied to the femur, including the unilateral (68,86,87) and transfixation (60,65,69,70,77,88,89,90,91,92,93,94,95) systems. The Wagner frame has been used on children (71) and adults (61,64,66,67,73,96,97). War time experience in Israel (97), Vietnam (98) and Iraq (99,100) has provided additional patient material.
It is possible to achieve satisfactory results even with a simple fixator. The AO ASIF tubular frame has been applied to the femur on a limited scale (66,101). In ten children, cortical screws were joined together using polymethylmethacrylate; functional adjunct therapy appeared to be feasible (102). In a series of 21 patients with a femoral fracture in combination with blood vessel injuries, eight underwent internal osteosynthesis and eleven external fixation (103). If femoral fixation is necessary in the case of accompanying burns, external fixation is an acceptable choice (95,104), although internal osteosynthesis is sometimes worth considering (105).
Various types of fixation device have been used to treat (infected) pseudarthrosis of the femur (80,90, 93). In orthopaedic surgery, ring fixators (106) and other types of frame (67,107,108) have been used for limb lengthening procedures, particularly the Wagner frame (109,110,111, 112,113,114,115) and the Orthofix (116,117,118,119,120,121).

### Indications

Whether or not external fixation of the femur should be applied and on what grounds can depend on various factors. From the literature it appears that a number of categories can be distinguished:

**(A)** Femoral shaft fractures with very extensive soft tissue injuries (particularly grade I and grade II open fractures with and without bone loss).
**(B)** Serious comminuted fractures (an external fixator can maintain the correct position of the bone fragments very adequately without extra devitalization of loose fracture fragments, in contrast to plate osteosynthesis).
**(C)** Femoral fractures in multitrauma patients if it is impossible to conduct lengthy surgical procedures.
**(D)** Femoral fractures in children; particularly proximal femoral shaft fractures because they can be very difficult to treat. Long term traction and hospitalization are, therefore, prevented.
**(E)** Miscellaneous applications: treating pseudarthrosis, arthrodesis and leg lengthening procedures.

## 1.6 Various types of femoral fixators

The anatomical relationships of the upper leg make it impossible to mount all the types of frame which are suitable for use on the lower leg. At the proximal end, transfixation is contra indicated due to the blood vessels and nerves which run along the medial side of the upper leg. Transfixation pins can be applied to fractures at the distal end. The impossibility of mounting transfixation pins at the proximal end means that a full bilateral or quadrilateral frame cannot be used. It is also impossible to use a ring system in the proximal area. A two dimensional (unilateral) configuration hardly has any anatomical limitations. By placing the pins ventrally and laterally, a three dimensional fixator can be mounted. In the case of two dimensional variations, all the pins are inserted from the lateral side in the proximal and distal portion. A few types of two dimensional external fixation devices can be converted into three dimensional systems if so desired.

### Study material

External fixation of the femur is applied infrequently. Experience has been gained with several types of device. In this study biomechanical research was carried out into the various systems available in the Netherlands (Chapter 5). All the frames are manufactured abroad and are imported by firms acting as agents. The polymethylmethacrylate version is not used in the Netherlands, but finds some application in other countries. For the build-up of each frame, the thickest pins available were used. (Some importers do not import all pin diameters).

### 1.6.1 ACE Fischer aluminum (Ace Medical, Los Angelos, CA)

Fischer, from America, developed an open ring system on the basis of the Soviet

(Ilizarov) and American (Kronner) ring frame (38,122). It can be made up of aluminum (or titanium) components. Holes have to be predrilled. The pins have self-tapping threads and are made of stainless steel (or titanium). For use on the femur, two open rings are required (Figure 1.6), which are joined together by means of three jointed connecting tubes. In this way a threedimensional construction is produced. According to the manufacturer, this system offers stability and correction possibilities in all planes.
It appears that securing the many components after repositioning is a very intricate and time consuming procedure and the possibility of redislocation is fairly high. Secondary correction of the bone fragments also gives rise to problems due to internal stress within the frame. The open rings can only move slightly in relation to each other. A fully built-up frame is very bulky.

### **1.6.2 Ace Fischer titanium** (Ace Medical, Los Angelos CA)

Most external fixation systems are made of aluminum or stainless steel. The Ace Fischer device is also available in titanium. Titanium has a number of physical, chemical and mechanical characteristics which make it very suitable for surgical implantation (189). It is very biocompatible and is almost completely resistant to corrosion (Figure 1.7)

### **1.6.3 Ace Hoffmann frame** (Ace medical, Los Angelos, CA)

Except for a couple of details, the American Ace Hoffmann fixation system is an exact copy of Raoul Hoffmann's basic configuration. It finds limited application in the Netherlands in the (anodized) aluminum version and has been tested on the femur (Figure 1.8). Titanium components are also available.

The standard pins are 4 mm thick, with self tapping threads, or in the case of the titanium version, they are 4 and 5 mm thick and have to be predrilled (123). In the original Hoffmann design, isolating synthetic material was used in the clamp units (Resofil); in the American version UHMW poly-ethylene is used which is more robust.

*Figure 1.6 Ace Fischer femoral frame (anodized aluminum)*

*Figure 1.7 Ace Fischer femoral frame, made up of anodized aluminum and titanium (horseshoe shaped) rings.*

*Figure 1.8 The American version of the fixation system originally designed by Raoul Hoffmann, made up of anodized aluminum for use on the femur.*

*Figure 1.9 Triangular Hoffmann femoral frame (simple triangular) with newly developed aluminum clampunits. The pins are inserted proximally on the ventral side.*

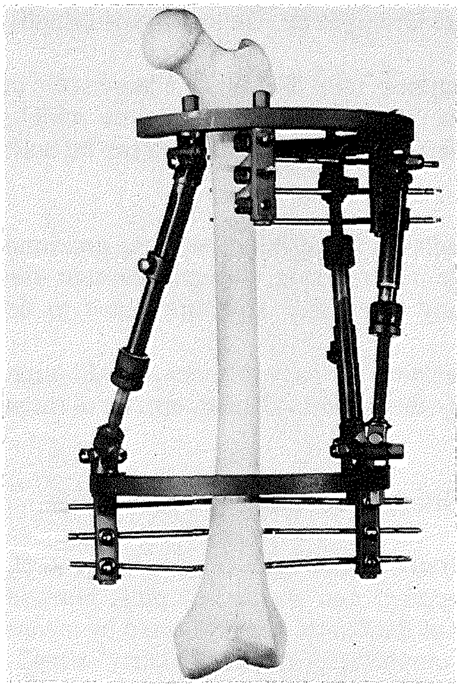


Fig. 1.6

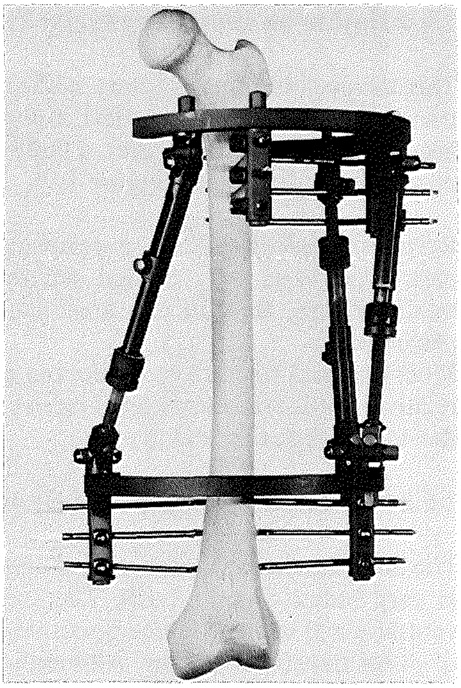


Fig. 1.7

Fig. 1.8

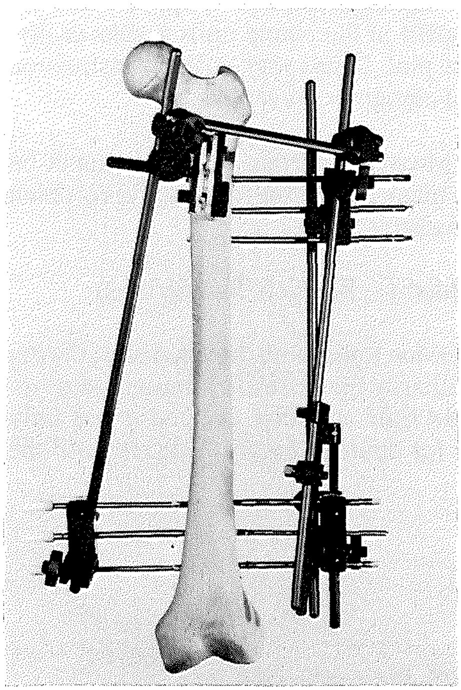
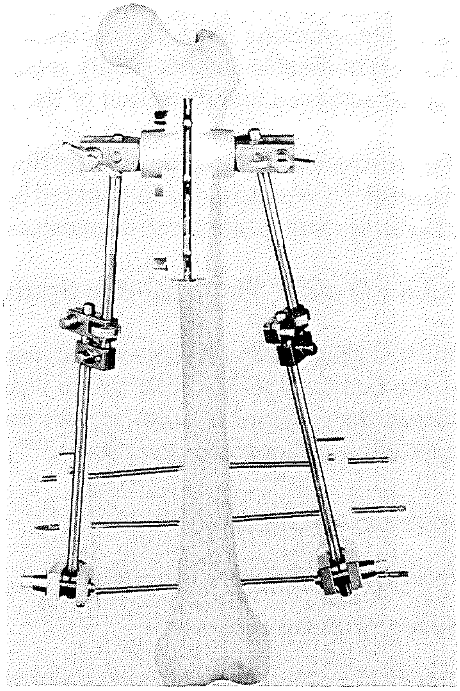


Fig. 1.9



### **1.6.4 Hoffmann simple triangular** (Jaquet Orthopaedie, Geneva, Switzerland)

The universal Hoffmann frame, made of stainless steel, is used on a large scale in traumatology. Recently, a new aluminum clamp was developed with which, according to the manufacturer, a three dimensional, triangular frame can be built up for use on the femur (Figure 1.9).

Results of clinical application are not yet available. It is striking that in the proximal part, fixation is only carried out on the ventral side, straight through the m. quadriceps. It is in this area that many soft tissue structures have to be perforated.
Mounting and fracture repositioning procedures are easy to manage. Although relatively little fixation material is necessary, the system still takes up a lot of room due to the large size clamp units.

### **1.6.5 Hoffmann femoral frame** (Jaquet Orthopaedie, Geneva, Switzerland)

The three dimensional Hoffmann femoral frame, which is made of stainless steel, is very bulky (Figure 1.10). The (self-tapping, non predrilled) pins, inserted ventrally and laterally in the proximal part of the femur, are connected by means of distal transfixation pins. Although the mounting procedure is fairly complicated, in experienced hands it is not all that difficult to manage. Some experience has been gained with primary fracture treatment as well as secondary treatment. The system is heavy, but patients do not complain about this. It appears that the isolating synthetic resin-canvas layer (Resofil) in the clamp units breaks easily. But it is malleable and fits snugly around the pins. In this way, a rigid construction can be achieved and distortion of the metal clamps is prevented.

The insulation of the pins is superfluous. Measured current densities cannot be harmful (27). Wound care is hampered by the many connecting pieces. This problem also arises with other three dimensional fixation frames.

### **1.6.6 AO ASIF Threaded Rod System** (Mathys, Bettlach, Switzerland)

In 1952 Müller designed an external compression frame with threaded bars. Owing to the fact that the AO ASIF group were primarily interested in internal osteosynthesis, the external fixation system received little attention. At first it was only applied in orthopaedic procedures (124), not for traumatology. It was not until the

*Figure 1.10 Hoffmann femoral frame*

*Figure 1.11 AO ASIF threaded rod system*

*Figure 1.12 AO ASIF tubular system*

*Figure 1.13 Unilateral Hoffmann fixator, as used for tibial fixation, mounted on the femur*

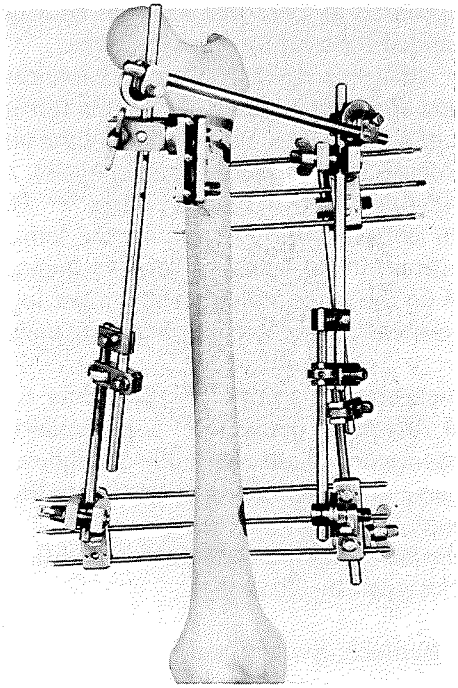


Fig. 1.10

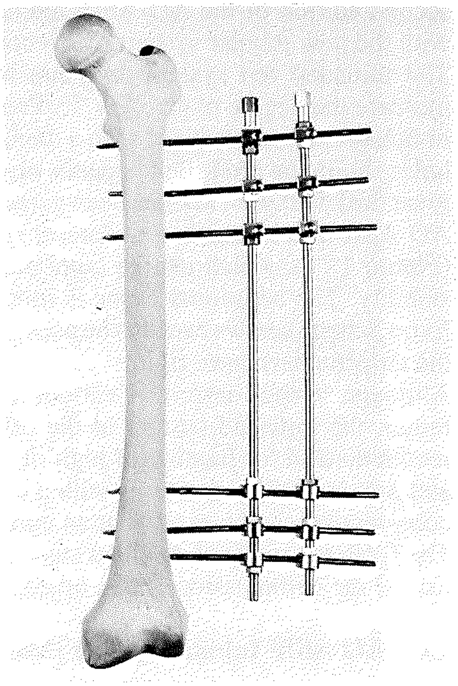


Fig. 1.11

Fig. 1.12

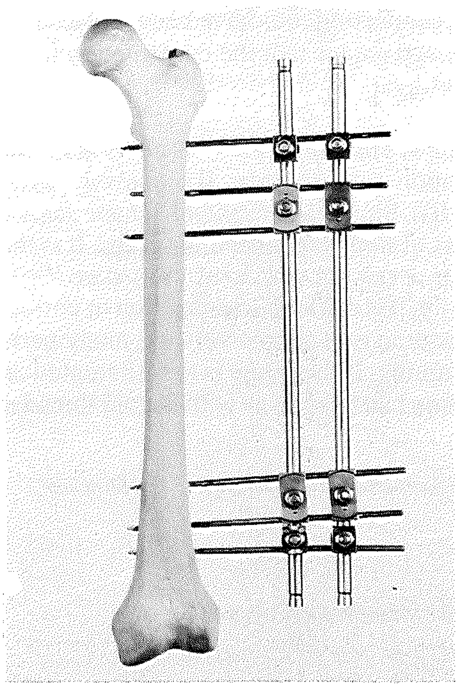
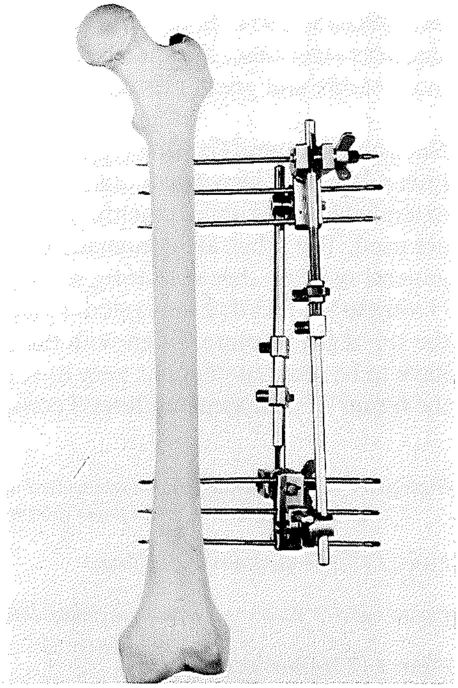


Fig. 1.13



second edition of the AO-ASIF manual appeared in 1977 that external fixation with the new tubular system was recommended for treating open fractures.
The threaded rod system does not offer sufficient rigidity. Compression can increase the degree of stability (27). Predrilled Steinmann pins with a screw thread or Schanz screws are used with a diameter of 4.5 to 5 mm. Whether or not the pin holes should be predrilled depends on the localization (diaphysis, metaphysis). A great deal of experience has been gained with this system at several clinics (125). The AO ASIF recommends a unilateral system as basic configuration for the femur (Figure 1.11), which can be combined with a second frame to achieve greater stability. The additional frame is mounted on the anterior side of the upper leg. Extra Schanz screws can also be used, or stress can be applied to the frame to make the construction more rigid.
Although Weber described various applications in his book (125), including the femur, the threaded system in the official AO ASIF manual (126) is particularly recommended for fixation of high tibial osteotomies, knee and ankle arthrodeses and proximal tibial fractures with a transverse or slightly oblique course, so that compression can be exerted at an early stage.
The fixator is made of stainless steel and the basic version comprises a modification of the compression clamp originally designed by Charnley.

### **1.6.7 AO ASIF tubular system** (Mathys, Bettlach, Switzerland)

The lack of stability and the resulting clinical problems were the reason for developing a new fixation device. The new system (designed by Mathys) was introduced in 1976. In the new version, the connecting rods have been replaced by stainless steel tubes (Figure 1.12). This design means that the construction is far more stable and greater distances can be bridged (27,54,127,128,129,130,131,132).

Not only unilateral fixation (type I according to Hierholzer) (54,129) is advised for the lower leg, but also particularly transfixation frames (type II), possibly even extended to a triangular construction (type III). Steinmann pins and Schane screws are used. The tubes are connected by means of hinged connecting pieces. It is the general opinion that mounting the frame is a very complicated procedure (27,128). Owing to the fact that the system twists easily, it is difficult to reposition or correct the set of the fracture. Even with the application of a simple version, many parts have to be secured which is very time consuming. If the frame is to be mounted on the femur (101), the same unilateral construction can be used as with the old threaded

*Figure 1.14 Simple external fixation constructed using Schanz screws and a anaesthetic tube filled with polymethylmethacrylate (bone cement)*

*Figure 1.15 Orthofix dynamic axial fixator*

*Figure 1.16 The Wagner apparatus, originally designed for leglengthening procedures*

*Figure 1.17 The Monofixateur*

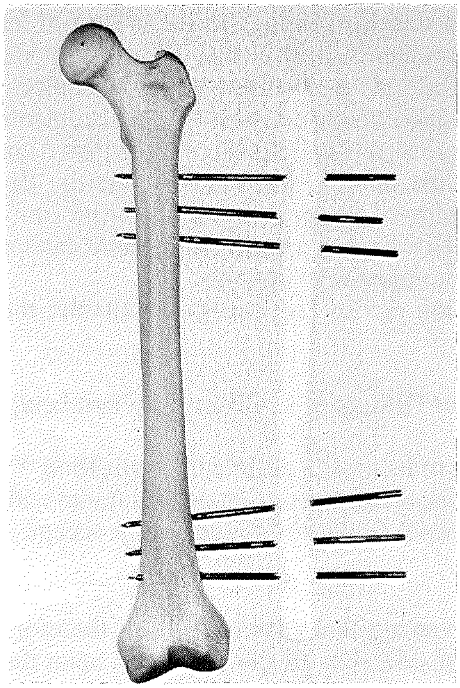


Fig. 1.14

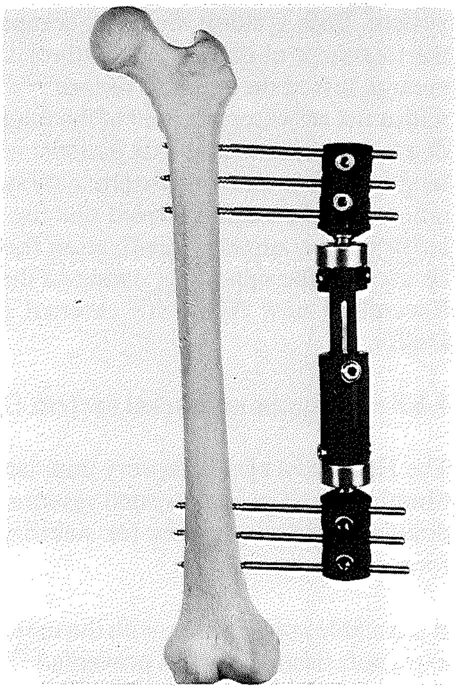


Fig. 1.15

Fig. 1.16

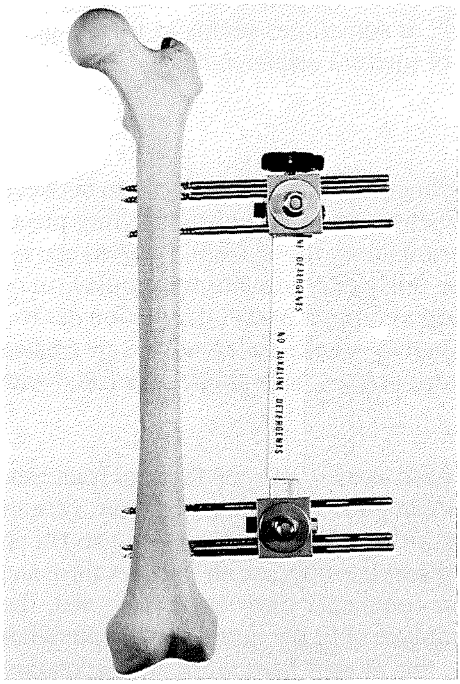
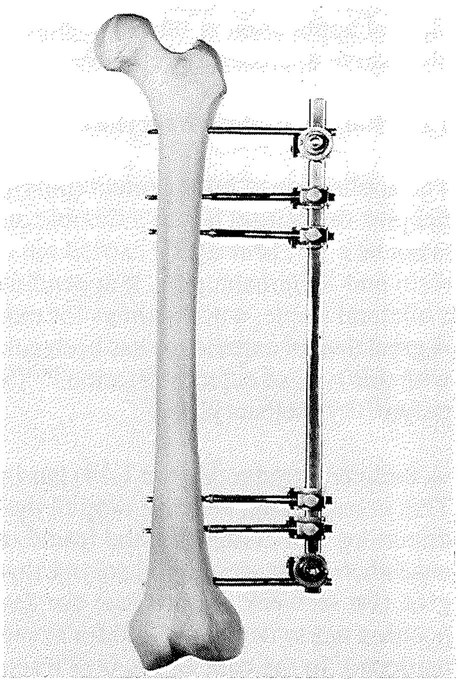


Fig. 1.17



system. Both systems are fairly compact in size. If external fixation is applied for the treatment of defect pseudarthrosis, a unilateral construction will not provide enough rest at the fracture fissure (131,132). The rods are liable to twist, particularly with axial stress, on account of the long distance which has to be bridged. Problems due to instability caused six patients with a femoral shaft defect of more than 6 cm length to request both external fixation and internal plate osteosynthesis. Biomechanical research proved that the stability of this combination showed similarities to a complete transfixation frame. However, a transfixation frame cannot be used on the upper leg, owing to the anatomical relationships.
Recently a new AO ASIF external fixation device has become available: the Unifix.

### 1.6.8 Hoffmann unilateral system (Jaquet Orthopaedie, Geneva, Switzerland)

The Hoffmann system is very popular due to its universal field of application (88). Simple as well as complicated systems can be constructed. A unilateral frame with double connecting pieces for stabilizing tibial fractures is a generally accepted form of treatment.

It is a stable construction with the major advantage that transfixation and therefore extra soft tissue injury is prevented (27). Considerably greater forces act upon the femur (see Chapter 4, page 44). Therefore, a unilateral system (Figure 1.13), which was designed for the lower leg, is not very suitable for use on the femur because the components are liable to twist. From our own experience and from reports on clinical application at other hospitals (68,86,87), it sometimes seems to form a good alternative approach for children, instead of internal osteosynthesis.

### 1.6.9 Polymethylmethacrylate

The application of bone cement (polymethylmethacrylate) or epoxy resin between the pins or pouring it into a flexible anaesthetic tube to make a connecting piece, is not new (173). Murray (133) carried out experiments on this system. He used epoxy-resin and Steinmann pins. It appeared to be fairly easy to build up a unilateral or a bilateral frame, with facilities for mounting a compression or distraction device. A great deal of experience has been gained in Iraq, where war casualties are treated with this type of external fixation (99) (Schanze screws, anaesthetic tube filled with polymethylmethacrylate).

A unilateral frame (Figure 1.14) has been used to treat 70 open femoral fractures. This is surprising, because despite the fact that pins can be inserted from various directions and connected, the frame offers little stability. It is difficult to fill an anaesthetic tube with liquid polymethylmethacrylate because air bubbles form and give rise to weak spots. Once the fracture fragments have been realigned, the position has to be maintained for several minutes until the liquid bone cement has hardened. In the case of femoral fractures, this is very hard work and secondary

correction is impossible.
Murray designed an auxiliary apparatus which maintained the correct position of the fracture while the rest of the frame was being built up. At the end of treatment it can be very difficult to remove the hardened bone cement and it is sometimes necessary to cut or saw through the pins. Sawing through the pins produces a great deal of heat.
Ten children with a femoral fracture were treated by means of a three dimensional methylmethacrylate fixator (102). AO ASIF cortical and cancellous screws were used instead of pins and the resulting structure was stable enough to withstand functional therapy.

### 1.6.10 The Orthofix frame (Orthofix, Verona, Italy)

The anodized aluminum dynamic Orthofix axial fixator, with two ball and socket joints, was developed by De Bastiani in Italy in 1977 (Figure 1.16).

The need for such a design arose from the problems associated with, for instance, leg lengthening and trauma procedures using the Hoffmann and Wagner frame (141). The Wagner frame was specifically developed for lengthening procedures, the Hoffmann frame was not.
It is fairly easy to mount an Orthofix frame. Thanks to the special clamps, repositioning of the fracture does not give rise to difficulties. Compression and distraction can be exerted by means of a separate top piece and axial compression (dynamization) is possible using a telescope mechanism. Mounting the fixator is quick and easy as a result of this. The self tapping, tapering screws (6-5 mm) need to be predrilled. Transfixation pins are not used. The frame is small and can easily be concealed under the patient's clothes. De Bastiani uses this frame for most orthopaedic or traumatology procedures, having largely given up the use of internal osteosynthesis, traction and plaster casts. Apart from Italy, experience has also been gained with this system in other parts of Europe, particularly in England, Germany and the Netherlands. From publications on the use of this fixator on large series of patients with tibial and femoral fractures (Figure 1.16), it appears that good results can be achieved (7,82,83,85), as well as in femoral lengthening procedures.

### 1.6.11 Wagner apparatus (Mathys, Bettlach, Switzerland)

The Wagner apparatus (made of stainless steel) was originally designed for lengthening long bones, particularly the femur (Figure 1.15) (110,111,112,113,114,115). It is a modified version of Anderson's design. Initially, Schanze screws were used, but self tapping, predrilled Hoffmann pins (6 mm) can also be applied. The construction later appeared to be suitable for treating (infected) defect pseudarthroses and femoral fractures.

The frame makes a robust impression and is considered to be very stable (96). The pins are grouped around the extremity of the fixator and have to be mounted parallel to each other, which can be difficult in the case of a femoral fracture. After the pins have been inserted, repositioning or correction is only possible to a small degree; compression or distraction can be carried out. Mounting the fixator on a intact femur, e.g. for leg lengthening procedures, is much easier partly due to the availability of an alignment apparatus for the pins.

### 1.6.12 **Monofixateur** (Orthopedia, Kiel, FRG)

The Monofixateur is (as with the Orthofix) a development of the last ten years. It is a universal system made up of relatively simple components (134,135), in which Schanze screws are joined together by means of one single square connection tube (Figure 1.17).

Dynamization is possible. It is easy to subject a fracture to axial compression using the available instruments. However, the square connection rod, which gives the frame a great deal of stability, limits the possibilities of repositioning. After the first two pins have been inserted, the others can only be mounted on the same plane, which hampers the speed of mounting and optimal repositioning.

## 1.7 Conclusion

During the last 100 years, new and better materials for constructing external fixation devices have steadily come to light. One of the outcomes has been that the field of indication has gradually broadened.

Lambotte, in Europe and Parkhill, in America, were the first to apply external fixation successfully at the turn of the century. In all its variations, this form of therapy is now essential in traumatology and orthopaedic departments and has become increasingly popular over the last 15 years. Its application in open fractures is no longer a topic for discussion and it is also being used more and more frequently as an alternative for conservative treatment on closed fractures.

With the fixation material presently available, a choice can be made between a frame construction which is as rigid as possible, an elastic frame, or a 'dynamization' frame. New developments have given rise to frames which can be converted into an elastic construction after several weeks of rigid stabilization.

It is clear that transfixation should be avoided as much as possible on account of the extra soft tissue injury involved.

The application of external fixation for femoral shaft fractures (in a two or three-dimensional form) is still a little used treatment method. It appears to be an alternative solution if other fracture treatments (particularly internal osteosynthesis) are too risky or impossible. External fixation deserves a place as temporary or definitive therapy for femoral shaft fractures in selected patients.

Recent publications, mainly on limited numbers of cases, have contributed to the definition of a field of indication and provided an insight into the advantages and disadvantages of the technique. Treatment results have shown that an external fixator can provide sufficient stability for femoral fractures. The choice of fixation device is a matter of personal preference, but a quick and easy mounting procedure, universal applicability, compact size and as little extra soft tissue damage as possible are arguments, which weigh heavily. The application of an external fixator on the femur makes it possible to stabilize fractures in a patient group which, in the past, has always been difficult to treat surgically. Postoperative mobilization and functional therapy can be started at an early stage, as is also the case with internal osteosynthesis, therefore preventing post operative complications.

# CHAPTER 2 FRACTURE HEALING AND THE CLINICAL CONSEQUENCES

## 2.1 Primary and secondary fracture healing of cortical and cancellous bone

The healing of bone is one of the most remarkable recovery processes in the human body because ultimately full restitutio ad integrum takes place (136). Damaged bone is replaced by tissue which matches the original.

Nearly all fractures heal whether they are immobilized or not. The chief objective of immobilization is to maintain satisfactory positioning of the bone fragments during consolidation. In order to prevent muscle atrophy, osteoporosis, joint-stiffness and chronic oedema, rigid fixation followed by functional treatment is the treatment of choice according to the AO ASIF philosophy. The main objectives are anatomical repositioning and to give enough stability to permit active training and weight bearing of the extremities (for example, by means of interfragmentary compression) so that primary fracture healing can take place. This occurs via osteogenic bridging and the direct formation of bone. Therefore, the phase of callus formation is omitted. Bone deposition takes place via recanalization of Haversian canals and along blood vessels which have grown between the bone fragments. If optimal fixation is achieved, there is no resorption of the fracture extremities (137,138).

A condition which must be fulfilled to achieve primary fracture consolidation, is that the bone fragments must be fitted together in such a way that no more than 5 to 10 micron of movement is possible between them (27). Through the absence of interfragmentary movement there is no stimulus for callus formation. Internal osteosynthesis with plates or screws requires open repositioning which also relieves the fracture haematoma. Surgical treatment and the achievement of optimal stability by means of adequately executed compression osteosynthesis, are techniques which have developed during the last thirty years. This process involves a new form of bone healing, introduced by man, which, in a certain sense, can be regarded as unnatural. Primary fracture healing takes months but good osteosynthesis can lead to excellent results and help prevent complications caused by long term (plaster) immobilization.

Secondary fracture healing, in which fixation callus develops, is characteristic for fractures which have not been treated surgically (125). The phenomenon is based on a feed back mechanism. Movement at the site of the fracture causes callus formation. The newly formed callus prevents further movement. In secondary healing, electrical potential differences and the fracture haematoma play an important part. The PO2 and acidity level are low in the haematoma (Ph 7.0). The formation of callus is stimulated by the lack of oxygen and the presence of decomposition products in the haematoma. Under the influence of a rise in the Ph level (to 7.5) which occurs after about two weeks, calcium phosphate crystals develop in the fibrous callus (139). Through micromovements of the bone fragments, prostaglandins are released which cause the mesenchymal cells to differentiate into bone forming osteoblasts. Although stimuli are particularly produced by axial movements (59), twisting and bending movements are also not without influence. A number of phases can be distinguished during secondary healing which gradually overlap each other. After a bone has been fractured there is a phase of inflammation, followed by a phase of initially soft callus which later becomes hard. This is followed by a phase in which the fracture consolidates and ultimately by remodelling of the bone. Although micromovements stimulate callus formation, excessive rotation and shearing stress are probably detrimental. Under the influence of these forces only fibrous tissue is formed between the bone fragments instead of bone. The objective of fracture treatment, surgical or conservative, is to eliminate detrimental movement. Although axial compression stimulates fracture healing, necrosis of the bone ends can arise if the pressure is too great. Constant pressure does not have any influence on the ultimate consolidation time. However, it seems that variegated axial pressure promotes the healing process. For this reason, the leg is fully burdened at an early stage in Sarmiento's brace treatment.

In the case of 'dynamic fracture treatment', it is assumed that stability is important during the first few weeks post injury; it promotes the healing of soft tissue. When the first signs of callus formation become visible on X -rays, regulated movement (especially axial) is permitted. This 'dynamism' was introduced in Germany in 1975 by Klemm and Schellmann by means of interlocking nailing and in France in 1976 by Grosse and Kempf. There is a certain amount of elasticity involved with an interlocking nail which allows movement and stimulates callus formation. Depending on the burden and locking mechanism, the random callus formation can be formed into a spindle shaped callus mass which promotes quick consolidation. The same treatment principles can be applied using a few of the external fixation devices presently available (such as the Orthofix, with sliding mechanism).

Not only cortical bone but also cancellous bone can undergo primary or secondary healing, depending on the circumstances. Well vascularized cancellous bone fragments will grow together without callus formation if they are properly stabilized (primary healing). Less stabilization leads to secondary healing with callus formation (125). However, sometimes consolidation does not take place even in well vascularized cancellous bone, because of the lack of stability. Under these circumstances too little firm callus is formed.

The role of electrical stimuli, magnetic fields and ultra sound is still unclear. Incidental experiences have been published, with varying results.

## 2.2 Vascularization and fracture healing

An adequate blood supply to the fracture area is essential for undisturbed healing. Directly after a fracture, the blood flow at the site of the fracture decreases. This is followed by a sharp increase two weeks later. After about 120 days, there is a gradual decrease to normal levels (140). Naturally, the soft tissue injuries and the treatment method applied play a part in the circulation of the fracture area. Osteosynthesis using an intra medullary nail (if the site has to be drilled out) causes a clear decrease in the cortical endosteal circulation, which is still visible after 14 days (140). A decrease in cortical circulation has not been observed with external osteosynthesis. Plate osteosynthesis involves the risk that the blood supply to the bone might be cut off as a result of the periosteum becoming damaged during the operation itself and/or owing to the location of the plate on the cortex. It is possible under stable conditions for new blood vessels and bone to be laid down, which originate from adjacent vital bone. If this does not take place, the result is an avascular non union. The transplantation of vital bone (such as bone grafting) and the stimulation of the circulation (via decortication) will then be necessary to achieve consolidation, if stable fixation follows.

The prognosis is determined by: the damage resulting from the accident, contamination, the state of the soft tissue and the treatment method.

## 2.3 External fixation and fracture healing

The manifestation of primary or secondary bone healing depends on the stability of the external fixation frame and the vitality of the bone fragments.

On theoretical grounds, primary bone healing can only be expected if external fixation is applied in combination with compression of the fracture fragments. Due to the fact that it is nearly impossible to achieve completely rigid immobilization using a fixation frame, consolidation usually takes place by means of callus formation, i.e. via secondary bone healing. Thanks to the formation of callus, there will be sufficient solidity after several weeks or months to make it is possible to (re)expose the bone to stress.

Treatment by means of traction, plaster of Paris or a brace gives rise to a large amount of callus formation. Fractures treated with external fixation consolidate with much less callus formation (141). Some authors seem to harbour the misconception that consolidation with the use of external fixation takes place more slowly. In the past the delay in consolidation was attributed to the fixation device. But several researchers failed to realize that external fixation had been chosen particularly on account of the complex nature of the (often compound) fractures (which always take a long time to heal). Therefore, the nature of the primary injury is often more important than the stabilization method. This has been demonstrated in a study on over 1400 patients with tibial fractures (41).

## 2.4 Conclusion

The healing process of a fracture depends partly on the movement between the bone fragments. As a rule, rib fractures heal while the fracture ends are in constant motion. But a fracture of the tibial shaft will not heal unless the amount of movement between the bone fragments has been restricted. Rigid immobilization (using plate osteosynthesis) has an adverse affect on the consolidation speed. Primary fracture consolidation, in the absence of callus formation, is judged to be good by the AO ASIF, but others are more inclined to consider it to be a harmful side-effect than a desirable development.

It is very likely that a certain amount of movement is necessary for secondary healing to take place (within certain limits) and the optimum amount of movement is different for every fracture.
Contrary to internal osteosynthesis, it is more or less impossible to achieve completely stable fixation of the bone fragments using external fixation. Primary fracture consolidation by means of recanalization and direct osteogenic bridging is seldom possible. The slight amount of movement between the bone fragments (in the case of closed fractures in combination with the fracture haematoma) gives rise to a stimulus for callus formation and the start of secondary fracture healing. In comparison with internal osteosynthesis, an external fixation device does not have any influence on the blood circulation of cortical and cancellous bone. If secondary consolidation takes place with external fixation, it is seldom accompanied by mass callus formation. It is a misconception that the application of an adequately built up fixation device causes delayed consolidation. The nature of the fracture is responsible for the delay, not the method of fixation.

*Figure 3.1* *CT scan illustrating both upper legs (female, 20 years).*
*Left:the (right) femoral shaft, defined as the portion of the femur from the trochanter minor, as the proximal limit, to 6 cm cranial from the joint fissure of the knee, as the distal limit* (18).
*Right:the femur can be divided into four parts with the trochanter major and lateral femoral condyle as palpable external points of recognition (left femur: 1 - 4) . At levels 1 and 2, only unilateral pin fixation is possible. In the proximal third of level 2, the point of a unilateral pin may damage branches of the a. and v. femoralis profunda which run parallel to the dorso - medial cortex* (38).
*At levels 3 and 4 transfixation pins can be used in addition to unilateral pins as long as the pins are inserted at an angle of 30° dorsolaterally.*

# CHAPTER 3 ANATOMY OF THE UPPER LEG IN RELATION TO EXTERNAL FIXATION

## 3.1 The anatomy of the upper leg

The femur is the longest bone in the human body. The head of the femur articulates with the acetabulum and the condyles with the plateau of the tibia. The femoral shaft can be defined as running from the trochanter minor, at the proximal end, to six centimeters cranial from the joint fissure of the knee, at the distal end (14) (Figure 3.1).

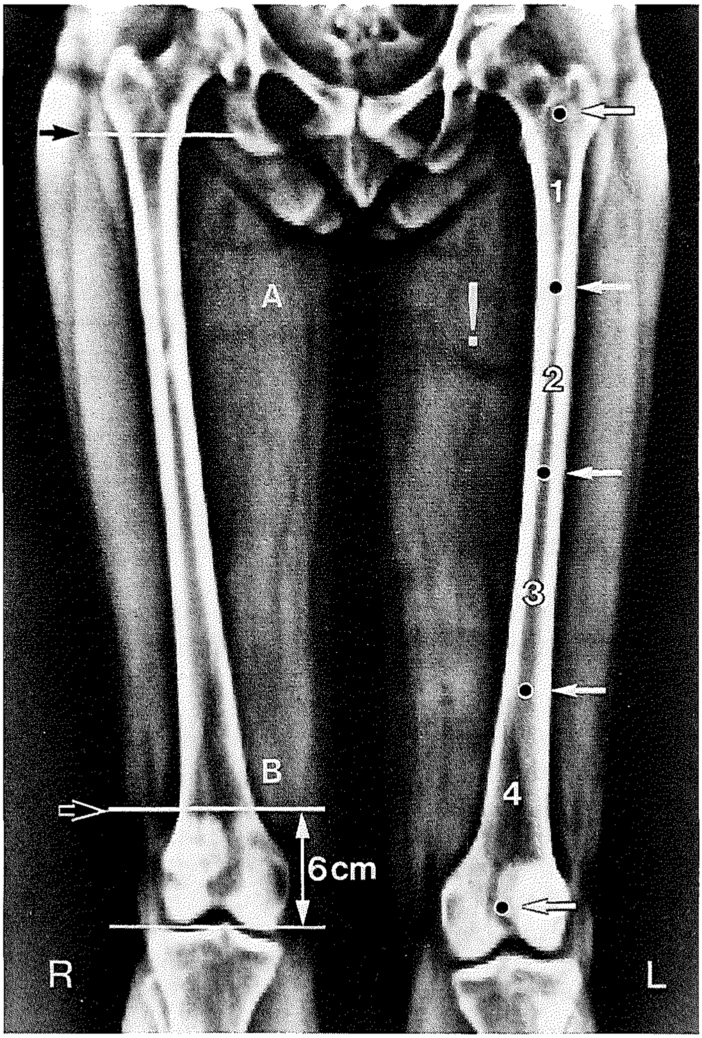


*Fig. 3.1*

The shaft bends slightly in the ventral direction and is somewhat triangular in form. The sharp dorsal edge (liniae aspera) is the site of insertion of various muscles, including the adductor muscles. The whole of the upper leg is covered by a stiff facial sheath (fascia lata) which is joined to the deep fascia of the trunk at the proximal end and to the tibia at the distal end. The shaft of the femur is covered by a thick sheath of soft tissue, which mainly consists of muscle tissue. The soft tissue is less thick on the distal side, at the level of the condyles. The muscles are divided into compartments by intermuscular septa. The femoral blood vessels enter the leg from the abdomen in the groin area. The n. femoralis lies on the lateral side of the blood vessels. The n. ischiadicus runs along the dorsal side of the leg and splits up at various levels into smaller branches (n. tibialis, n. peronealis). The a. femoralis divides into a superficial branch (a. femoralis superficialis) and a deep branch (a. profunda femoris). The a. profunda femoris gives off many branches to the upper leg muscles.

Owing to the fact that the large blood vessels and nerves are situated on the medial side of the leg, the safest surgical approach to femoral shaft fractures is via the (dorso) lateral aspect.

### 3.2 Soft tissues and a femoral shaft fracture

Compound fractures can be classified into three grades in accordance with the Cauchoix classification system (142), depending on the seriousness and extent of soft tissue injury.

A **grade I** fracture is classified as a small puncture wound in the soft tissue, caused by a bone end or splinter penetrating the skin from the inside.

In a **grade II** fracture there is more extensive soft tissue injury with bruising of the skin and subcutis usually caused by the action of external forces.

A **grade III** fracture involves extensive soft tissue injury, including muscle damage and blood vessel and/or nerve injury. The wounds are always contaminated with (street) dirt.

The strong muscles attached to the femur often cause characteristic angles and shortening if the bone is fractured. The powerful abductor muscles which are inserted near the trochanter major are a good example of this. In high femoral shaft fractures the proximal bone fragment tends to be abducted. The adductor muscles are inserted on the medial side of the femoral shaft at the level of the medial condyle. The distal bone fragment tends to be adducted by these muscles.

These muscles can have a long term influence and even give rise to lateral angulation more than three months post injury (24). For this reason it is difficult to treat proximal femoral shaft fractures using traction. The strong adductor muscles and hamstrings are also responsible for the distal bone fragment being pulled under the proximal fragment, which causes shortening and angulation of the upper leg.

If displacement of the distal bone fragment occurs in the dorsal direction, under the influence of the m. gastrocnemius, the a. and v. poplitea and n. ischiadicus or n. tibialis can become damaged.

## 3.3 The type of external fixation and the anatomical consequences

If a lateral (twodimensional) external fixation frame is applied to the femur, the pins will penetrate the skin, subcutis and m. vastus lateralis.
At the level of the proximal part of the upper leg, the muscle is several centimeters thick and becomes thinner as it continues in the distal direction. The m. vastus intermedius runs from the anterior and lateral portion of the shaft in the distal direction and is partially covered by the m. vastus lateralis (and m. vastus medialis). Particularly at the distal end of the shaft, the positioning of the m. vastus intermedius under the m. vastus lateralis is such that fixation pins have to be passed through both muscles (Figures 3.2 and 3.3).

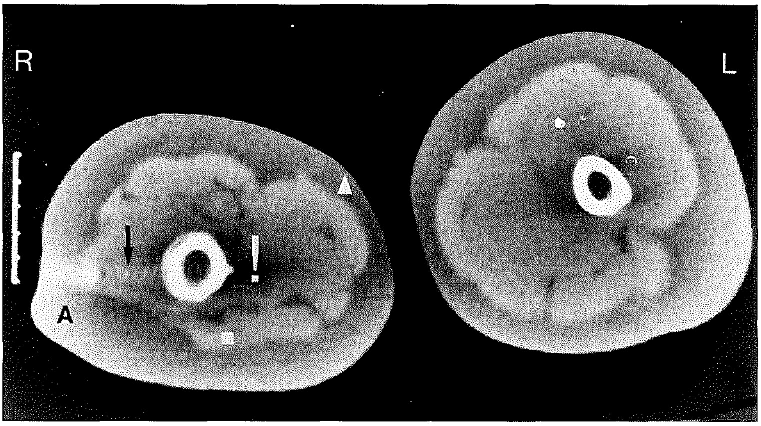


*Figure 3.2* *CT scan at the level of a proximal fixation pin inserted on the lateral side (right femur).*

■ *n . ischiadicus*

! *the area in which the a. and v. femoralis are situated*

▲ *v. saphena magna*

*Transverse section of the right femur at level 'A' of Figure 3.1. The CT scan shows the metal fixation pin (arrow) which penetrates the m. vastus lateralis (female, 11 years, Orthofix).*
*Muscle atrophy of the fractured leg (arising through inactivity) is clearly visible in comparison with the well developed muscles of the contralateral side.*

*Figure 3.3 CT scan at the level of a distal fixation pin inserted on the lateral side (right femur).*
■ *n. ischiadicus*
● *a. and v. femoralis and poplitea*
▲ *v. saphena magna*
*Transverse section through the distal portion of the right femur at level 'B' of Figure 3.1 (female, 11 years, Orthofix).*
*The metal pin is visible (arrow) which penetrates the m. vastus lateralis and m. vastus intermedius. Transfixation pins can also be inserted at this level; on the medial side they would penetrate the m. vastus medialis and m. vastus intermedius.*

Little or no risk is involved if the femur is approached from the lateral side (preferably from 30° dorsolaterally). If unilateral fixation is applied the points of the pins can only cause damage to blood vessels on the medial side in the proximal third of level 2 (Figure 3.1).
If a three dimensional frame is mounted, pins must be inserted on the ventral side, straight through the m. vastus intermedius and m. rectus femoris (levels 1 and 2, Figure 3.1). This does not endanger the blood vessels or the n. ischiadicus.
If the pins in the distal portion of the upper leg are inserted on the ventral side, there is a risk that the supra patellar bursa of the knee joint will be damaged, which can cause arthritis and stiffness of the joint. Pins which penetrate the quadriceps musculature limit muscle movement. The range of movement of adjacent joints is hindered more by pins inserted ventrally than by those inserted from the lateral side. In particular the range of movement of the knee will be hampered.

On the distal portion of the femur, transfixation from the lateral side can be mounted without risk. But in the case of ventrodorsal transfixation, the n. ischiadicus and femoro-popliteal vessels can become damaged, thus this approach is contraindicated.
Such a construction is not advisable because the patient will be unable to lie on his/her back and it means that nursing is more or less impossible.

### 3.4 Mounting fixation pins close to the arteria femoralis

The a. femoralis and accompanying veins run through the adductor canal on the medial side of the upper leg. In the upper two thirds (levels 1 and 2, Figure 3.1) they are situated on the ventral side of the shaft. About half way down, in the distal third (level 3, Figure 3.1) the artery crosses the femoral shaft and runs further on the dorsal side. In view of anatomical variations, transfixation on theoretical grounds can only be carried out without risk in the distal portion of level 4. The risk of damaging arteries at levels 3 and 4 decreases if the transfixation pins are inserted in a more dorsolateral direction (ca. 30°). In this way the risk of damaging the n. ischiadicus is also reduced.

### 3.5 Complications

The number of soft tissue and pin tract infections reported in the literature varies considerably, from 0 - 50% (143). These data were reported for external fixation of the lower leg. Few data are available on pin tract infections at other sites, such as the upper leg.

Although pin tract infection seldom involves serious clinical consequences, local skin irritation around the pins occurs in all patients. Ring sequesters and osteitis hardly ever give rise to serious problems. If these complications arise they are usually attributed to the lack of experience of the operator (38). However, exact study data are lacking. Also the incidence of sepsis from an osteitic lesion caused by fixation pins varies considerably (2.5% to 35%).

During the Second World War external fixation was brought into discredit in America on account of infection problems.

In Europe, on the contrary, the use of external fixation was continued and improvements were made by Raoul Hoffmann in particular.

Burny has demonstrated that the chance of tibia pin tract infection increases if the pins are left in situ for more than 150 days (41). The infection incidence of pins proximal to the tibial fracture is lower (20% infected after 250 days) than those situated distal to the fracture (50% after 250 days). In a study conducted by Magis on 376 fractures of the lower leg, the incidence of inflammation around the pins was found to be 2.5% (144). A similar percentage was observed in a series of 52 lower leg fractures which had been treated using the Orthofix frame (145).

Pin problems can also arise during external fixation of the femur. Pin tract infections have been recorded in 12% (Anderson's external fixator) to 22% (Wagner apparatus). After removal of the pins the infection generally heals spontaneously and surgical intervention is seldom necessary (38). Our own experience with external fixation of the femur in older patients with osteoporotic bones or in young patients with inactivity osteoporosis has made it clear that it is very difficult to achieve sufficient fixation of the pins. This leads to their becoming loose and, in turn, to pin tract infections. The risk of these complications occurring is particularly high if the fracture area is already infected. Despite the great thickness of muscle on the upper leg which must be penetrated by the external fixation pins, there are no indications that pin tract infections occur more frequently in the upper leg. Neither do they cause more problems during lengthening procedures or the treatment of injuries than at any other site.

Pin tract infections can be largely prevented through careful nursing of the pin holes in the skin.

In patients with reduced immunity (such as those suffering from diabetes mellitus), it is the general view that the use of external fixation is contra indicated on account of the risk of pin tract infection. However, investigations to establish whether more infection is present in these patients are not always conducted or mentioned in the literature.

Wide incision of the skin prevents the pins from causing pressure wounds which, in turn, would lead to necrosis and inflammation. Irritation of the soft tissue can also arise if the patient exercises his/her muscles too extensively (the muscles continually rub against the pins) or if the leg is burdened at a too early stage (instability through insufficient fracture consolidation).

Infection at the site of the fracture can also cause pin tract infection and therefore, loosening of the pins. An unstable frame allows movement at the pin bone junction and also causes necrosis. If pins without a screw thread are used it is more likely that pin tract infection will arise than if pins with a screw thread are used. Pins without a screw thread can shift inside the bone and cause instability of the frame.

It is assumed that if the surgical mounting procedure is carried out carefully, problems with the pins can be prevented. If the bone is drilled incorrectly (at high revs) the bone will become very hot and necrosis might result. Temperatures of 140°C have been measured in bone. Experiments have shown that osteocytes die if they are exposed to a temperature of 55°C for one minute. If a small diameter drill (in a protective cover) is used first, the hole can subsequently be enlarged using a hand drill. As a result the heat production is kept to a minimum and does not rise above 45°C. Necrosis also occurs at the junctions between the pins and the bone if the fixation frame is used to compress the ends of the fracture fragments with too much force (146,147). A pressure bandage around the pins under the clamp unit hinders the movement of soft tissue but can also lead to the retention of wound exudate. For this reason it is advisable to start treating the pin tract wounds without pressure bandages as soon as possible. Baths and swimming are not contra indicated.

The insertion of fixation pins seldom causes blood vessel or nerve damage. There have been incidental reports on nerve injury of the n. peronealis superficialis, n. ulnaris, with temporary palsy (38).

Research on amputation and cadaver material has shown that blood vessels are not often perforated by fixation pins, but are pushed aside (147). It is probable that damage occurs at a later stage through erosion of the blood vessel against the fixation pin. In the literature, mention has been made in case histories of injuries of the a. femoralis superficialis, a false aneurysm of the a. profunda femoris and of a branch of the a. tibialis anterior (38,148) and an arterio-venous fistula of the

a. femoralis superficialis (138,148). Amputation of a foot was necessary after the a. tibialis posterior had been damaged by a fixation pin (149).

No data was found on material breakages. If fixation pins are only used once, it is not very likely that they will break.

### 3.6 Conclusion

The anatomical relationships of the upper leg do not form an obstacle for the application of an external fixation device. The risks are justifiable.
Transfixation is not possible on the proximal side of the upper leg, but is practicable at the distal end. It is safer not to insert the pins from a pure lateral direction, but at an angle of 30° dorsolaterally. The insertion of pins on the ventral side limits knee function and is only indicated if it appears that knee arthrodesis is unavoidable or it is the aim of the trea ment. A unilateral (two dimensional) frame is considered to be a better choice than a three dimensional one because it does not involve ventral fixation.
External fixation can give rise to a number of problems, such as pin tract infection. A small amount of tissue irritation occurs in all patients. It is necessary to treat infection problems in 2.5% to 35%.
There are no indications that external fixation of the femur causes more pin tract infections and pin problems than are seen at other locations.
Most complications can be prevented if the treatment is carried out with sufficient care and attention. Although external fixation does not involve any serious complications, it can be a nuisance for the patient. Regular care is a necessity. These arguments are the reason why external fixation of the femur is only applied in situations where other alternatives are impossible or will not give satisfactory results.
Improvement of external fixation material has clearly led to an increase in its applicability, also on the femur.

# B BIOMECHANICAL INVESTIGATION

## CHAPTER 4 BIOMECHANICS AND STABILITY

### 4.1 Forces which act on the femoral shaft

Knowledge of the basic concepts of biomechanics is important for everyone who is concerned with the treatment of muscular and skeletal injuries. Rational treatment protocols can only be drawn up if surgeons are sufficiently familiar with the relationships between force, distortion and movement.

It is possible to calculate the forces which act on the femur with the aid of average values for mass and length (Table 4.1). The stress exerted on external fixation devices, when applied to the femur, are closely related to this. In patients with a femoral shaft fracture, the fixation device must be stable enough to withstand the stress involved.

| Weight (N) | | Location of centre of gravity (cm) |
|---|---|---|
| Head and neck | 56.0 | collectively to crown 60.4 |
| Trunk | 350.0 | and to mid. femoral head 39.6 |
| Arm | 35.0 | |
| Whole leg | 112.0 | |
| Upper leg | 70.0 | prox. 18, dist. 24 |
| Lower leg | 31.5 | prox. 18, dist 23 |
| Foot | 10.5 | |

*Table 4.1 Weight and centre of gravity of the upper and lower leg (averages in round figures) of an adult of average build (body weight 700 N and height 178 cm)* (12).

*Figure 4.1* *Schematic representation of a patient in prone position with articulation axes of the trunk, the upper and lower leg. When the extended leg is lifted, angle $\alpha$ changes. M2 is the moment which acts on the leg and that which is necessary to lift the whole weight of the leg. If angle $\alpha$ is 0°, the moment M2 is the greatest.*

*Figure 4.2* *Schematic representation of the forces and moments which act on the lower leg (prone position; $\alpha = 0°$).*

*Figure 4.3* *Schematic representation of the forces which act on the upper leg (prone position; $\alpha = 0°$). MA =is the moment which acts on the upper leg at the level of articulation axis A and is caused by the weight of the lower leg. MB =is the moment of the hip joint which is necessary to lift the total weight of the leg.*

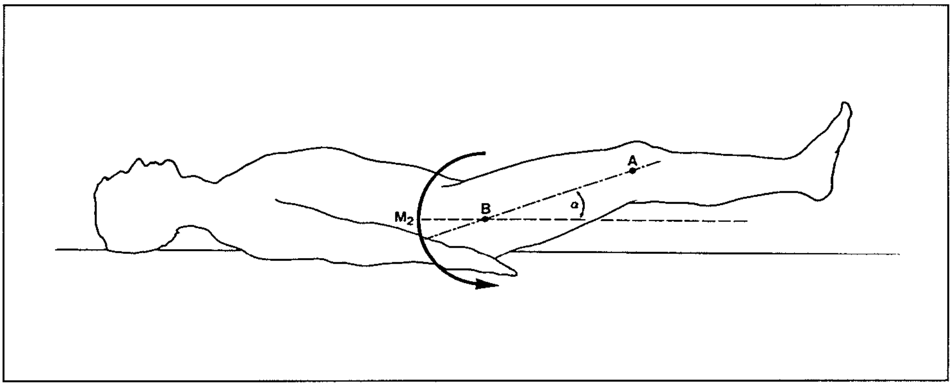


*Fig. 4.1*

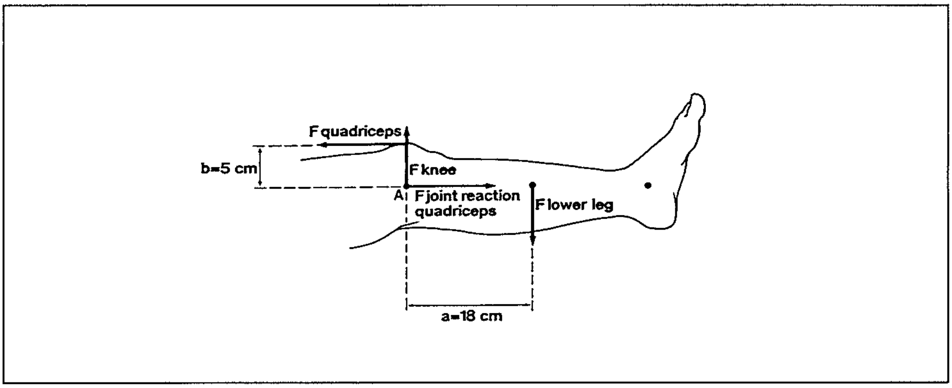


*Fig. 4.2*

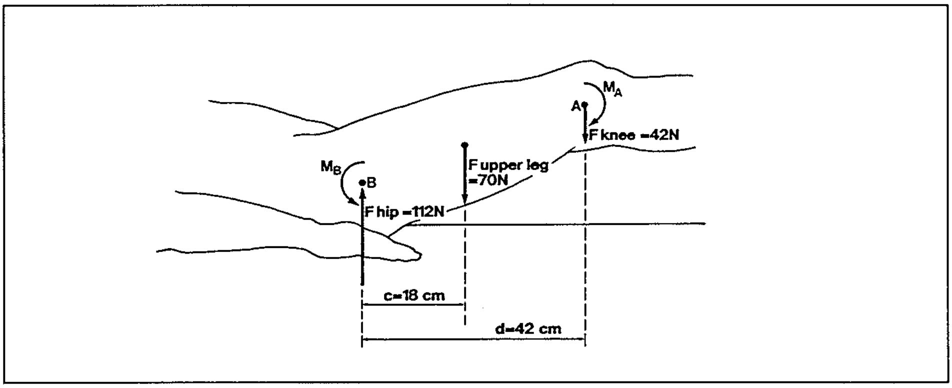


*Fig. 4.3*

The femur of a healthy person in everyday life is exposed to different degrees of stress than the femur of a bedridden patient after an accident. In an adult weighing 70 kg (700 N), the maximum force which acts on the femur under normal circumstances is 125 Nm. This is about half of the moment (250 Nm) necessary to fracture the femur (151,152).

The amount of stress which acts on the femur in the recovery phase of a fracture can be illustrated by means of equations.
These are based on practical situations, for instance the patient lifting up his leg while in the prone position, walking with and without weight bearing. The influence of the m. quadriceps on the femur has been represented by a force vector. This produces a value for the resulting muscle power for an estimated distance between the work line and the joint axis.

The leg must be divided into parts in order to be able to make the calculations (upper and lower leg, including the ankle). The knee and hip serve as hinges A and B (Figure 4.1). Separate forces act on the upper and lower leg (Figures 4.2 and 4.3).

### Lower leg, analysis of equilibrium

Equilibrium of forces in a vertical direction produces (Figure 4.2):

$$\sum Fv = F\ \text{knee} - F\ \text{lower leg} = 0, \text{ thus}$$

$$F\ \text{knee} = F\ \text{lower leg}$$

Equilibrium of forces in a horizontal direction produces:

$$\sum Fh = F\ \text{quadriceps} - F\ \text{joint reaction quadriceps} = 0$$

$$F\ \text{quadriceps} = F\ \text{joint reaction quadriceps}$$

where F quadriceps is the force exerted by the m. quadriceps femoris at the tuberositas tibiae

Moment equilibrium with regard to the knee axis (A) produces:

$$\sum M = -F\ \text{lower leg} * a + F\ \text{quadriceps} * b = 0$$

$$F\ \text{lower leg} * a = F\ \text{quadriceps} * b$$

Given: $a = 18$ cm,
$b = 5$ cm

and F lower leg = 42 [N],

then

42 * 18 = F quadriceps * 5, therefore

F quadriceps = (42 * 18) / 5 = 151 [N].

## Upper leg, analysis of equilibrium

Equilibrium of forces in a vertical direction produces (Figure 4.3):

$$\sum Fv = F\ hipv - F\ upper\ leg - F\ knee = 0$$

$$F\ hipv = F\ upper\ leg + F\ knee$$

Moment equilibrium with regard to the hip axis (A) produces:

$$\sum M = -F\ upper\ leg * c - F\ knee * d - MA + MB = 0$$

$$MB = F\ upper\ leg * c + F\ knee * d + MA$$

where MB = resulting moment of muscle power with regard to the hip joint and

$$MA = F\ lower\ leg * a$$

Given

F upper leg = 70 N,
F knee = F lower leg = 42 [N],
a = 18 cm,
c = 18 cm and
d = 42 cm,

then

$$MB = 70 * 18 + 42 * 42 + 42 * 18 = 3780\ [Ncm], \text{ or}$$

$$MB \approx 38\ [Nm].$$

If the patient is mobilized (on crutches) the non weight bearing leg hangs down vertically. In order to analyze the forces acting in this situation, they must once again be calculated separately.

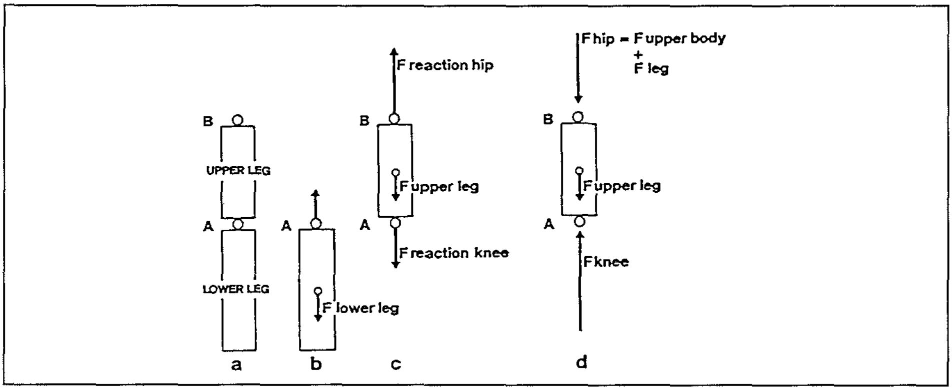


*Figure 4.4 Schematic representation of the forces acting on the leg during non weight bearing mobilization, with leg hanging down vertically (A,B,C) and during full weight bearing (D). Equation for an average adult patient: weight 700 N; height: 178 cm.*

Forces acting on the lower leg hanging downwards (Figure 4.4 B):

$$\Sigma F = F\text{ reaction knee} - F\text{ lower leg} = 0$$

$$F\text{ reaction knee} = F\text{ lower leg} = 42\ [N]$$

Forces acting on the upper leg (Figure 4.4 C):

$$\Sigma F = F\text{ reaction hip} - F\text{ upper leg} - F\text{ reaction knee} = 0$$

$$F\text{ reaction hip} - 70\ [N] - 42\ [N] = 0$$

$$F\text{ reaction hip} = 112\ [N]$$

If a patient stands on the leg bearing a fixation frame or burdens the leg (and the fixation frame) accidentally during a fall, the leg will be exposed to considerably greater forces. The femur will be burdened with a weight which is at least equal to the patient's own weight minus the supporting leg (Figure 4.4 D).
In a vertical direction, given that the patient is standing still and upright on the leg:

$$\Sigma F = -F\text{ hip} - F\text{ upper leg} + F\text{ knee} = 0$$

$$-588 - 70 + F\text{ knee} = 0$$

$$F\text{ knee} = 658\ [N]$$

(F hip in an upright position is the weight of the upper body, including the head, arms and contralateral leg: 588 [N])

If the patient stands on the leg, the mass of the rest of the body is carried by the lower leg, which gives rise to a reaction force on the femur in an axial direction at the level of the knee of 658 N. In a healthy leg this force is exerted on the femoral shaft. If the femur is stabilized using external fixation, this force must be intercepted by the fixation device.

## 4.2 Biomechanical characteristics of an external fixation device

Achieving stability is a major problem in the external fixation of fractures (1,24,27,153,154,155,156,157,158). In the past, insufficient stability was considered to lie at the root of complications (54). Therefore, the application possibilities remained limited. By using rigid fixation, it was found that the loosening of pins and the number of pin tract infections could be reduced. However, elastic fixation promotes the formation of callus (41,174,175).

Clinical experience has supported the notion that a second treatment consisting of internal fixation is seldom necessary after treatment by external fixation (159). Thanks to the availability of frames which offer greater stability, external fixation has become the treatment of choice for compound fractures and bone infections (160).

It is not exactly known how rigid a frame should be, but it is clear that shear stress retards fracture consolidation most (161). Non union occurs if the amount of movement is too small to induce callus formation, but too much movement will prevent primary bone consolidation.

Mounting complicated fixation devices is very time consuming. If the various parts have to be screwed together, the correct positioning of the bone fragments can be upset if the system twists during manipulation. If the length of the pins and their positions have been chosen correctly, the pins will not obstruct the contralateral healthy leg. Mounting pins on the medial side, on the cranial portion of the femur, is risky owing to the anatomical relationships. With pins in this position it is no longer possible for the patient to walk and sit and the pins will also interfere with the personal hygiene. Similarly, if pins are mounted on the dorsal side the patient will not be able to sit down and will have to adapt his sleeping position. If pins are mounted at unusual angles it might even be necessary to make adaptions to the patient's bed or chair. Greater stability can be achieved using transfixation pins at the distal end of the femur. But this involves extra damage to the soft tissue and the risk of infection. Adhesion can occur through necrosis of muscle and fascia which can give rise to limitations of movement in the adjacent joints.
A loose pin indicates a pin hole infection and no longer contributes to the stability, therefore it is better removed.

## 4.3 The stability of an external fixation device

The most vulnerable points in a frame construction are the connections between the fractured bone and the pin, between the pins and the clamp unit and between the clamp unit and the bar of the frame. Using a simple frame with few parts which can be mounted quickly means that there is less chance of assembly faults being made. Parts can become loose in the course of treatment and will therefore need to be checked during follow up at the outpatients clinic.

The ideal external fixation device should offer rigidity but also (if necessary ) flexibility and have a strong pin bone interface connection. Extensive research has been conducted in this area (27,39,54,101,127,128,160,161,162,163,164,165,166,167,168,169,170,171). Most of the studies have been carried out on the tibia. It is clear that incidental rigid external fixation promotes primary bone consolidation. However, secondary consolidation is the more usual result (153).

The quality of the frame components and their relationship to each other are chiefly responsible for the stability of an external fixation device.
A frame is more stable when the distance between the bone and the clamp unit is kept to a minimum. However, this hinders wound care. Also the connection pieces between the clamp units must be kept short and, if possible, pins should be mounted along the whole length of the fractured bone. In the case of a trauma patient for whom external fixation has been chosen as the treatment of choice, this cannot often be achieved owing to the nature of the fracture.

The thicker the pins, the less the distortion , especially in patients with serious fractures without bone contact. In these cases the external fixation device only has to provide stability which is dependent on adequate pin fixation in the bone fragments. If there is some bone contact, axial stress will be partly absorbed by the bone itself. Stability can be promoted by bending the pins in advance or by introducing internal twisting of the frame using special tools.
If the pins are only fixed to the tip of the frame (such as with the Wagner apparatus) it is very likely that the fracture fragments will tilt and become dislocated.
By attaching pins along the whole length of the fixation frame the stability of the system is increased (in particular A/P angulation) and more rotational stability is achieved.
The application of pins with a screw thread is preferred in order to limit the action of shearing forces between the bone and the pin.

Occasionally a combination of external fixation and (minimal) screw osteosynthesis is used. Good results have been achieved using this method, but dynamisation of the frame is somewhat difficult. However, there is no quick callus formation owing to the additional compression screw, which produces stable osteosynthesis, in combination with the neutralizing external fixation.

## 4.4 External fixation and interfragmentary compression

The stability is increased if bone contact is achieved by compressing the bone fragments. In traumatology the nature of the fracture does not often lend itself for this, but if, for example, in corrective surgery a (transverse) osteotomy can be compressed, this is the preferred treatment method.
Interfragmentary compression prevents varus or valgus angulation of the bone fragments. More uniform compression can be achieved using a transfixation frame than by using a unilateral system (39). The major portion of the forces acting on the bone are absorbed by the bone itself and in this way the pins and fixation apparatus are hardly affected. But, in principle, a unilateral frame is always stable enough if there is any bone contact present, particularly if interfragmentary compression can be exerted. Without bone contact a full three dimensional construction is preferred on theoretical grounds. Therefore, the disadvantages of bulky frames with multiple (transfixation) pins have to be accepted. However, it is not possible to apply this system (with extensive transfixation) to the upper leg in view of the local anatomical relationships.

## 4.5 Conclusion

The forces acting on the femoral shaft are very changeable and are dependant on the position of the leg and the amount of stress involved. By means of biomechanics, these forces, which comprise many components, can be calculated separately. The maximum, average moment to which a femur is exposed under normal circumstances is about 125 Nm. A femur will break if it is subjected to a moment of 250 Nm (in an adult weighing 70 kg). Far less stress is involved initially in the case of a trauma patient during the rehabilitation phase (bedrest, mobilization on crutches), except under exceptional circumstances, such as a fall.
If it is decided to treat a femoral shaft fracture using an external fixation device, it is important for the frame to be able to withstand the stress to which it will be exposed. In cases where there is no bone contact the device will have to be able to withstand the full amount of stress; in cases where there is some bone contact it will have to withstand part of the stress. If there is good bone contact and interfragmentary compression is being exerted, the fixation frame will be subjected to far less stress.

To a large extent, the thickness of the pins, their positions and the localization of the pin clamps determine the amount of stability which can be achieved with each separate type of fixation device.
The anatomy of the upper leg limits the construction possibilities of an external fixation device at this location.

It is not always clear how stable the immobilization should be. In the case of secondary fracture consolidation, elastic fixation seems to be indicated because it stimulates callus formation, but too much movement will cause the newly formed callus to rupture.

Adequate fracture stabilization creates favorable circumstances for the healing of soft tissue, especially in cases of bacterial contamination. Animal experiments have shown that unstable fracture immobilization promotes the resorption of nonvascular loose bone fragments (56,57). Therefore and on the basis of clinical experience, it is important to strive for optimal stabilization (27).

# CHAPTER 5 FEMORAL SHAFT FRACTURES AND EXTERNAL FIXATION
# BIOMECHANICAL INVESTIGATION

## 5.1 Definition and presentation of the question

Stabilization of a fracture at an early stage after the accident improves a multiple injured patient's chance of survival. It can bring about a reduction in the incidence of Adult Respiratory Distress Syndrome (ARDS) and of Multi Organ Failure (MOF) (47,48,49,50,172). It also promotes healing of the fracture if bacterial contamination is involved or there are loose bone fragments (56,57).

Although external fixation is applied on a large scale for treating fractures, very few people consider it to be the treatment of choice for femoral shaft fractures. Usually, stable internal osteosynthesis or a form of traction are the preferred techniques. Nevertheless, over the last few years, more and more use has been made of external fixation for femoral fractures. The indications vary and are determined by the circumstances. It is often an alternative solution if internal osteosynthesis is undesirable or impossible.
We have treated various types of compound and closed femoral shaft fractures with different external fixation systems. From data in the literature and our own clinical experience with 40 patients, it has been possible to specify a field of indications (see Table 5.1).

-compound fractures
-serious comminuted fractures
-short operation necessary
-alternative to traction (children)
-others (leglengthening, arthrodesis, pseudarthrosis)

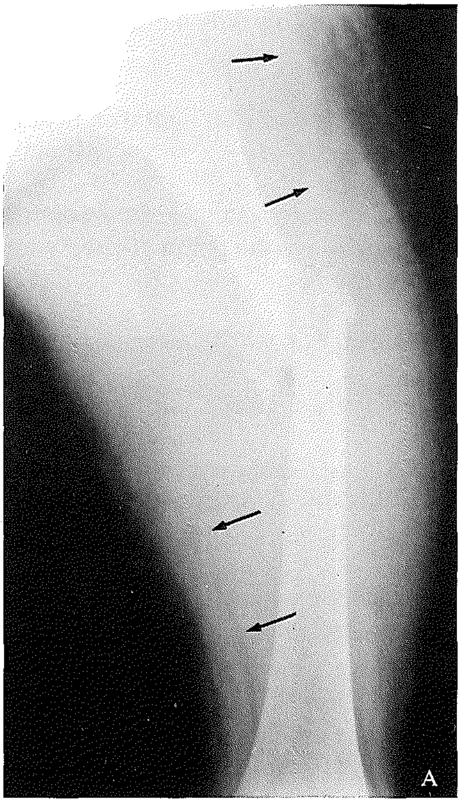
*Table 5.1 Indications for which external fixation of the femur may be considered*

In the beginning, the Wagner apparatus was particularly popular. It is possible to achieve good repositioning of a fracture peroperatively using this device, but secondary dislocation occurs frequently; sometimes within a few days or at a later stage, after callus formation (Fig. 5.1).

*Fig. 5.1 Secondary dislocation (ruptured callus) in a femoral shaft fracture immobilized using the Wagner apparatus.*

In children, where there is less stress on the fixation apparatus, the Wagner apparatus does not give rise to so many problems. However, after good repositioning, consolidation in varus position often seems to occur. Obviously, the Wagner apparatus does not always offer sufficient stability for treating femoral fractures (Fig. 5.2). These clinical problems were the reasons we decided to test other external fixation devices, both clinically and in experimental laboratory research.

On the assumption that external fixation would form a good alternative treatment in selected patients (in 'problem fractures' of the femur), twelve fixation devices were tested. They are all representative of various frame configurations with which experience has been gained on the femur and for which treatment results have been reported in the literature.



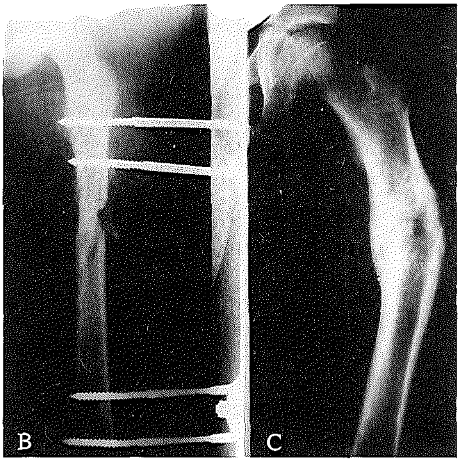


*Fig. 5.2 Grade I femoral shaft fracture (female, 10years old). Treatment by means of 10 days of traction and complicated by gas gangrene.*

*A: X-ray appearance of gas between muscle fibres (arrows).*
*B: Other than wound debridement,intravenous antibiotics and hyperbaric oxygen therapy, the fracture was immobilized in anatomical position using the Wagner apparatus for 11 weeks.*
*C: Ultimate consolidation in varus position (X-ray: 1 year post trauma).*

The most important question was: How much movement do the fixation frames in this study allow and which of these twelve external fixation systems offer optimal stability?
Moreover, quick and easy assembly was considered to be of importance and a simple construction and small sized frame gives easy access with regard to wound care.

## 5.2 Experimental design

In order to find out which was the most stable device, the following systems were tested under the most unstable situation: on a fracture without bone contact:

**a & b)** the horseshoe shaped ACE Fisher fixation frame: in a version made of aluminum and a version with titanium components (horseshoes),both tested with 5 mm titanium pins.

**c)** the ACE Hoffmann frame, with 5 mm titanium pins.

**d)** the Hoffmann femoral frame. Diameter of the pins: 4 mm. Thicker pins

(5 mm) are available on special request. Until now only 4 mm pins were used.

e) the new version of the Hoffmann frame equipped with light weight aluminum clamps, with 4 mm pins.

f) the well known unilateral Hoffmann construction, suitable for fractures of the lower leg and (in children) also applied to the femur. Tested with 4 mm pins.

g) the AO ASIF threaded frame. With Schanz screws, diameter 5 mm.

h) the tubular AO ASIF frame. (Schanz screws, 5 mm)

i) the Orthofix fixation apparatus. (We did not make use of the telescopic body and dynamisation possibilities in this study). Screws with diameter of 6 mm tapering to 5 mm.

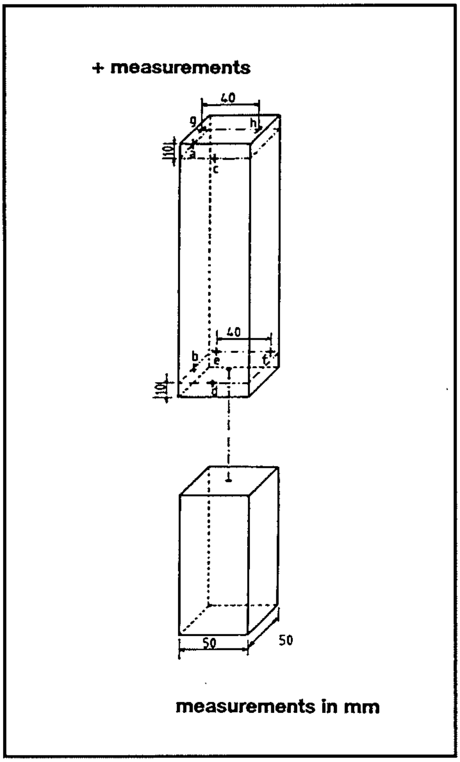
j) the fixation device made of an anaesthetic tube attached to Schanz screws (5 mm) and filled with polymethylmethacrylate (bonecement)

k) the Wagner apparatus, large model (Schanz screws, 6 mm)

l) the Monofixateur device. Tested with Schanz screws, diameter 6 mm.

In comparative research, in which the emphasis lies on the external fixation apparatus itself, the varying degrees of osteoporosis and differences in bone thickness reported can be extremely troublesome parameters. For this reason the fixation systems under investigation were set up in a laboratory in comparable cuboid perspex rods instead of in bone (Fig. 5.3)

In the laboratory the experimental bone model was set up in a vertical position. Two rectangular perspex rods (50 x 50 x 100 mm and 50 x 50 x 180 mm) represented the femoral shaft fragments and were connected by means of an external fixation device. Rectangular blocks of perspex were chosen for the bone model to make it easier to calculate translations (the displacement of all points of the fracture surface in the same direction over the same distance) and rotations (the angle of displacement of the fracture surface from the chief axis in relation to the starting position). Another reason for choosing this construction was the fact that the elastic transformation of the bone model was very small.
In this way the pins applied could be considered to be firmly clamped in and during measurement only the displacement, which arose through elastic or plastic deformation of the fixation device itself in combination with the pins was measured.
The parts making up the twelve external fixation devices tested, differed consid-



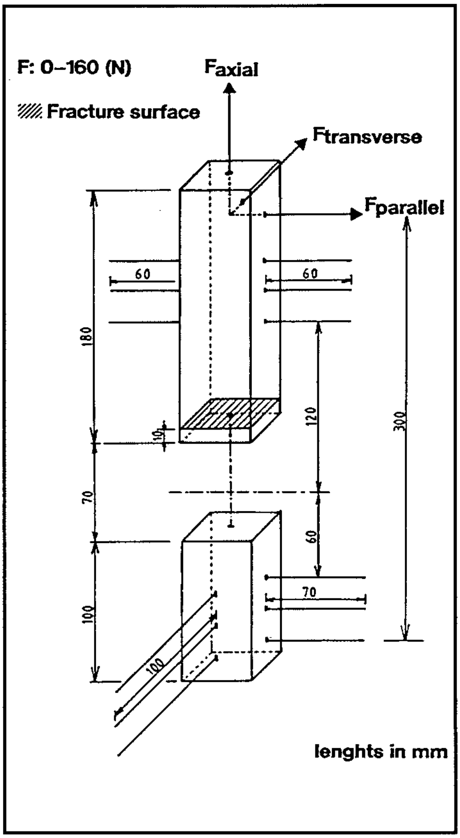


*Fig. 5.3 In the laboratory, rectangular perspex rods were used as 'imitation femur' with measurement points a to and including h. The proximal portion of the fracture was situated below the distal portion. By means of a 'bone defect' 70 mm long, no contact was possible between the ends of the 'bone' fragments.*

*Fig. 5.4 Standardized position of pins and fixation clamps in order to achieve an analogous assembly of the various types of frame. The fracture surface measured has been shaded in. Axial, parallel and transverse forces grip the distal portion, the proximal portion is fixed.*

erably from apparatus to apparatus. Owing to the fact that these differences may have some affect on the measur ment results, it was decided to use a standardized position for the pins and clamp units (Fig. 5.4).

In this way all fixation devices were built up in approximately the same manner (always in accordance with the manufacturers' instructions). It was aimed to achieve the most stable construction possible, making use of the thickest pins available for each device. Fixed measurements were maintained for the cortex clamp unit distances, in agreement with the actual situation on the upper leg. For the three dimensional fixation devices, distal transfixing pins are applied and for the two dimensional fixation devices (unilateral) only lateral pins. The various perspex fixation combinations were then attached to a firm base in the measurement set up (Fig. 5.5).

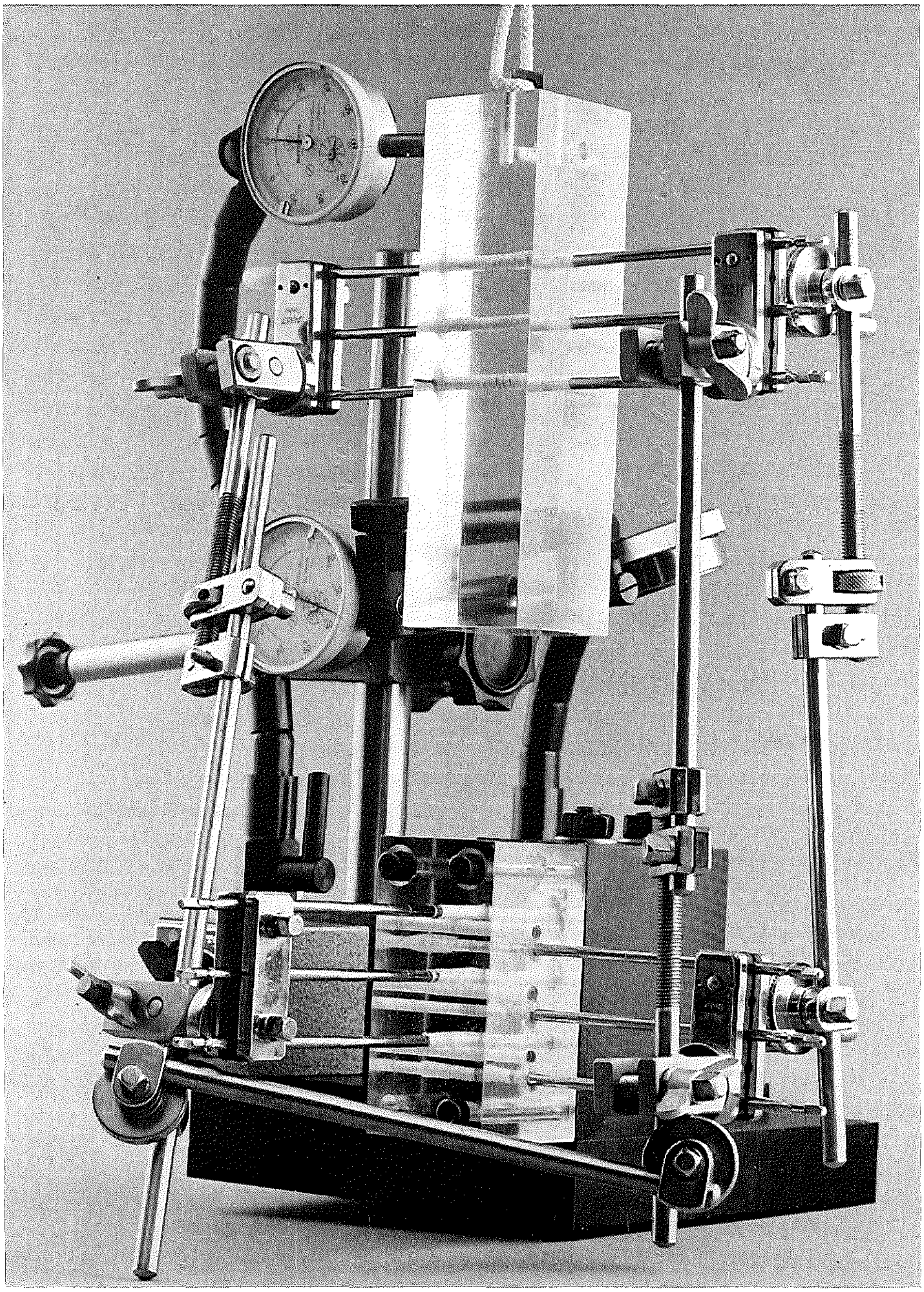


*Figure 5.5 Overview of the measurement set up showing the Hoffmann femoral frame. The displacement of the distal perspex block was measured using clock gauges at each measuring point.*

Force was exerted with the use of a nylon rope with weights attached, running over pulleys. If separate forces were being applied to the system, the displacement of the distal perspex rod in relation to the fixed proximal rod was measured using four clock gauges (Mitutoyo; type number 2046E 08; accuracy 0.01 mm). Per direction, the stress was increased in steps of 10 newton (N) from 0 N to a maximum of 160 N. The force applied to the bone model is a reproduction of that which occurs in clinical reality in an adult patient. The influence of upper leg muscles was ignored, a realistic outlook, because in the post operative phase following a serious upper leg injury, little or no use is made of the muscles. In agreement with an earlier study on the lower leg (27), the three directions of stress were:

**A:** the direction without weightbearing of the bone axis (axial), simulating a patient who is mobilized on crutches;

**B:** the direction (in the coronal plane) of the surface formed by the bone and the pin units (parallel), simulating a leg being lifted in abduction;

**C:** the direction (in the sagittal plane) transverse to the surface formed by the pin units and the bone (perpendicular), simulating a patient who, while lying on his back, lifts his leg from the surface on which it is resting.

In the experimental investigation a random fracture position was chosen for the bone defect on which all calculations of translations and rotations were based (Fig. 5.6).
The amount of displacement of the chosen fracture positions was registered using clock gauges; the translations and rotations were subsequently determined.

| | |
|---|---|
| Ta: | Translation in axial direction |
| Tp: | Translation parallel direction |
| Tt: | Translation transverse direction |
| Tr: | Translation translation resultant |
| Ra: | Rotation around axial axis |
| Rp: | Rotation around parallel axis |
| Rt: | Rotation around transverse axis |
| Rr: | Rotation around rotation resultant |

The displacement of points a-h were measured for the calculation of the above quantities (Fig. 5.3).

The total weight of an adult's leg is about 16% of the total body weight (12). Due to the fact that body weight seldom exceeds 100 kg, the maximum weight which a fixation frame will be required to carry is 16 kg (i.e simulating a patient standing in a upright position, with his leg hanging downwards). The leg of an average adult (70 kg) weighs just over 11 kg. As the fixation frame is situated a little way down the upper leg, the distal part of the leg will weigh less than 16 kg in the clinical situation, therefore representing a force of less than 160 N. On these theoretical grounds a maximum stress of 160 N was chosen; exceptional circumstances (such as a fall or the burdening of the leg contrary to medical advice) were not taken into consideration.

## 5.3 Translation and Rotation

### 5.3.1 Translation

For translation in an axial direction (Ta) measurement points g and h were used.

$$Ta = 0.5 * (g + h) \quad [mm]$$

For parallel translation (Tp) measurement point b was used.

$$Tp = b \; [mm]$$

For transverse translation (Td) measurement points e and f were used.

$$Tt = 0.5 * (e + f) \quad [mm]$$

In order to limit the number of end variables as much as possible, the three translation vectors (Ta, Tp, Tt) were combined using Pythagoras' law to form a resultant translation vector (Tr).

$$Tr = \sqrt{(Ta^2 + Tp^2 + Tt^2)} \quad [mm]$$

The resulting translation vector Tr and the rotation around the three main axes (Ra, Rp, Rt) and the resulting rotation vector (Rr) are shown in the spacial diagram in Fig. 5.6.

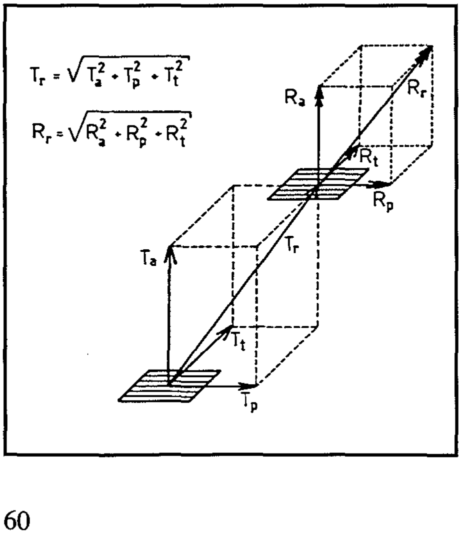


*Figure 5.6 Spatial diagram of the translation vector in the three main directions and their resultant Tr. The rotations around the three main axes and the resultant vector Rr.*

For the three directions in which the stress was applied, the resulting displacement (Tr) has been set out against the force (of 0 to 160 N). There is a linear relationship between translation and force (Tables 5.2, 5.3, 5.4), therefore the translation per 10 N force can be calculated, i.e. the translation (in millimeters) from the centre of the fracture surface if the force is increased by 10 N. This 'displacement coefficient' is represented in the histogrammes in Table 5.5. Two dimensional (unilateral) fixation devices allow more displacement of the fracture surface in a transverse direction during stress than three dimensional devices. This is the result of the fact that transverse forces cause the pins to bend and twist strongly.

### 5.3.2 Rotation

From the translations measured, the rotation of the fracture surface around the three axes (Ra, Rp, Rt) can be calculated during axial, parallel and transverse stress.

Around the axial axis:

$$Ra = \text{Arctan}^{\bullet}\{\,(e - f)/M\,\}\ \text{[degrees]}$$

Around the parallel axis:

$$Rp = \text{Arctan}\{\,(c - d)/N\,\}\ \text{[degrees]}$$

Around the transverse axis:

$$Rt = \text{Arctan}\{\,(a - b)/M\,\}\ \text{[degrees]}$$

• Arctan: the angle $\alpha$ which belongs to the gonometric function tangens $\alpha$.

M: the distance between measurement points e and f (40 mm).
N : the distance between points c and d and a and b (160 mm), respectively, in Fig 5.3.

An example of the rotation calculated during transverse stress (Rt) is shown in Figure 5.7 (page 64).

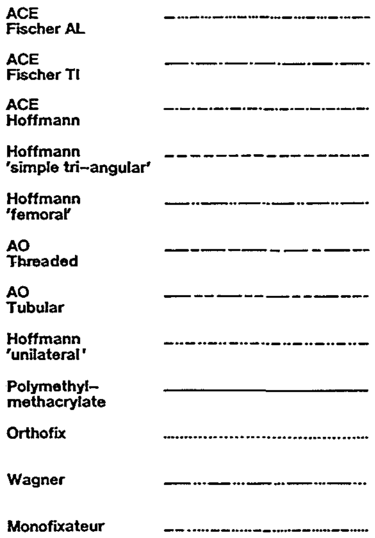


*Table 5.2 Translation resultant (Tr) of the displacement of the centre of the fracture surface under stress in an axial direction.*

*Table 5.3 Translation resultant (Tr) of the displacement of the centre of the fracture surface under stress in a parallel direction.*
*Note: Despite adequate assembly, the pins slipped out of the clamp unit.•*

*Table 5.4 Translation resultant (Tr) of the displacement of the centre of the fracture surface under stress in a transverse direction.*

*Table 5.5The displacement (resultant) of the centre of the fracture surface per 10 N force.*
■ *External fixation device broke under 120 N stress*
■ *External fixation device broke under 140 N stress*
▼ *Slipping pin clamp unit (0-70 N : 0.14 mm and 0 -110 N : 1.01 mm)*
*Translation resultant (Tr) of the centre of the fracture surface per 10 newton force in an axial, parallel and transverse direction.*

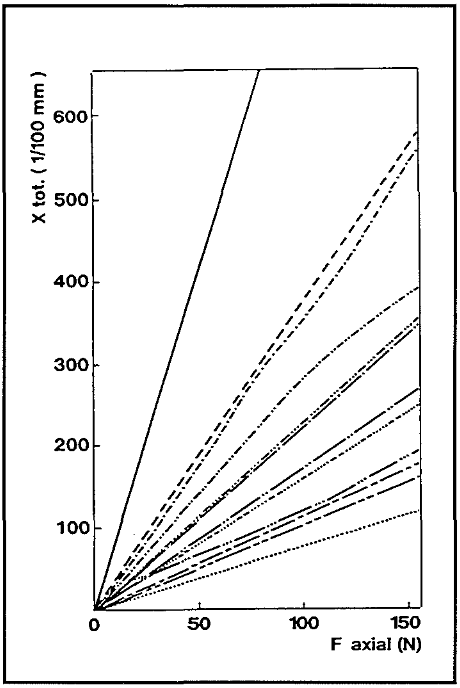


Table 5.2

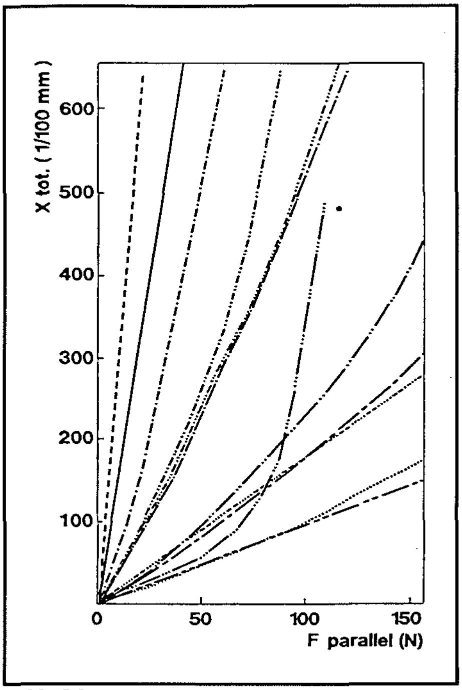


Table 5.3

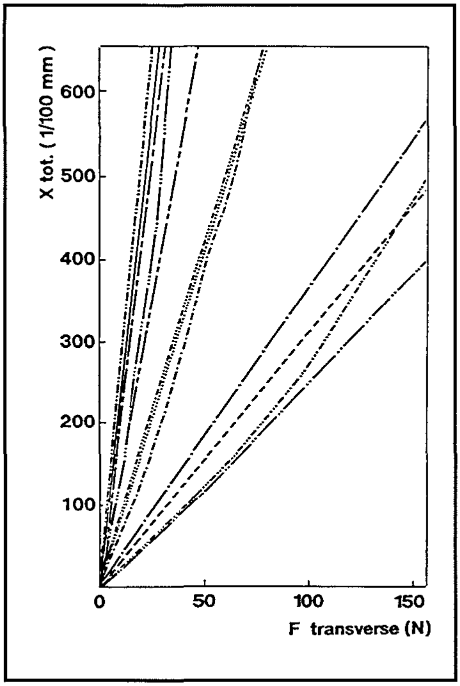


Table 5.4

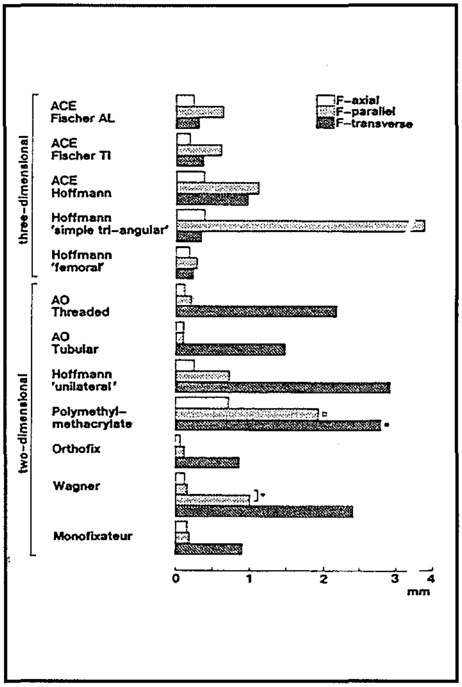


Table 5.5

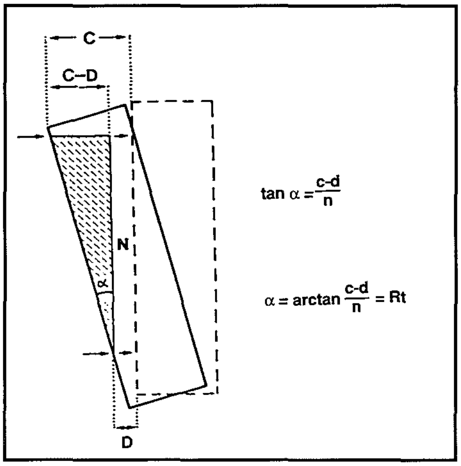


*Figure 5.7 Calculation example of rotation during transverse stress (Rt).*

The rotation of the fracture surfaces measured per 10 N force in axial, parallel and transverse direction are presented in Tables 5.6,5.7 and 5.8, from which (in Table 5.9) the rotation resultants (Rr)• of the fracture centre were determined.

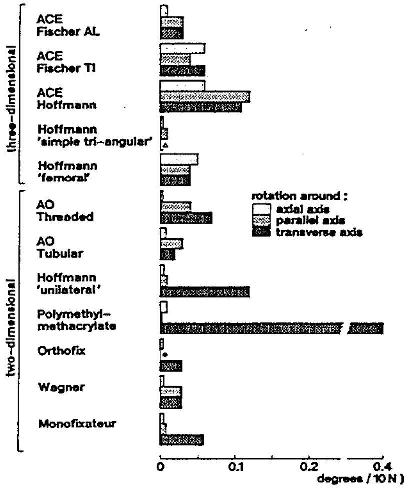
•$Rr = \sqrt{(Ra^2 + Rp^2 + Rt^2)}$

*Table 5.6 Rotation (Ra) of the fracture surface per 10 N force in an axial direction.*

*Table 5.7 Rotation (Rp) of the fracture surface per 10 N force in a parallel direction.*

*Table 5.8 Rotation (Rt) of the fracture surface per 10 N force in a transverse direction.*

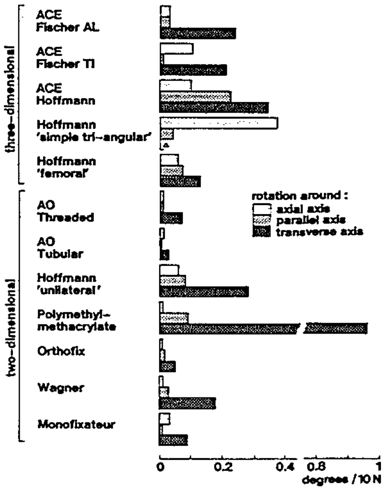
*Table 5.9 The rotation resultant (Rr) of the fracture surface per 10 N force in an axial, parallel and transverse direction.*



Rotation of the fracture plane ( per 10 N load in axial direction ).

- ▵ not stable enough for measuring
- • rotation zero degrees

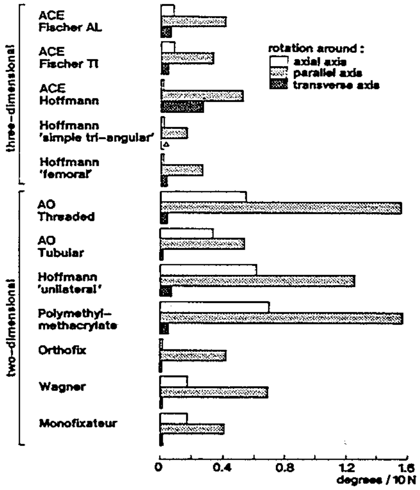
Table 5.6



Rotation of the fracture plane ( per N load in parallel direction ).

▵ not stable enough for measuring

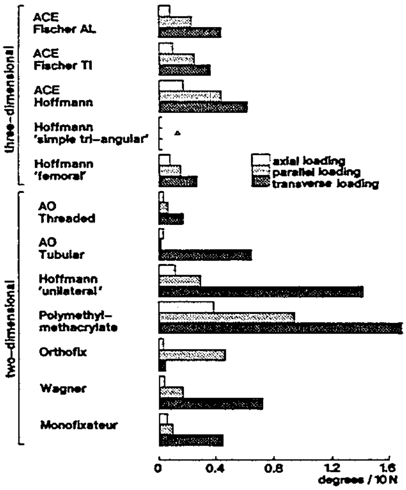
Table 5.7



Rotation of the fracture plane ( per 10 N load in transverse direction ).

▵ not stable enough for measuring

Table 5.8



Rotation (resultant) of the fracture plane.

▵ not stable enough for measuring

Table 5.9

## 5.4 The representativeness of the study

All twelve external fixation devices tested were built up and mounted in the study set up by the same researcher and in accordance with the investigation protocol and the manufacturers' instructions. The researcher had extensive practical experience with these instruments. The distribution of the results of the experiment were examined when the researcher built up a particular frame for the second time. The effects on the distribution of the experiment results when two different people set up a particular frame, were also examined. For this purpose two frames (Hoffmann femoral frame, Orthofix) were built up a second time by a different researcher after the initial measurement. The experiment was repeated such that comparable measurements were obtained (Tables 5.10, 5.11 and 5.12).
The intra individual distribution did not appear to be larger than the interindividual distribution.

The distribution of the experimental results when the devices were mounted on perspex and human cadaver femur (male, 73 years) was also investigated. Both the Hoffmann and Orthofix frames were tested via these two methods. Similar results were obtained. (Tables 5.13, 5.14 and 5.15)

Part of the laboratory experiment was repeated in vivo.
In one patient (male, 50 years) an AO ASIF tubular frame was applied under general anaesthetic to an infected pseudarthrosis on the distal portion of the femur. The frame was set up in a similar way to that on the perspex rods in the laboratory experiment. With the patient's permission, the in vitro experiments were repeated in vivo with the frame applied to the patient (Figs 5.8, 5.9, 5.10).

*Table 5.10* *Measurement (following re-set up of the fixation devices by researchers A and B). Translation resultant (Tr) of the displacement of the centre of the fracture surface with stress in an axial direction.*

*Table 5.11* *Measurement (following re-set up of the fixation devices by researchers A and B). Translation resultant (Tr) with stress in a parallel direction.*

*Table 5.12* *Measurement (following re-set up of the fixation devices by researchers A and B). Translation resultant (Tr) with stress in a transverse direction.*

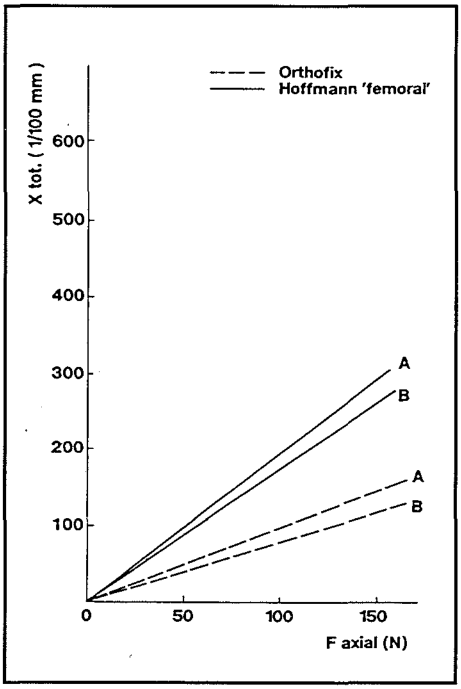


*Table 5.10*

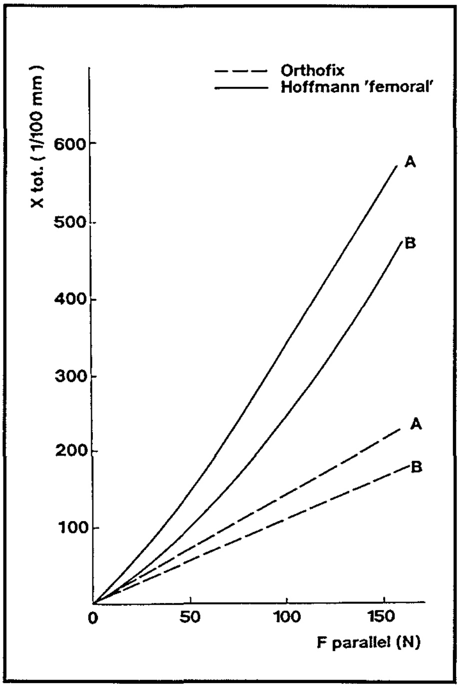


*Table 5.11*

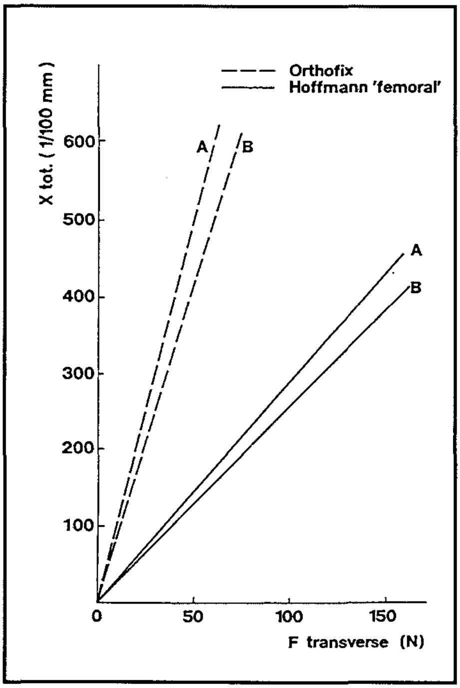


*Table 5.12*

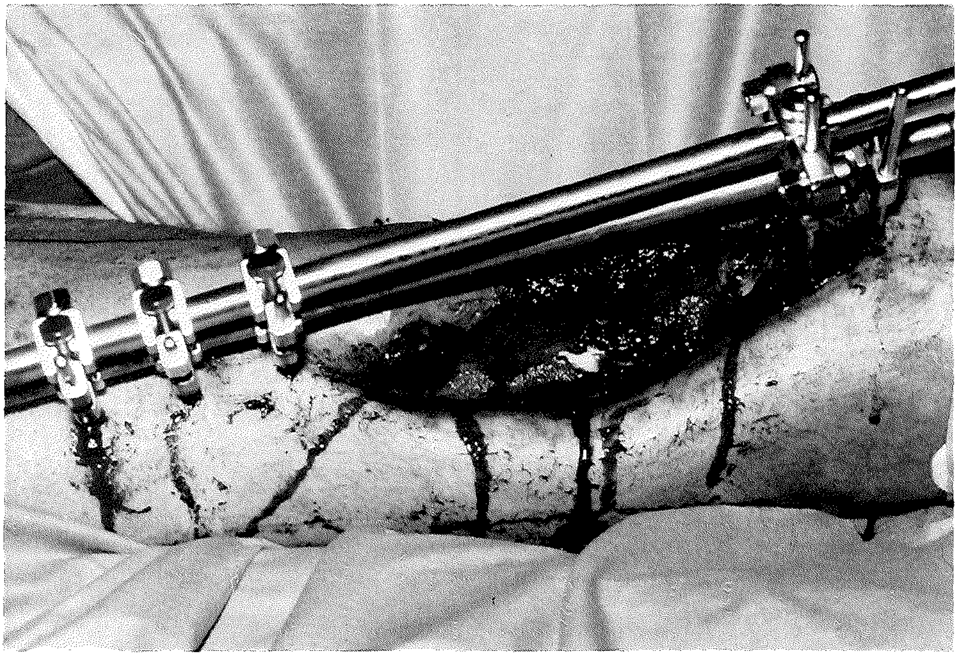


*Figure 5.8 Infected defect pseudarthrosis of the distal portion of the femur (male, 68 kg, 50 years). On the photograph: hip left, knee right.*
*Immobilization using a tubular AO ASIF external fixation device.*

Force was applied to the leg and the movement of the fracture portions was followed by means of white markings on the bone. In rest (Fig 5.9) no angulation was observed. Stress in a transverse direction produced similar angulation to that seen in the experimental perspex model (Fig 5.10).

Table 5.8 shows that the tubular AO ASIF, tested in the laboratory set up, rotated 0.54 degree under the influence of a transverse force per 10 N force (around the parallel axis).
An angle $\alpha$ of 11 degrees, as was measured in the patient, would occur in the experimental situation with a force of 11/0.54 = 20.37 kg = 203.7 N. In the patient the distance between the fixation point of the transverse force and the most cranial pin was not equal to that used in the laboratory experiment (300 mm in the experiment, 455 mm in the patient).
If the distance between the fixation point of the transverse force and the most cranial pin had also been set at 455 mm in the experimental situation, then a rotation of 11 degrees would have occurred around the parallel axis with a force of 134.3 N. In reality, the amount of force necessary to produce 11 degrees of rotation in this patient was well over 130 N.

*Table 5.13 Remeasurement (following re-set up by researcher B). Translation resultant (Tr) with stress in axial direction. The devices were mounted on perspex (B1) and in human cadaver femur (B2; male, 73 years).*

*Table 5.14 Remeasurement (following re-set up by researcher B). Translation resultant (Tr) wih stress in parallel direction. The fixation devices were mounted on perspex (B1) and on human cadaver femur (B2; male, 73 years).*

*Table 5.15 Remeasurement (following re-set up by researcher B). Translation resultant (Tr) with stress in transverse direction. The fixation devices were mounted on perspex (B1) and on human cadaver femur (B2; male 73 years).*

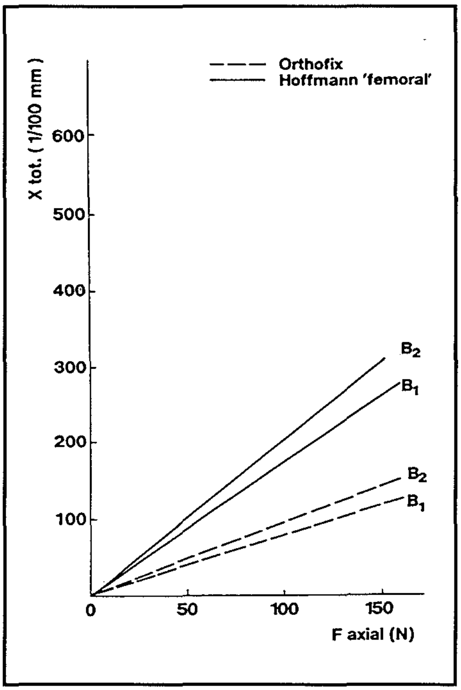


*Table 5.13*

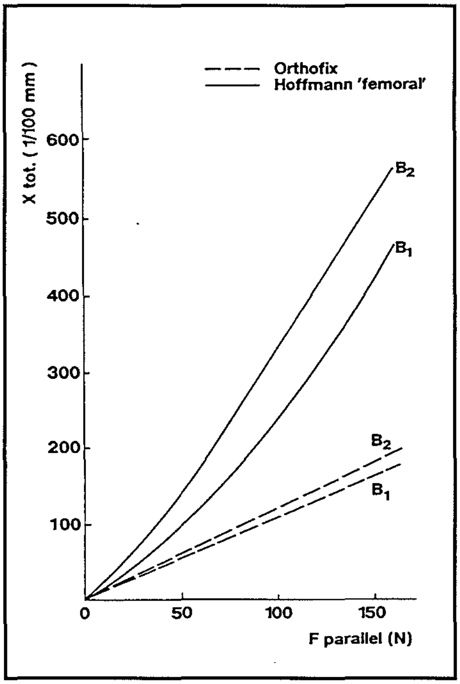
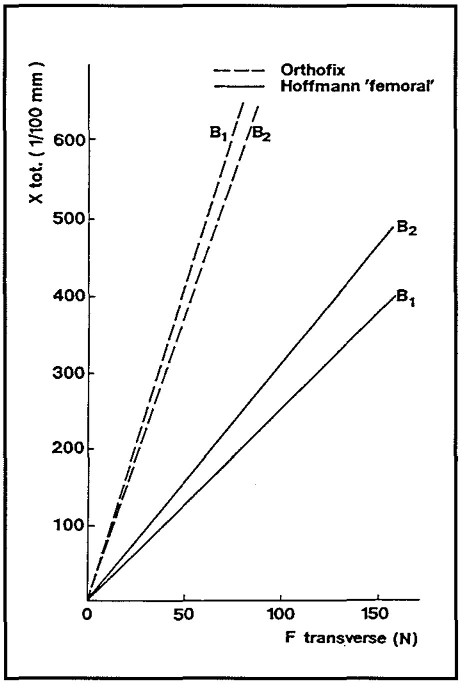


*Table 5.14*



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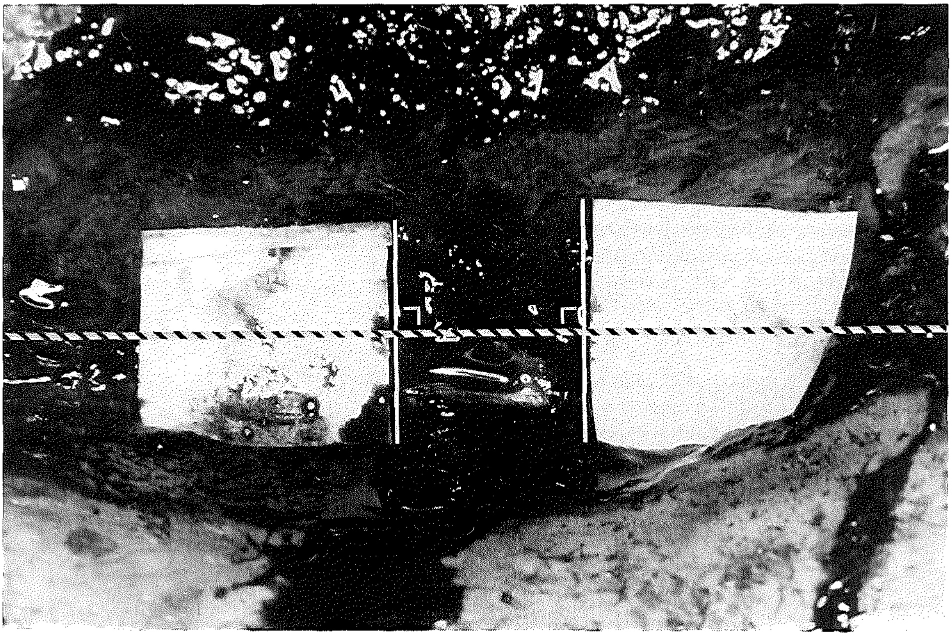


*Figure 5.9 Detail of the wound. The proximal and distal portions of the bone are covered with granulation tissue, to which square, white marks were applied. In rest no angulation was observed.*

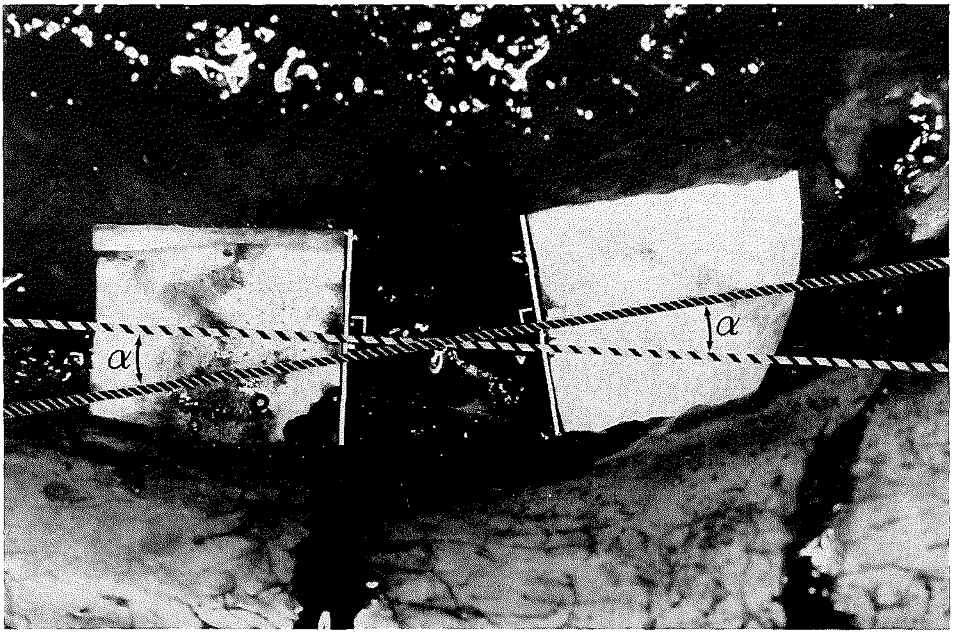


*Figure 5.10 When force was applied to the leg the fracture portions were displaced, in agreement with the data from the laboratory experiment. (Angle $\alpha$ = 11 degrees with a force of 130 N in a transverse direction (displacement around the parallel axis)).*

## 5.5 The weight and stability of femoral fixation frames

All the devices tested were weighed (together with their pins). The weights varied considerably (Table 5.16).

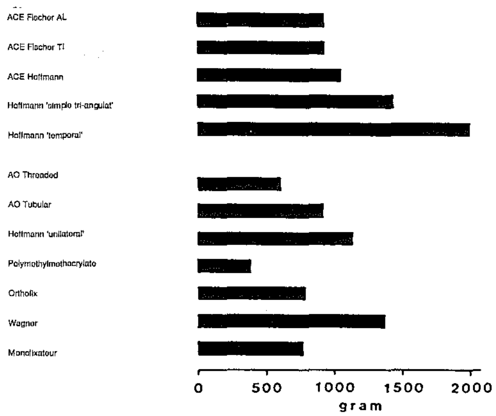


*Table 5.16 Weights of the external fixation frames tested, pins inclusive.*

A three dimensional frame weighs at least 1000 gram. Although the heaviest frame (Hoffmann femoral) weighing 2000 gram, scored the highest with regard to stability and the lightest frame (polymethylmethacrylate: 400 gram) appeared to be the least stable, no other relationship between weight and stability could be demonstrated. It was striking that when large parts (horseshoes) of the aluminum ACE Fisher frame were replaced by titanium ones, there was no difference in weight. Despite the new light weight aluminum parts for the Hoffmann simple triangular frame, its weight remained high (1500 gram).

Patients do not generally complain about the size and heaviness of a femoral frame. However, a compact and light weight frame is preferred because it allows easier access for wound care and personal hygiene and is easier to camouflage under the patient's clothing.

## 5.6 Conclusion

During clinical application, the Wagner apparatus gave rise to instability problems when it was used for external fixation of the femoral shaft. The experiment results show that despite its robust appearance, there is indeed instability. These were particularly expressed by the fact that it was difficult to fix the pins firmly into the clamp unit. Other fixators made of polymethylmethacrylate, whose successful applications have been reported in the literature, were unable to withstand the forces expected to be involved with femoral fixation and broke as a result.

The stability of external femur fixators, in this in vitro study at least, is a fairly elastic notion. The stress displacement relationships were in fact determined via frames which had been mounted by one researcher. It was discovered that assembly by another experienced researcher gave rise to slightly different results. Although this can give rise to small shifts in the rank order of stability of the various frames in relation to the operator, a distinction between stable and unstable will not be demonstrated in this way. There appear to be sufficient differences in stability between the various fixation devices.
Translations of 1 mm to 4 cm and rotations varying from practically 0 to 16 degrees were measured, assuming that the forces applied to an experimental bone model are in agreement with the situation in a femoral fracture (without bone contact) in an average patient.

Primary fracture consolidation is impossible at all locations using external fixation without bone contact and this also holds true for femoral fractures. For this purpose more stability is necessary than that offered by external femoral fixation.
The weight of the various fixation devices tested varied considerably (400 - 2000 gram). The three dimensional devices consisted of many separate (heavy) components and were therefore difficult to mount. The procedure was very time consuming. The chance of mistakes being made increases.
With the exception of the effect of transverse forces, a fairly small two dimensional (unilateral) frame is just as stable as a much larger and heavier three dimensional model.
The results of the in vitro investigation showed that the three-dimensional Hoffmann femoral frame and the two dimensional Orthofix, the AO tubular frame and the Monofixateur scored highest with regard to stability.
On account of its stability, quick and easy assembly and compact, light weight design, the Orthofix frame is our first choice in the clinical situation where a femoral shaft fracture needs to be treated using external fixation.

# C CLINICAL EXPERIENCE WITH EXTERNAL FIXATION OF THE FEMUR

## CHAPTER 6 introduction and case history

Although external fixation of the femur has become an increasingly popular form of treatment over the last few years, it is still fairly uncommon. On estimation, not many more than 150 patients have been treated in this way in the Netherlands over the last 10 years. In view of the rare nature of the indication and the heterogeneity of the patient material, retrospective research was not considered to be worthwhile. It has therefore been decided to illustrate our own clinical experience by means of representative patient material. The data are derived from a group of 40 trauma patients (treated from 1980 onwards) in whom the fracture or fractures of the femur were treated using external fixation.

In some cases external fixation was applied because other treatment methods had failed and in other patients, depending on the situation, it was the primary choice of treatment. It was firstly applied purely as a temporary measure and followed by other therapies (usually plate osteosynthesis). However, external fixation of the upper leg is becoming an increasingly well favoured method of achieving definitive consolidation.

### 6.1 Compound fractures

In the past, the Wagner apparatus was particularly popular. However, optimal repositioning was technically difficult and the immobilization proved to be unstable. As a result, a first degree compound fracture of the shaft of the femur,

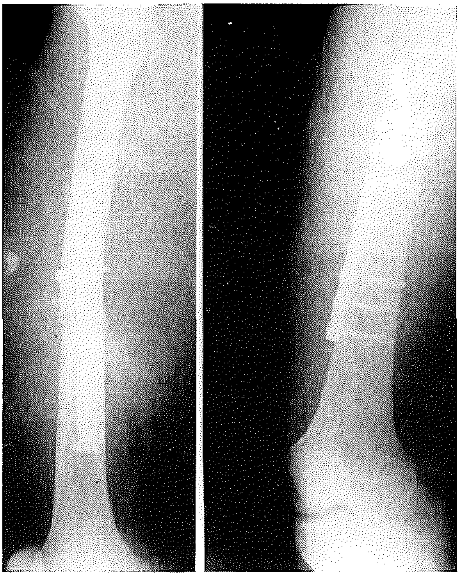


*Figure 6.1 Grade III compound femoral shaft fracture (subtotal upper leg amputation), stabilized using a 10 hole AO ASIF plate.*

which was treated using the Wagner apparatus, consolidated in a varus position (see fig. 5.2; page 55).
It is possible to achieve sufficient stability clinically using, for example, the Hoffmann femoral frame. Definitive repositioning during the operation can be postponed until the very last moment and adaptions can even be made after the frame has been mounted.

Patient A, a seaman, 38 years of age, suffered a subtotal right upper leg amputation, caused by a steel hawser. He sustained serious injuries of the soft tissue and a femoral shaft fracture. Reconstructive surgery was carried out, including restoration of the arterial and venous circulation by means of by pass grafts. After the wound debridement, fixation followed with a ten hole AO ASIF plate was applied to the fracture (fig 6.1).
Nine supplementary operations were necessary, in which revision of the vessel reconstructions and repeated debridement took place. It was possible to cover the wound almost completely using omental flaps and various skin transplants. However, the ultimate outcome was persistent plate infection with several fistulae on both the medial and lateral side, from which multiresistent bacteria were cultured. Post operative X-rays showed the presence of osteolysis around the screws, caused by osteitis, and the plate had become loose (Fig. 6.2).
External fixation was applied (Hoffmann femoral frame) four months after the accident, following sequestrectomy, removal of the plate and removal of infected, exposed umbilical vessel prosthesis (Fig. 6.3).

The patient was treated at the out patients department and the external fixation remained in situ for 11 months. He adapted well to the treatment, in spite of the large, heavy frame attached to his upper leg. He was able to hide the frame by wearing loosefitting clothing equipped with zip fasteners. The wounds in the soft tissue healed and the fracture consolidated. Bone grafting was considered, but did not turn out to be necessary (Fig. 6.4 and 6.5).
Although the patient had become permanently disabled, his leg remained usable. The articulatory capacity of his knee was nil. There were areas of hypoaesthesia on the lower leg. The sensibility of the sole of the foot was good. It was not possible for him to go back to sea.

## 6.2 Comminuted fractures

Sometimes patients (usually multi trauma patients) have such comminuted femur fractures that there are hardly any therapeutic possibilities. These serious comminutive fractures can be accompanied by serious soft tissue injuries.

Patient B, a male, 36 years of age, was involved in an accident on his motorcycle. He was admitted to hospital in shock because of loss of blood from a ruptured spleen. He also had plexus brachialis injury and various fractures, including a

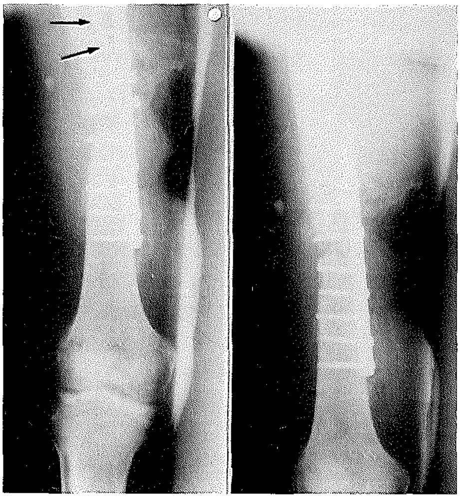


*Figure 6.2 Owing to infection the plate had become loose, four months posttrauma. No consolidation visible.*

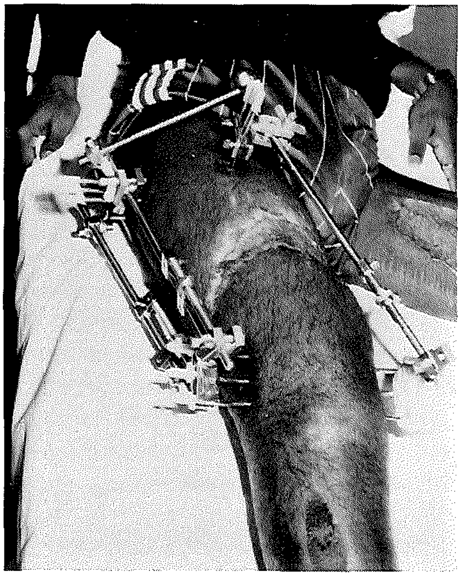


*Figure 6.3 Hoffmann femoral frame applied after removal of the plate.*

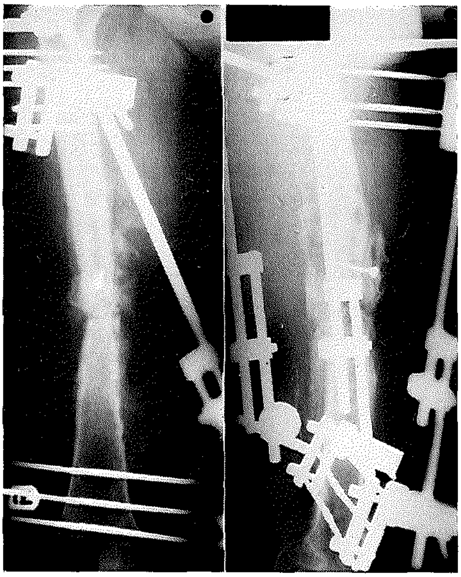


*Figure 6.4 The beginning of callus formation more than 6 months post trauma.*

*Figure 6.5 One and a half years post trauma, full consolidation. The leg was being fully burdened.*

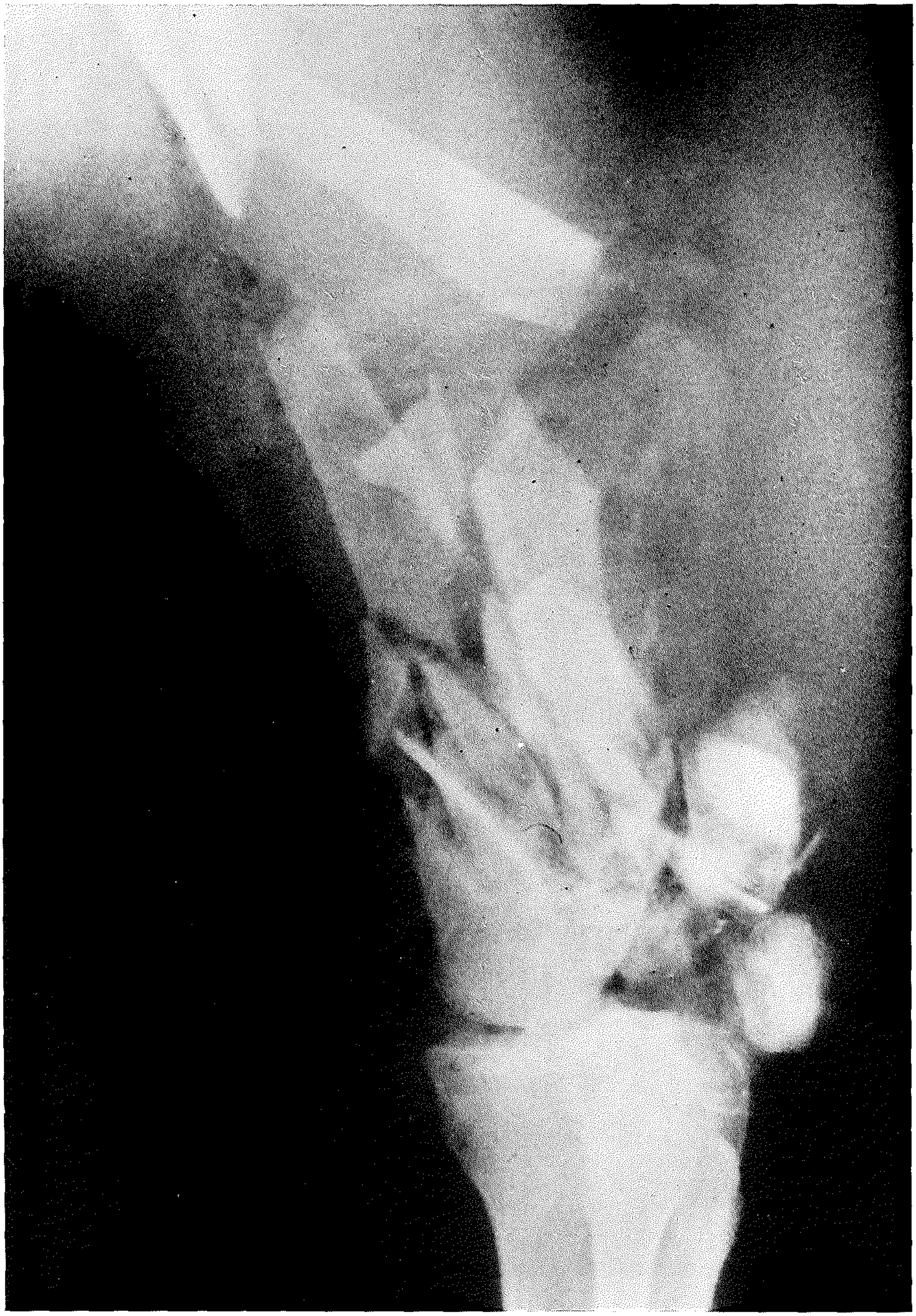


*Figure 6.6 Serious comminuted (and compound) femoral shaft fracture in a multitrauma patient, admitted in shock, because of loss of blood by a ruptured spleen.*

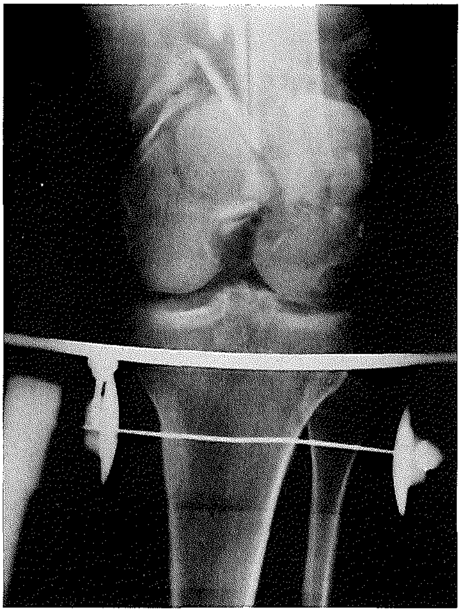


*Figure 6.7 Treatment via tuberositas tibiae wire traction, the condylar form of the femur is again recognizable.*

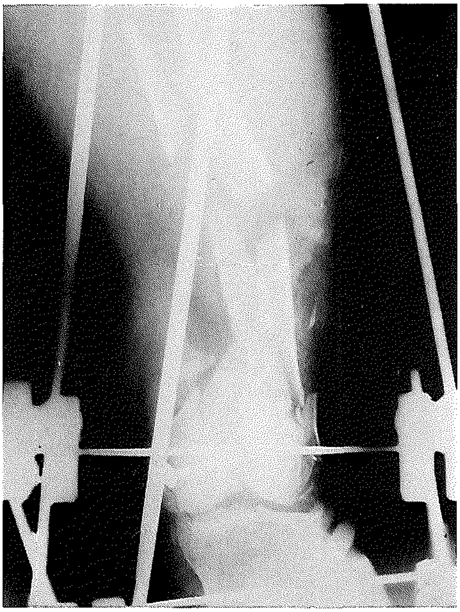


*Figure 6.8 Minimal internal osteosynthesis of the femoral condyles. Hoffmann frame built out over the knee.*

serious comminuted fracture of the left femur with extensive soft tissue injuries (Fig 6.6).
Following surgery for the ruptured spleen and extensive wound toilet, the fractured femur was initially treated via tuberosity wire traction (Fig. 6.7).

One week later, a Hoffmann frame was applied, over the knee joint. The femoral condyles were fixed with the aid of minimal screw osteosynthesis and the wounds were dressed with skin transplants (Fig 6.8).

During the postoperative phase, serious soft tissue infection arose with gram positive and gram negative bacteria, necessitating repeated necrotomies. Finally, the skin defect could be closed by means of skin transplants (Fig 6.9).

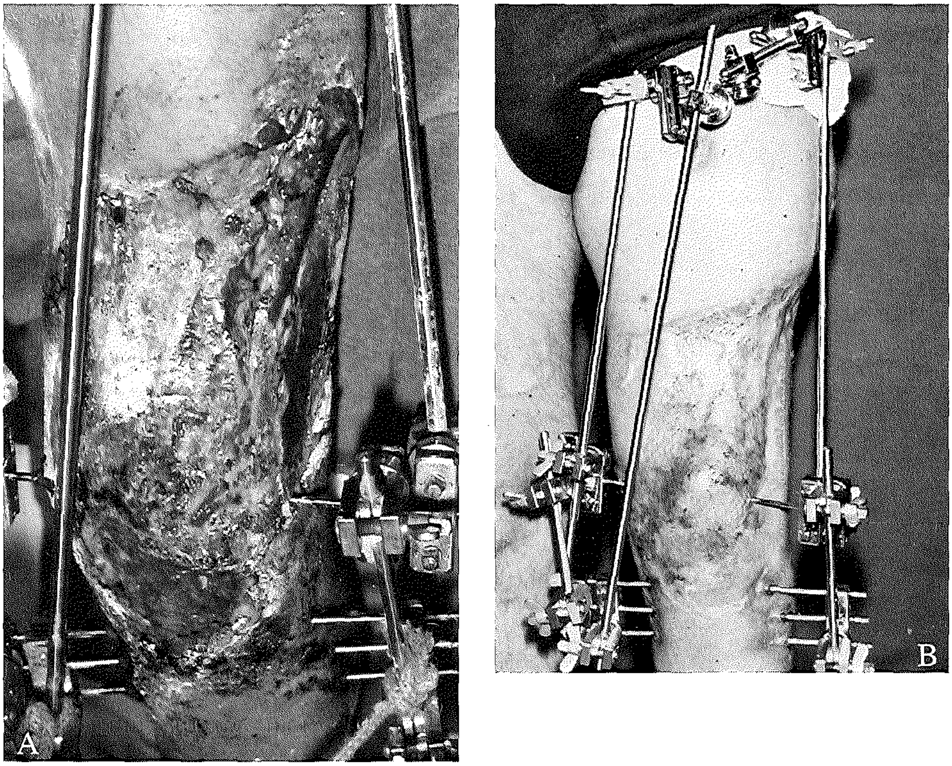


*Figure 6.9 Hoffmann frame built out over the knee.*
*A:Wound defect with granulation tissue*
*B:Wound area healed by means of skin transplants.*

In total, three bone grafting procedures were carried out and gentamycine beads were left in the wound. The patient was discharged from hospital after nine months. He was readmitted nineteen months after the accident for removal of the Hoffmann frame. A few weeks later he presented with a supracondylar refracture in the badly misformed bone (Fig. 6.10), after partial weight bearing.

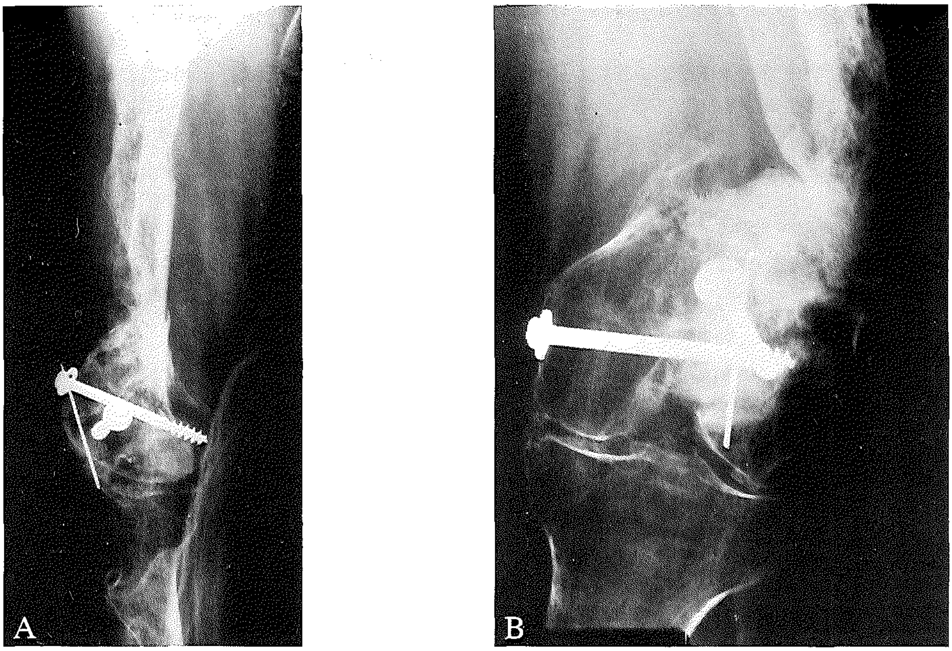


*Figure 6.10 Refracture occurred few weeks after removal of the Hoffmann frame.*
*A:Badly misformed, yet some amount of recovery of the continuity of the shaft is visible.*
*B:Detail of refracture. The patient withdrew from further treatment.*

Full of resentment, severely handicapped, with a paralysed arm and stiff knee, the patient refused to undergo new bone grafting procedures. As a result of severe neurological pain he had become addicted to morphine. All other forms of treatment except for plaster casts were refused. The patient withdrew from further treatment and became lost for follow up.

## 6.3 Fractures in combination with accompanying (brain) injuries

In (multi) trauma patients with serious accompanying (brain) injuries, there may be contraindications for lengthy surgical procedures. Nevertheless fractures must be adequately immobilized and long term nursing in traction is more or less impossible. Adequate osteosynthesis can be achieved with the aid of external fixation, even in cases with bilateral fractures (Fig. 6.11, patient C, female, 35 years old).

In this patient external fixation was the definitive choice of treatment. It was removed six months later after complete consolidation had taken place.

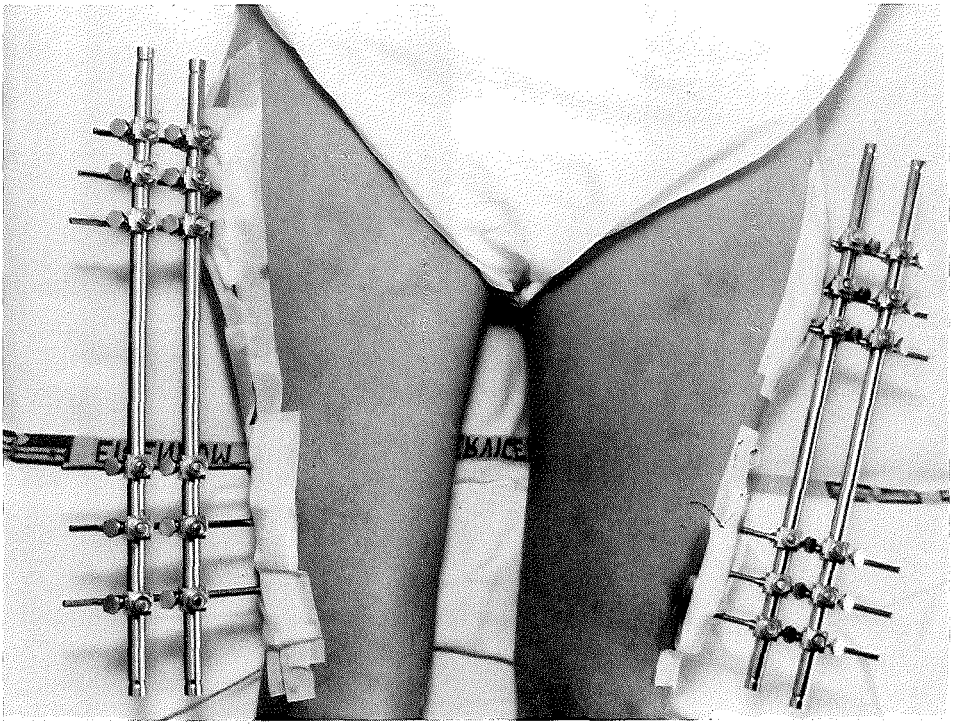
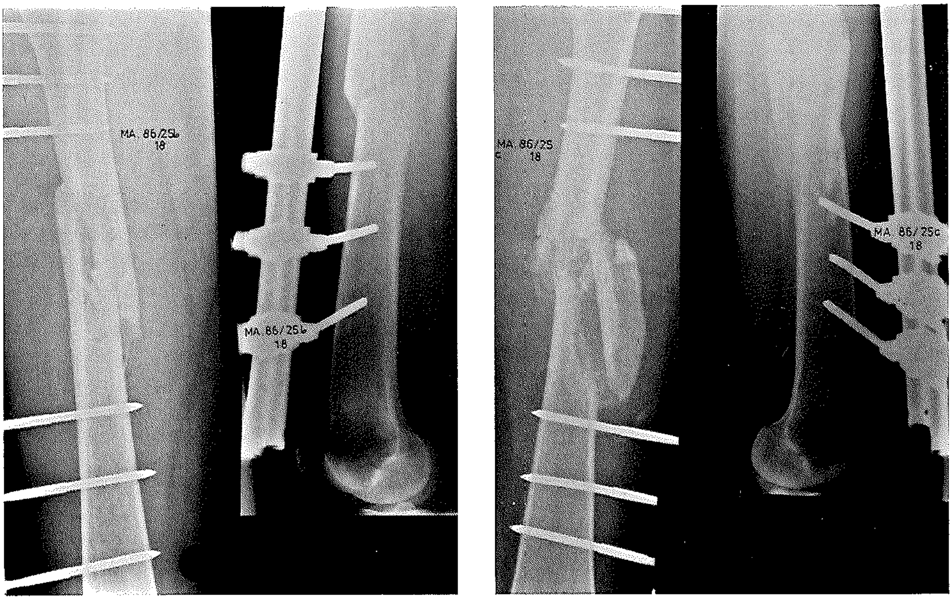


*Figure 6.11 Bilateral femoral shaft fracture in a patient with brain injury, in whom a lengthy surgical procedure was contraindicated*

*Figure 6.12* *X rays of the femoral shaft fractures (patient C).*
*A:right leg, on admission*
*B:left leg, on admission*
*C:right leg, 20 weeks post trauma*
*D:left leg, 20 weeks post trauma*
*E: right leg, 8 months post trauma*
*F: left leg, 8 months post trauma*



## 6.4 Alternatives to traction

In children particularly, traction is the treatment of choice for femoral shaft fractures. Proximal fractures of the femur can be difficult to treat with traction (as a result of the tendency of the proximal part to abduct) and consequently consolidate in a poor position. Long term traction is sometimes impossible owing to post traumatic spasticity and fits. Plate osteosynthesis forms an alternative in these cases. It is true that external fixation of the femur is rarely applied in children, but occasionally it proves to be a good solution (Fig 6.13, patient D, male, 12 years

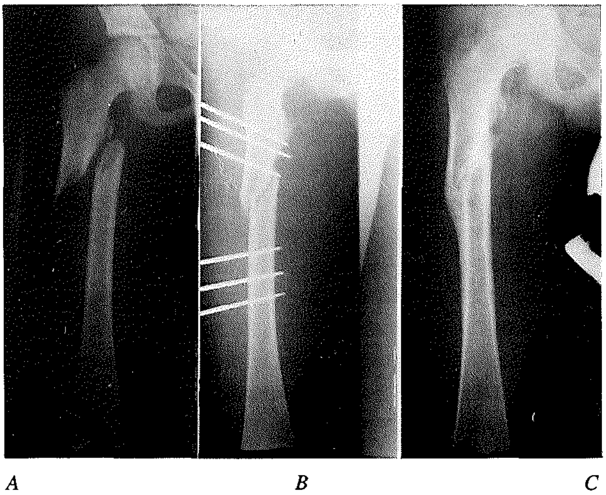


*Figure 6.13 Proximal fracture of the femoral shaft in a 12 year old boy, in whom it was not possible to achieve satisfactory repositioning using traction.*
*A:X-ray on admission*
*B:Fracture position after the application of a simple unilateral Hoffmann frame; patient could be discharged from hospital with the frame in situ (nonweightbearing) 2 weeks post trauma.*
*C: Follow up X-ray one year post-trauma, there was no apparent difference between the length of his right and left leg.*

old). A simply built frame is sufficient and the operation trauma is slight. Long term traction and long term hospitalization can be prevented in this way and the method promotes quick rehabilitation at home.

## 6.5 Pseudarthrosis

Internal osteosynthesis is not the treatment of choice in the case of infected pseudarthrosis. For this reason external fixation is the regular and preferred treatment method for this condition in the lower leg. Pseudarthrosis of the femur is seen less often, but can be treated in a similar way to the lower leg, i.e. by means of external fixation.

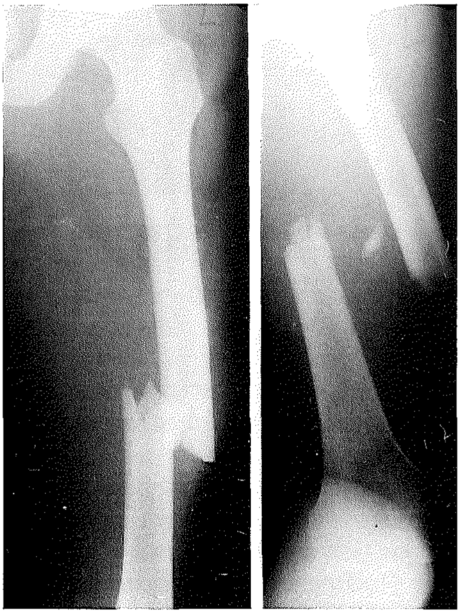


*Figure 6.14 Grade I compound fracture of the middle portion of the femoral shaft (left).*

Patient E (male, 20 years old) had an accident on his scrambling motorcycle and suffered a grade I compound fracture of the left femoral shaft (Fig. 6.14).
At that period (1980) internal osteosynthesis was only carried out after preceding wire traction for seven to ten days. Despite excision of the wound, an extensive abscess manifested itself in the wound on the third day post trauma (during continuous weight traction), in which staphyloccus, streptococcus and clostridium were present. This made it impossible to conduct internal osteosynthesis as planned, therefore a Hoffmann femoral frame was applied. After the infection had more or less cleared up one month posttrauma, the patient was discharged from hospital, walking without weightbearing on two crutches (Fig. 6.15).

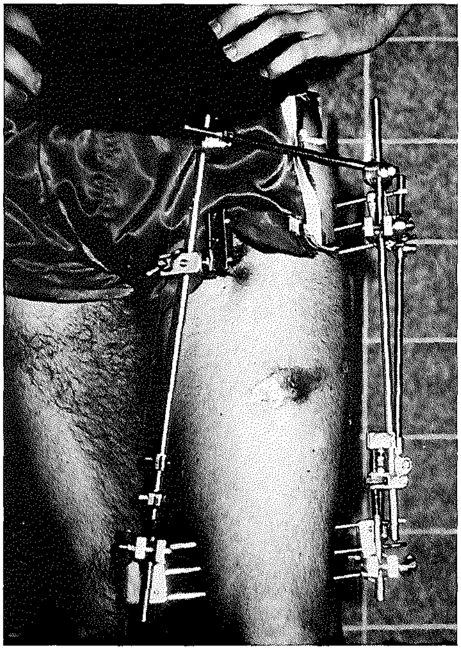


*Figure 6.15 Treatment using a Hoffmann femoral frame. The infected fracture of the femoral shaft did not show consolidation and a pseudarthrosis was formed.*

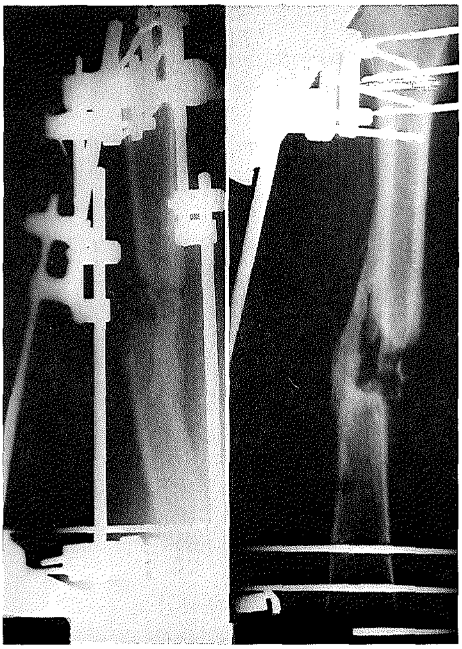


*Figure 6.16 Progressive osteolysis in the case of low grade infection.*

At follow up, persistent infection and fistula formation were observed. Osteolysis had occurred as a result of the chronic osteitis. A callusbridge had only developed on the medial side without further fracture healing (Fig 6.16).

After the infection had largely been arrested, (open) bone grafting was performed (nine months post trauma). A corticocancellous pelvic wedge was inserted and fixed using two screws. The presence of the Hoffmann femoral frame did not hinder the surgical procedure to any great extent. Thirteen months posttrauma, the infection had healed and the fracture had consolidated; the Hoffmann frame was removed. Although the patient was suffering from limited knee function at that time, partly due to intensive physiotherapy complete recovery followed (Fig. 6.17) and the fracture healed without any further problems (Fig 6.18).

A

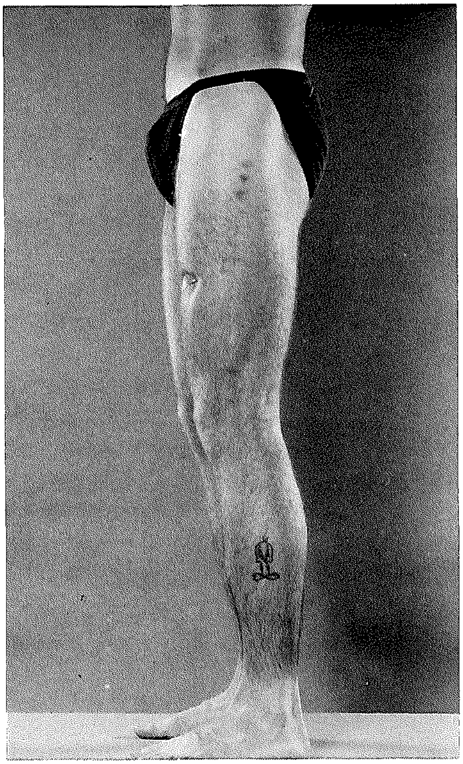
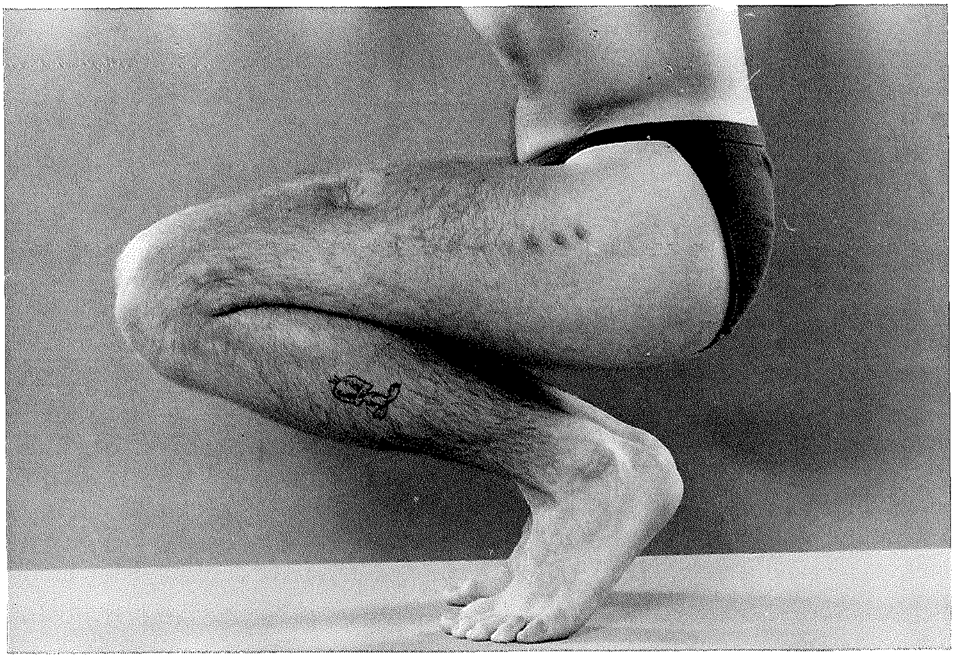


Figure 6.17 *There are equal knee movement left and right following external fixation of the femur for over 13 months.*
*A:extension*
*B:flexion*
*The patient is completely free from complaints and has resumed his sporting activities.*

B



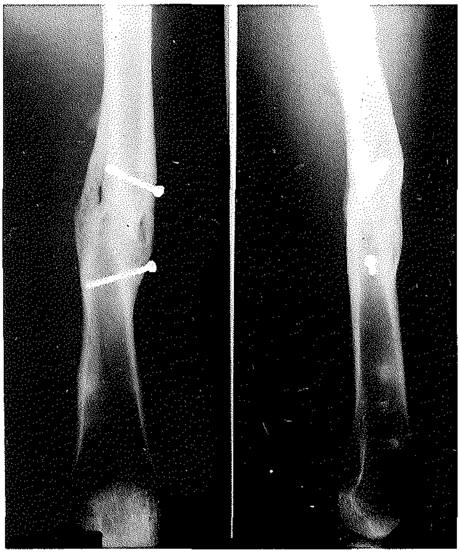


*Figure 6.18 Follow up X-ray 2 years post trauma, the bone graft and corticocancellous wedge have been incorporated.*

## 6.6 Conclusion

Our clinical experience has proved that in selected cases external fixation of the femur is a very satisfactory solution. Pintract infection does not form a clinical problem and can be prevented by means of good pin hygiene, a good implantation technique and a stable frame. The fact that the fixation pins interfere with the function of the knee appears to be a disadvantage but this need not necessarily lead to permanent problems if the patient receives good physiotherapy. Whereas in the past, we saw external fixation as a temporary solution to be followed by definitive plate or nail osteosynthesis, we now prefer to regard external fixation, applied directly after the trauma, as the ultimate treatment method. Thanks to new technical developments and the availability of compact, stable fixation apparatus which can be applied quickly, there is no longer any great hesitation to implement external fixation whenever necessary. Although internal osteosynthesis is the treatment of choice, external fixation does not cause patients much inconvenience, even if long term fixation is indicated.

The group of patients, in which we have so far gained experience, is too heterogeneous to allow us to draw definite conclusions. It is clear that in the difficult task of trying to achieve consolidation in patients with 'problem fractures', it is possible to achieve adequate fixation by means of external fixation. It therefore forms a valuable addition to the therapeutic arsenal and is a treatment method which should be kept in mind if other possibilities are doomed to failure or involve too many risks.

# CHAPTER 7

# FINAL CONCLUSION

## 7.1 Epidemiological research and review of the literature

In the Netherlands over 60% of closed femoral fractures and over 80% of compound femoral fractures are treated surgically. It is very seldom that external fixation is chosen as the primary treatment method (<1% in a series of 568 fractures (11). For most surgeons, external fixation of femoral fractures does not seem to be the treatment of choice and its application is usually limited to 'problem cases'.
Nevertheless, the clinical application of external fixation is already a century old. Many years ago, surgeons conducted their first experiments using fixation pins made of ivory and iron.
At the turn of the century it was particularly Lambotte and during the Second World War, Raoul Hoffmann, who developed external fixation for various indications. Since then it has become the generally accepted method of treating compound fractures of the tibia.

Serious compound fractures of the femur occur less frequently because the bone is covered by a considerable amount of protective soft tissue. In the past, many problems were associated with external fixation of the upper leg. These could always be traced back to the materials used (e.g. corrosion of iron pins) and particularly to the lack of stability.

The Wagner apparatus, developed for bone lengthening, has proved to be unsuitable for the treatment of fractures. Of all the fixation devices which have appeared during the last decades, the Orthofix is the only one which has been tested extensively, but only on a limited scale, for treating femoral fractures. The advantages and disadvantages involved with this system have become clearer from incidental data in the literature and through our own experience. The new types of fixation device give enough stability to bring about fracture consolidation without clinical complications. Thanks to these developments, it is now possible to offer fracture stabilization and functional treatment to a group of patients for whom adequate surgical treatment was previously lacking. Which external fixation device is the most suitable is a matter of personal experience.
Beside stability and easy mounting, other important factors such as simple, universal applicability, small volume and as little soft tissue damage as possible should be considered when choosing an external fixation device for a particular area of application.

## 7.2 Biomechanical research

Owing to progress in bio-engineering and research into the design and application of external fixation devices, interest in this field is increasing. It has become clear that external fixation can offer a solution to more clinical problems than compound fractures of the tibia alone.

If the sole intention is to tide over the period until the soft tissue wounds have healed, a simple frame is sufficient. Definitive fracture treatment can follow at a later date. However, if external fixation is chosen as the primary and definitive form of treatment, more demands must be made. The basic conditions which an external fixation device must fulfil have been ascertained by means of biomechanical research. Stable (but not excessively rigid (174)) fixation, in which compression is also possible, is the preferred technique. The application of axial strain to healing fractures, via external fixation, may increase the rate of consolidation (175). The positioning of the pins and the contact between the pins and the bone are very important. This transition point forms the weakest link in the application of external fixation to bone fragments.
Stable fixation reduces the chance that the pins will become loose and also the chance of pin tract infection. The incidence of chronic osteitis on the basis of pin tract infection varies, in the case of adequate frame mounting from 0-4%. Most infections respond well to simple curettage.
Stability is improved using thick pins placed as far apart as possible along the bone, in clamp units situated as close as possible to the skin. Placing short connection bars close to the clamp units prevents twisting. Two dimensional frames are generally less stable than three dimensional frames. However, the latter require the use of transfixation pins (163).

Under normal circumstances, a moment of about 125 Nm acts upon a healthy femur. The force necessary to fracture a femur is about 250 Nm. The immobilization method chosen for the treatment of a fracture, must be able to withstand all the stress which it is likely to be subjected to. Compared with the demands made on the femur in everyday life, the forces acting on the femur of a bedridden patient following trauma or during rehabilitation are smaller. These can be demonstrated by means of equations (Chapter 4), in which the osteosynthetic material, such as an external fixation device, must be able to withstand the expected burden without becoming distorted.

Fracture consolidation, particularly where the application of external fixation is concerned, is dependent on the degree of rigidity of the immobilization device (27). Although primary fracture consolidation is possible using external fixation apparatus, the callus formation resembles that of secondary consolidation. This indicates that the bone fragments are not fully immobilized. Primary consolidation can only take place if there is a gap of less than 5-10 micron between the fragments. The conditions which have to be fulfilled to produce secondary fracture consolidation have not been fully investigated. However, it is clear that the number of delayed unions and the incidence of pseudarthrosis decrease if a rigid external fixation device is applied (27). Slight axial strain appears to promote the union of fractures (58,59).

Insight into the application and stability of external fixation devices mainly originates from their use on fractures of the tibia. The forces which act upon the upper leg (and on the external fixation device in the case of fractures) are greater than those acting upon the lower leg.

Our biomechanical research (Chapter 5) has shown that primary consolidation of femoral fractures cannot be expected using any of the twelve external fixation devices tested. There was a large amount of difference in the rigidity of the various frames.
When transverse forces acted upon the least stable fixation devices, displacement of the bone fragments occurred in the experimental bone model, of 40 mm and 16° rotation (based on an average adult weighing 70 kg). Such movement even appears to be too great to allow secondary fracture healing in adults. If unstable external fixation devices are mounted on the femur, various clinical problems can be expected (pin tract infection, redislocation, rupture of the newly formed callus, delayed or absent consolidation). The more stable frames tested also allowed a small amount of movement of the bone fragments (translation 1 mm, rotation ±0°).

We have achieved good clinical results using the Hoffmann femoral, the Orthofix and the AO ASIF tubular frame. In our experimental research the stability score for those devices was fairly high. Instability problems were suspected with the Wagner frame and were confirmed in our experimental research.
In view of the fact that a simple unilateral frame is just as stable as a more complicated and bulky three dimensional frame (except under the influence of transverse forces), a small, simple, two dimensional external fixation device is, in our opinion, the preferred construction for the femur.

## 7.3 Results of clinical treatment

In Italy (Verona) the Orthofix external fixation device is considered to be the treatment of choice by De Bastiani and, as a result, internal osteosynthesis and traction techniques have been put aside. The results of (in the meantime) more than 100 patients are good (6). For closed and compound fractures, this treatment philosophy has also been adopted at some clinics in Germany and England.
The reason surgeons prefer external fixation is the small amount of surgical interference with negligible infection risk. By leaving the fracture haematoma intact and, if necessary, applying dynamization, secondary consolidation can very often be achieved.

The development and application of new external fixation devices has made these changes in treatment philosophy possible.
This also applies to the application of new internal osteosynthesis techniques.
An interlocking nail offers good stability and misses the disadvantages (devitalization, infection) which are involved with plate osteosynthesis. If it is possible to conduct internal osteosynthesis on the femur without complications, the general

opinion is that this is the preferred approach in femoral shaft fractures. It simplifies the rehabilitation period because it is possible to start functional follow up treatment at an early stage and, particularly in the case of an interlocking nail, the leg can be (partially) burdened early on in the rehabilitation process. Successful internal osteosynthesis offers advantages for the patient e.g. no long term bed rest, not having to wear a cumbersome external construction which requires intricate care and, depending on the position of the pins, may hinder remedial therapy (and other daily activities).

A modern external fixation device can form a suitable alternative if internal osteosynthesis or traction are impossible or contraindicated. Despite the fact that this method of approach involves patient selection (of the poorest patient material), who usually have serious accompanying injuries, the treatment results are, in our opinion good. It is still too early to make a more definitive statement: too few patients have so far been treated using this method.
The treatment results are such that it is worth considering external fixation of femoral fractures if other suitable forms of treatment are lacking. In this way the disadvantages become acceptable and the chance of complications arising is small. Our own experience with 40 patients is illustrated in Chapter 6 by means of a number of representative example cases.

Our study results show that external fixation is a suitable and safe method of treating femoral fractures. It has become an important addition to the arsenal of treatment methods.

# SUMMARY

The application of an external fixation device (an external splint construction consisting of pins drilled into the bone) is a generally accepted technique for treating compound fractures.
Owing to the development of new external fixators and an increase in biomechanical insights, the field of indication is no longer limited to compound fractures of the lower leg.
An external fixation device is seldom used on the upper leg, mainly due to the fear of complications, because fixation pins have to be inserted straight through the considerable mass of soft tissue on the upper leg.

For femoral fractures, preference is usually given to the application of stable internal osteosynthesis with an (interlocking) nail or plate, as soon as possible after the accident. Traction is the preferred technique for children. From reports in the literature and on the basis of our own clinical experience, external fixation also seems to be a good choice for the treatment of certain femoral shaft fractures.

There is little information available on the field of application of external fixation and experience with clinical application. Data from the literature has been collected in this thesis and supplemented by relevant case histories. In addition to an historical overview of the development of the treatment technique, a biomechanical study is presented, in which twelve representative femoral fixation devices have been tested and compared.

In **Chapter 1**, Dutch epidemiological data on the number of femoral shaft fractures and their treatment are shown (period 1983 1985). The development of external fixation in general and its application on the femur in particular is also discussed. Failures at the end of last century can mainly be attributed to problems with the material and insufficient stability. Nevertheless, at that time, developments were commenced which have led to the fixation devices presently available. From the rather limited experience world-wide during the last 100 years and particularly over the last 10 years, it appears that external fixation is a good choice of treatment in selected cases, for example, for compound fractures, serious comminuted fractures, if lengthy surgical procedures are contraindicated, in multitrauma patients and as a possible alternative for traction and various other indications, such as leg lengthening procedures, arthrodeses and pseudarthrosis.

In **Chapter 2** the differences between primary and secondary fracture healing have been summarized. Primary fracture healing can only be achieved with an optimally stable fixation frame, which exerts axial compression on the fracture fragments.Secondary healing is the usual result (and objective!) of external fixation. If an external fixator does not immobilize the bone fragments sufficiently, complications arise and fracture consolidation will not take place.
In contrast to internal osteosynthesis, the fracture haematoma remains intact (with

closed fractures) if external fixation is applied and the blood circulation is not hampered. Good vascularization is of importance in promoting the healing process of the fracture and soft tissue.

In **Chapter 3** the anatomy of the upper leg is described in relation to the consequences of mounting external fixation devices. The femur has been divided into four segments in order to indicate in which area(s) transfixation is possible. Although the chance of complications is small, occasional problems have been mentioned, particularly concerning the a. femoralis superficialis.

In **Chapter 4** equations have been formulated which give a clearer understanding of the forces acting upon the femur. These forces must be mainly intercepted by the osteosynthesis material in the case of femoral fractures.
Biomechanical research has shown that if specific pinning and frame constructions are used, the stability of external fixators can be improved and complications avoided.

In **Chapter 5** a biomechanical study is presented in which twelve different external fixation devices, applied to the femur, have been tested and compared by means of laboratory experiments.
The frames show widely differing degrees of stability. The most unstable frame allowed 40 mm of displacement of the fracture fragments and 16° of rotation under the influence of transverse forces. But even with the more stable frames (displacement of the bone fragments 1 mm, rotation ± 0°) it was not possible to achieve a completely rigid construction. A simple unilateral (twodimensional) frame appears to be just as strong as a threedimensional transfixation frame, except under the influence of transverse stress. The most stable constructions were achieved using a three dimensional Hoffmann frame and the unilateral Orthofix, the tubular AO ASIF system and the Monofixateur.
The stability experiments were conducted with the aid of a "bone model", made of perspex. As a control, some of the experiments were repeated on human cadaver femur. These data were consistent with those obtained on a patient (under general anaesthetic), on whom part of the experiment was repeated.

In **Chapter 6** representative case histories have been incorporated with data from the literature. The patients were treated at theZuiderziekenhuis in Rotterdam and the Academic Medical Centre (AMC) in Amsterdam, the Netherlands.
Patient records have shown that fracture consolidation can be achieved even under difficult circumstances. Major complications do not arise during the use of external fixation on the femur.
In **Chapter 7** the final conclusions are given. For a selected group of patients with femoral fractures, external fixation is a good alternative treatment. The stability of a simple unilateral femoral fixator is equal to that of a complicated three dimensional transfixation frame, except under the influence of transverse forces. Owing to the fact that the extent of immobilization necessary for femoral fractures to heal

is unknown, it is not possible to state which of the fixators is 'the best'.

The most rigid external fixation device is not necessarily the best fixator with regard to the speed and quality of fracture healing.

Nevertheless, stability is important. Thanks to good immobilization of the fracture fragments, the surrounding soft tissue injuries can heal. The resorption of loose bone fragments is particularly stimulated by instability and by bacterial contamination. The probability of pins becoming loose and pin tract infection increases if an unstable external fixator is used.

# SAMENVATTING

De toepassing van een externe fixateur (een met pennen in het bot geboorde, uitwendige spalkende constructie) is een geaccepteerde behandelingsmethode voor gecompliceerde fracturen. Doordat nieuwe externe fixateur typen zijn ontworpen en het biomechanisch inzicht is toegenomen is het indicatiegebied niet meer beperkt tot open fracturen van het onderbeen.
Op het bovenbeen wordt zelden of nooit van een externe fixateur gebruik gemaakt. Vooral uit angst voor complicaties, omdat fixateurpennen dwars door de omvangrijke weke delen massa van het bovenbeen moeten worden aangebracht.

Bij femurfracturen wordt meestal de voorkeur gegeven aan een stabiele interne osteosynthese met (grendel)pen of plaat, zo spoedig mogelijk na het ongeval. Bij kinderen wordt bij voorkeur tractiebehandeling verkozen. Uit literatuuronderzoek en uit eigen klinische resultaten blijkt echter dat ook een externe fixateur bij de behandeling van femurschachtfracturen een goede therapie keuze kan zijn.

Over indicatiegebieden en ervaringen bij klinische toepassing, is weinig informatie beschikbaar. In dit proefschrift zijn de literatuurgegevens verzameld en met patienten voorbeelden aangevuld. Behalve een historisch overzicht over de ontwikkeling van deze behandelingsmethode wordt een biomechanisch onderzoek gepresenteerd waarbij de stabiliteit van 12 representatieve femurfixateurs is vergeleken.

In **hoofdstuk 1** worden epidemiologische gegevens over het aantal femurfracturen en de behandeling ervan in Nederland vermeld (periode 1983-1985). Tevens wordt de ontwikkeling van de externe fixatie in het algemeen en vooral indien toegepast op het femur beschreven. Mislukkingen aan het eind van de vorige eeuw moeten worden toegeschreven aan materiaalproblemen en onvoldoende stabiliteit. Toch is toen de ontwikkeling in gang gezet naar de fixateur systemen die ons nu ter beschikking staan. Uit de nog beperkte ervaring die in de gehele wereld met deze behandelingsmethode op het femur in de laatste 100 jaar, en vooral in de laatste 10 jaar is opgedaan, blijkt dat het in geselecteerde gevallen een goede therapie keuze kan zijn. Bij gecompliceerde fracturen, ernstige comminutieve fracturen en indien bij een multi-trauma patient langdurige operaties onmogelijk zijn. Ook als alternatief voor tractie en indicaties zoals beenverlenging, arthrodese en pseudarthrose behandeling.

In **hoofdstuk 2** worden verschillen tussen primaire en secundaire fractuurgenezing opgesomd. Primaire fractuurgenezing is alleen bij toepassing van een optimaal stabiel fixateurframe, waarmee fractuurdelen onder compressie kunnen worden gebracht, bereikbaar. Met externe fixatie wordt meestal secundaire fractuurgenezing verkregen (en nagestreefd!). Indien met een externe fixateur onvoldoende immobilisatie van fractuurdelen wordt verkregen kunnen complicaties ontstaan en blijft fractuurconsolidatie achterwege.

In tegenstelling tot interne osteosynthese blijft bij het gebruik van een externe fixateur (bij gesloten fracturen) het fractuurhaematoom intact en wordt de doorbloeding niet verstoord. Een goede vascularisatie is van belang, het bevordert de genezing van de fractuur en de weke delen.

In **hoofdstuk 3** wordt inzicht gegeven in de anatomie van het bovenbeen en in de consequenties die het aanbrengen van een externe fixateur kan hebben. Door het bovenbeen in vier segmenten te verdelen wordt aangegeven in welk deel het gebruik van transfixerende pennen mogelijk is.
Alhoewel de kans op complicaties klein is, worden incidentele problemen vermeld die zijn beschreven, vooral van de a. femoralis superficialis.

In **hoofdstuk 4** zijn rekenvoorbeelden uitgewerkt, die inzicht geven in de krachten die op het femur inwerken. Deze krachten moeten bij een gefractureerd femur grotendeels door osteosynthese materiaal worden opgevangen.
Biomechanisch onderzoek heeft geleerd dat door specifieke penplaatsing en frameopbouw van externe fixateurs de stabiliteit kan worden bevorderd en complicaties kunnen worden voorkomen.

In **hoofdstuk 5** wordt een biomechanisch onderzoek gepresenteerd waarbij 12 verschillende externe fixateurs, toegepast op het femur, in een experimentele opstelling zijn onderzocht.
De stabiliteit van de diverse frames vertoonde grote verschillen. Het meest instabiele frame liet bij inwerking van dwarse krachten een verplaatsing van de fractuurdelen zien van 40 mm en 16°. Maar ook bij de meer stabiele frames (verplaatsing fractuurdelen 1 mm, rotatie ± 0°) was een volledig rigide fixatie niet mogelijk. Een eenvoudige unilaterale (tweedimensionale) opbouw blijkt net zo sterk als een (driedimensionaal) transfixie frame, uitgezonderd bij dwars inwerkende krachten. De beste stabiliteit werd verkregen met een driedimensionaal Hoffmann frame en de unilaterale Orthofix, het tubulaire AO ASIF systeem en de Monofixateur.
Het stabiliteitsonderzoek werd verricht met behulp van een "bot"- model, gemaakt van perspex. Ter controle werd een deel van het onderzoek herhaald met menselijk kadaverfemur. Deze gegevens komen overeen met de metingen die werden verkregen bij een patiënt, waarbij (onder narcose) een onderdeel van het onderzoek werd herhaald.

In **hoofdstuk 6** worden representatieve patientenvoorbeelden getoond. Deze zijn afkomstig van in het Rotterdamse Zuiderziekenhuis en in het Academisch Medisch Centrum (AMC) te Amsterdam behandelde patienten.
Er blijkt uit dat onder moeilijke omstandigheden toch fractuurconsolidatie kan worden verkregen. Belangrijke complicaties komen bij het gebruik van een externe fixateur op het femur niet voor.

In **hoofdstuk 7** wordt op de eindconclusies van het onderzoek ingegaan.
Voor een geselecteerde groep patienten met fracturen van het femur is een externe fixateur een goed behandelings alternatief. De stabiliteit van een eenvoudige unilaterale femurfixateur is, uitgezonderd bij krachten die dwars inwerken, gelijkwaardig aan die van een ingewikkeld drie dimensionaal transfixie frame. Omdat niet bekend is welke mate van beweeglijkheid voor de genezing van een femurschachtfractuur optimaal is, is een uitspraak over de "beste" fixateur moeilijk wanneer alleen stabiliteit wordt vergeleken.
De meest rigide externe fixateur behoeft niet noodzakelijk de, voor snelheid en kwaliteit van de fractuurgenezing, beste fixateur te zijn. Een snelle, eenvoudige (bij voorkeur unilaterale) montage en axiale dynamiserings mogelijkheid lijkt minstens zo belangrijk.
Maar stabiliteit is wel van invloed. Dankzij goede immobilisatie van fractuurdelen kunnen de omringende weke delen genezen. De resorptie van losse botfragmenten wordt vooral door instabiliteit (en bacteriële contaminatie) bevorderd. Ook de kans op penloslating en infectie van pengaten neemt toe als van een instabiele externe fixateur gebruik gemaakt wordt.

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## CURRICULUM VITAE

The author of this thesis was born in Schiedam, the Netherlands in 1949. After completing secondary school education (Dutch High School), he studied medicine at the Faculty of Medicine of the Erasmus University Rotterdam, where he graduated in 1976. Following the general practitioner's training, he specialized in surgery (1978-1984) at the Zuiderziekenhuis Rotterdam (Head: Dr G.A.A. Olthuis), where he remained as general surgeon (senior consultant) until 1986. He then became a staff member at the Department of Surgery of the Academic Medical Centre (AMC) Amsterdam (Head: Prof. Dr. M.N. van der Heyde), with traumatology as his special area of interest.

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