Biomechanical Principles

2

Leonid Nikolaevich Solomin

The biomechanics of external fixation consist of three inter-related aspects: (1) the relationship between the transosseous elements (wires, half-pins) and the surrounding tissues; (2) the control of bone fragment position; (3) the control of bone fragment rigidity. These are discussed in the following sections.

2.1 Relationship Between the Transosseous Elements and the Surrounding Tissues

Clinical implementation of the knowledge describing the biomechanical inter-relationships of the transosseous elements and the surrounding tissue enables the bone fragments to be forcibly fixed in such as way as to reduce device destabilization occurring because of bone resorption around the wires and half-pins as well as the risk of pin-induced joint stiffness and inflammatory complications (pin-tract infections).

To ensure the formation of an adequate bone–metal block after insertion of the wires, while taking care to reduce the risk of bone burn, it is necessary to use wires with special shapes, i.e., those with feather (bayonet-wires), single-facet, or drill cutting ends (Fig. 2.1). The feather-type cutting end partially "breaks" the canal whereas the single-facet cutting end enables the formation of a canal corresponding to the wire diameter. In addition, interrupted drilling is important at the maximal rotation rate of 850 revolutions per minute, as is cooling of the wire with alcohol and regulating (up to 20 N) the axial pressure exerted upon the wire.

Fig. 2.1 Variant forms of the cutting end of the wires: (**a**) three-facet, (**b**) feather, (**c**) single-facet, (**d**) drill

The biomechanical principles for the insertion of the half-pins also have their peculiarities. Half-pins for insertion into the diaphysis and metaphysis should be inserted with respect to the cortical and spongy thread. Prior to insertion of a half-pin into diaphyseal bone, a canal is formed with a diameter corresponding to the half-pin size, taking into account the density of the bone tissue. The canal diameter is 2.7 mm for a 4-mm half-pin; 3.8 mm for a 5-mm half-pin; and 4.8 mm for a 6-mm half-pin. In osteoporosis, the canal diameter must be reduced by 0.1–0.2 mm. Insertion of the half-pin through both cortical plates, in the projection of the mid-diaphyseal line is mandatory (Chap. 7). Experiments have confirmed the advantages of a thrust thread over a triangular thread [2].

The biological compatibility of the transosseous elements can be improved by forming a biologically inert (metal–ceramic) and biologically active (calcium phosphate) covering on their surface, which may solve the problem of

L.N. Solomin, M.D., Ph.D.
R.R. Vreden Russian Research Institute of Traumatology and Orthopedics, 8 Baykova Str.,
St. Petersburg 195427, Russia
e-mail: solomin.leonid@gmail.com

L.N. Solomin (ed.), *The Basic Principles of External Skeletal Fixation Using the Ilizarov and Other Devices*,
DOI 10.1007/978-88-470-2619-3_2, © Springer-Verlag Italia 2008, 2012

providing stable fixation of the implant in the bone [2–5]. The use of transosseous elements covered with hydroxyapatite promotes optimal transosseous synthesis in osteoporosis [6, 7] (Fig. 2.2). Hence, the approach to developing and creating transosseous elements for a particular orthopedic pathology should be recognized.

It is well known that soft tissues are displaced relative to the bone during joint movement. Transosseous elements fix the skin, fascia, and muscles to the bone, thereby limiting the physiological mobility of the soft tissues. The effect of inserting the wires and half-pins of an external fixation device can be compared to the creation of many local myofasciodeses. Thus, one should consider the contractures occurring as a consequence of using an external fixation device; these are referred to as "transfixation pin-induced joint stiffness" and in the Russian literature as "transfixion contracture." This phenomenon plays an important role in the development of soft-tissue inflammation due to the chronic trauma produced by transosseous elements.

There are two main ways to prevent pin-induced joint stiffness. The first involves the creation of a "store" of soft tissue by rendering in the extremity corresponding positions for insertion of the transosseous elements through the "flexor" and "extensor" surfaces of the segment (Fig. 2.3a). The second involves insertion of transosseous elements where there is minimum soft-tissue displacement for all possible movements of the joints adjacent to the segment (Fig. 2.3b). These positions serve as the basis for establishing the so-called reference positions (RPs) for insertion of the transosseous elements. These are discussed in Chap. 5 and a description of the method for establishing the RPs is presented in Chap. 35.

Fig. 2.2 Hydroxyapatite-coated half-pins

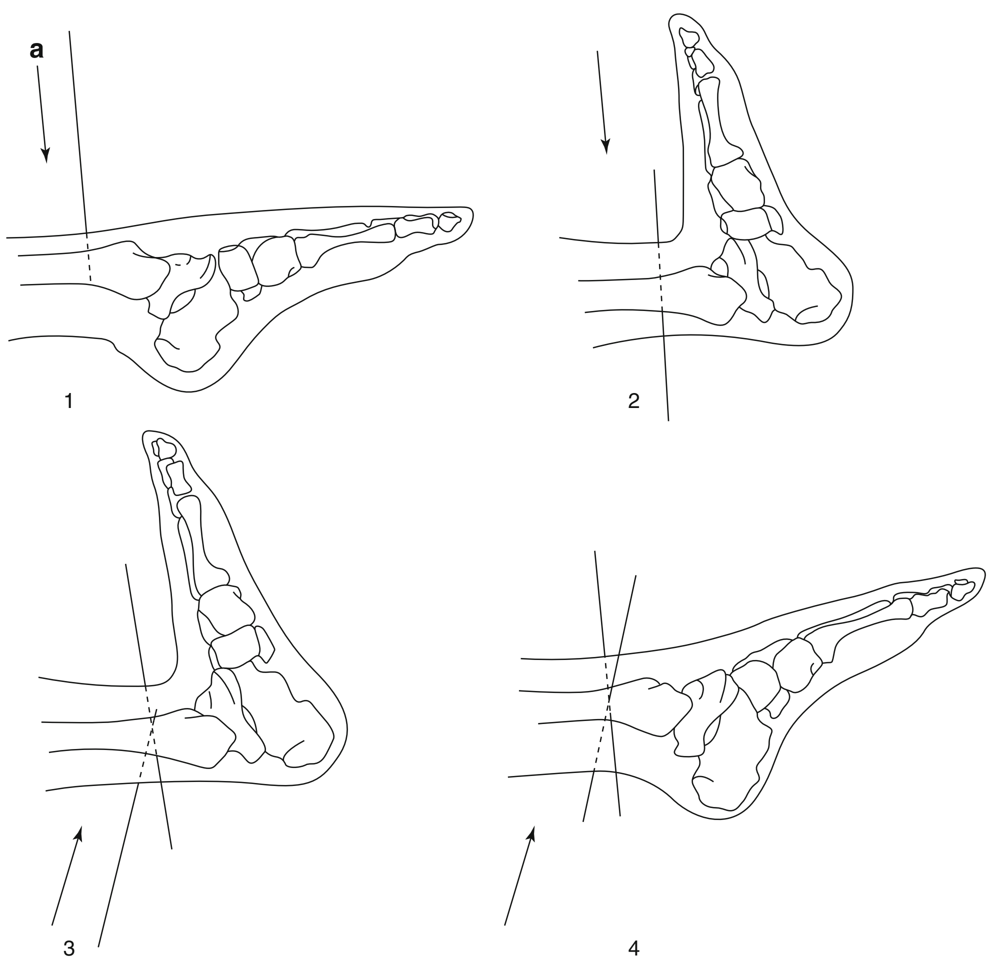


Fig. 2.3 Methods to prevent transfixation pin-induced joint stiffness: (**a**) change of position of an adjacent segment at wire insertion

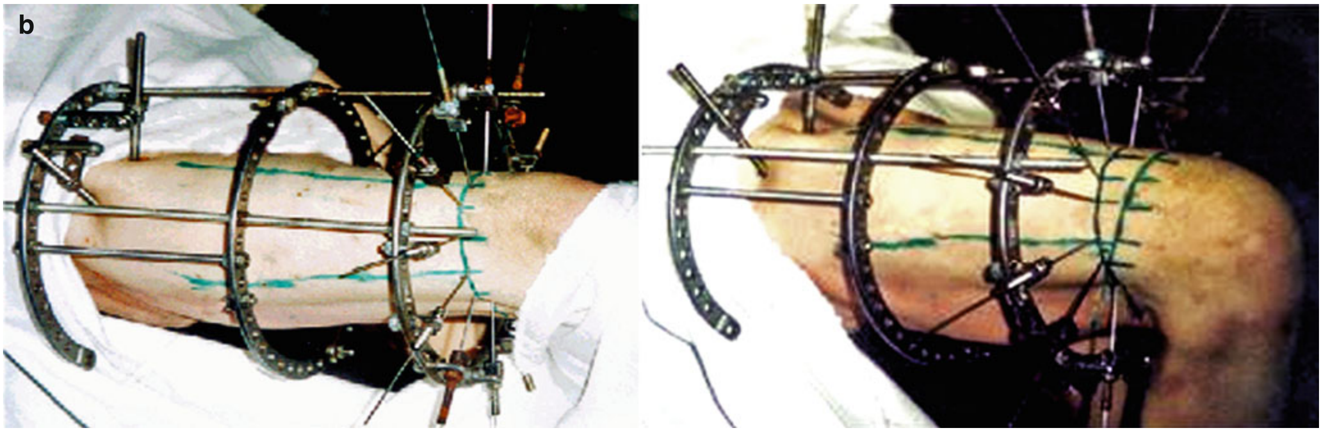


Fig. 2.3 (continued) (**b**) use of positions with the minimal soft-tissue displacement (here shown as an experiment on a cadaver). The control support is located at level VII. Feelers are positioned on the skin surface in each of 12 positions. As shown, after knee-joint flexion, skin displacement is absent in the projection of position 8

2.2 Control of Bone Fragment Position

To ideally control the bone fragment position, the external fixation device should allow directed movement of the fragments within the three-plane space (six standard degrees of freedom) both in a single step and stepwise over time. Changes in the spatial location of the bone fragments can be achieved in two ways. The first involves mutually moving the external supports fixing each bone fragment; the transosseous elements are statically fixed in the supports. The movement of transosseous modules with respect to each another can be carried out either by the use of unified reduction nodes ("Ilizarov hinges") or according to the principles of the Stewart platform and its analogues (Ortho-SUV Frame, Taylor Spatial Frame). The second consists of moving the transosseous elements that fix the bone fragments while the external supports and device modules remain immobile. In practice, the two repositioning methods (moving the external supports or moving the transosseous elements) complement each other. We consider each variant in more detail in the following sections.

2.2.1 Moving the External Supports with the Transosseous Modules Fixing the Bone Fragments

The various aspects of this method are illustrated in Figs. 2.4, 2.5, 2.6, 2.7, 2.8, and 2.9.

For *transverse movement (translation)* of the bone fragments, the two most commonly used methods are: (1) establishing the connective half-pins at an angle, considering that fragment displacement and distraction occur simultaneously in the transverse plane (Fig. 2.5a, b); (2) assembly of a uniform node (Fig. 2.5c, d).

2.2.2 Moving the Transosseous Elements Relative to the External Supports; External Supports and Modules Remain Immobile

These methods are illustrated in Figs. 2.10, 2.11, 2.12, 2.13, 2.14, 2.15, 2.16, and 2.17.

Since the early 1990s, computer navigation for the repositioning of bone fragments has been actively developed. The majority of investigations involve so-called passive navigation: i.e., identifying the optimal assemblage of external fixation devices for fragment transference with the aid of special software [8, 13, 14]. A particular focus has been software for producing optimal device assembly and for the correction of congenital and acquired deformities of the long bones [9, 15, 16].

A recent step in passive computer navigation was the development of devices for external fixation that are completely integrated with the software, i.e., the Taylor Spatial Frame (TSF), Ortho-SUV Frame, and Ilizarov hexapod system (Fig. 1.2p–r). For instance, in the TSF, 23 parameters identified radiographically and by measurements of several parameters of the frame are transformed into concrete recommendations by the computer program: i.e., the change in the length of each of the six struts necessary to achieve the required orientation of the bone fragments is identified and defined [17–21]. In this context, the work of Glozman et al. [22] on simplifying the processing of radiographic images to generate the necessary data for input to the computer is particularly important. The advantages of the use of Ortho-SUV Frame hardware and software are discussed in Chap. 17.

Transitional methods leading to active navigation include electromechanical devices temporarily attached to the device to enable repositioning of the fragments under fluoroscopy

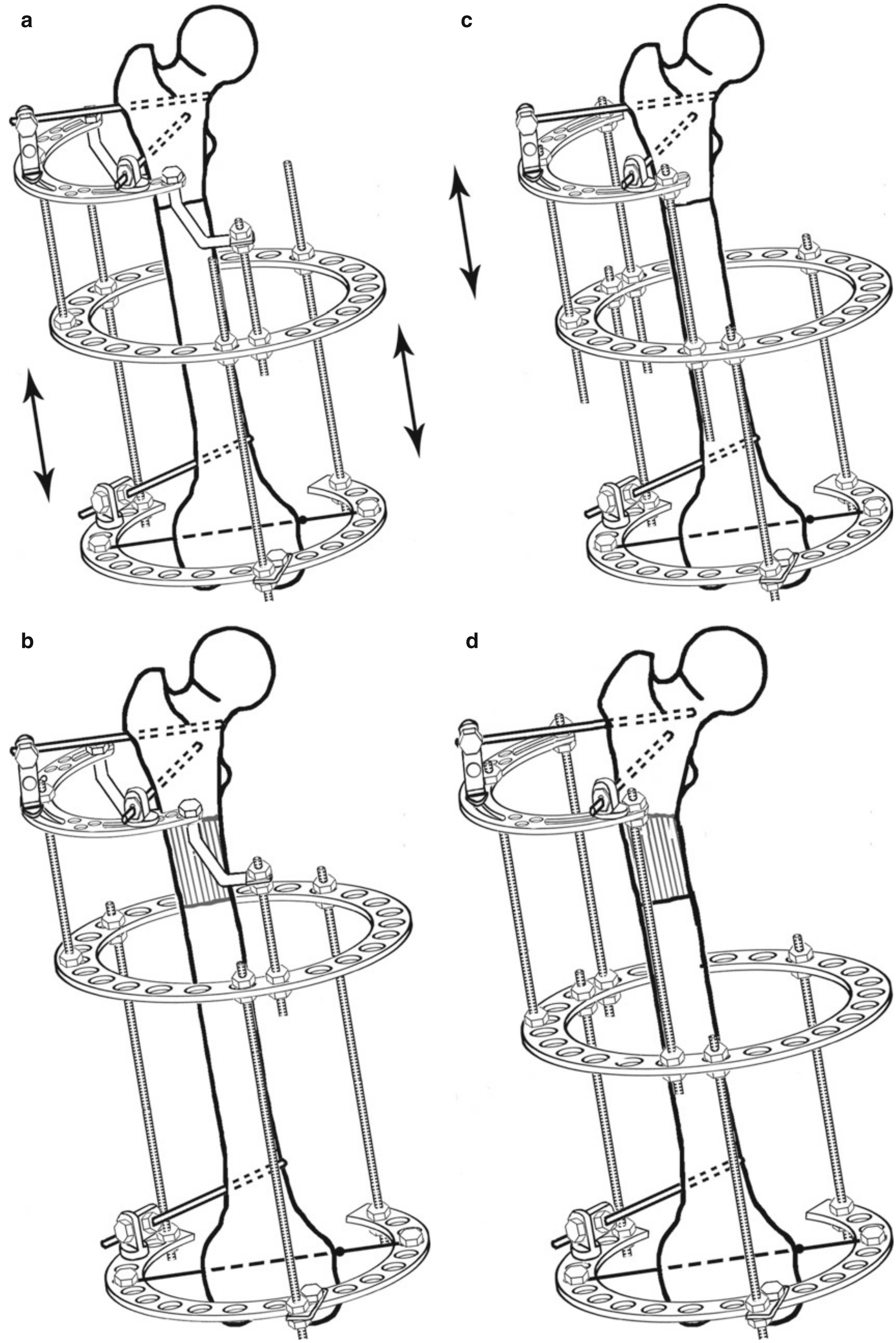


Fig. 2.4 In longitudinal transference (lightening), in order to avoid angular deformation due to an eccentric effect (eccentric distension or compression), the transosseous modules fixing the bone fragments must be connected with rods situated bilaterally relative to the bone and in the same plane. The use of circular and semicircular devices in which the half-pins connecting the modules are located in two planes encircling the bone is a more reliable way to avoid angular deformation. Therefore, in hybrid devices, establishing an additional support for distraction is recommended. The individual locations of the connecting half-pins enable special calculations to be used [8]. In the diagrams, rational (or efficient) (**a**, **b**) and irrational (or inefficient) (**c**, **d**) methods of distraction using hybrid devices are illustrated

guidance [23] and devices for automatic distraction [24–27]. Active navigation, which will undoubtedly become increasingly important in the near future, involves a complex of modules that automatically determines the spatial localization of the bone fragments, creates the necessary trajectory for their movement, and performs this movement. The work of the surgeon involves superimposition of the modules onto each bone fragment, approval of the trajectory created by the machine for fragment transference and, after the automatic repositioning step, assembly of the transosseous modules into an external fixation device to perform the internal fixation [28].

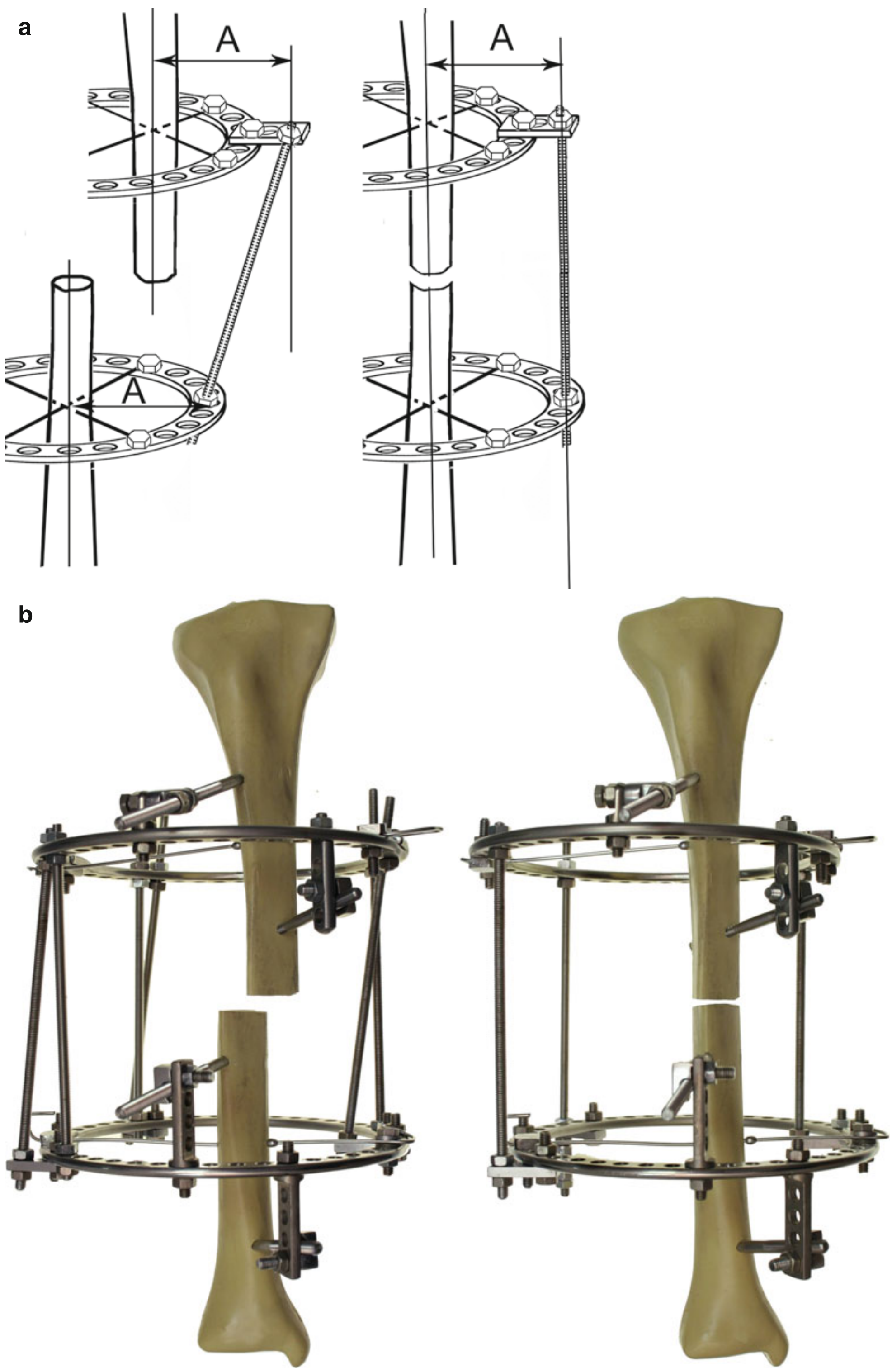


Fig. 2.5 Approaches to the elimination of transverse fragment displacement (**a**, **c** from [9])

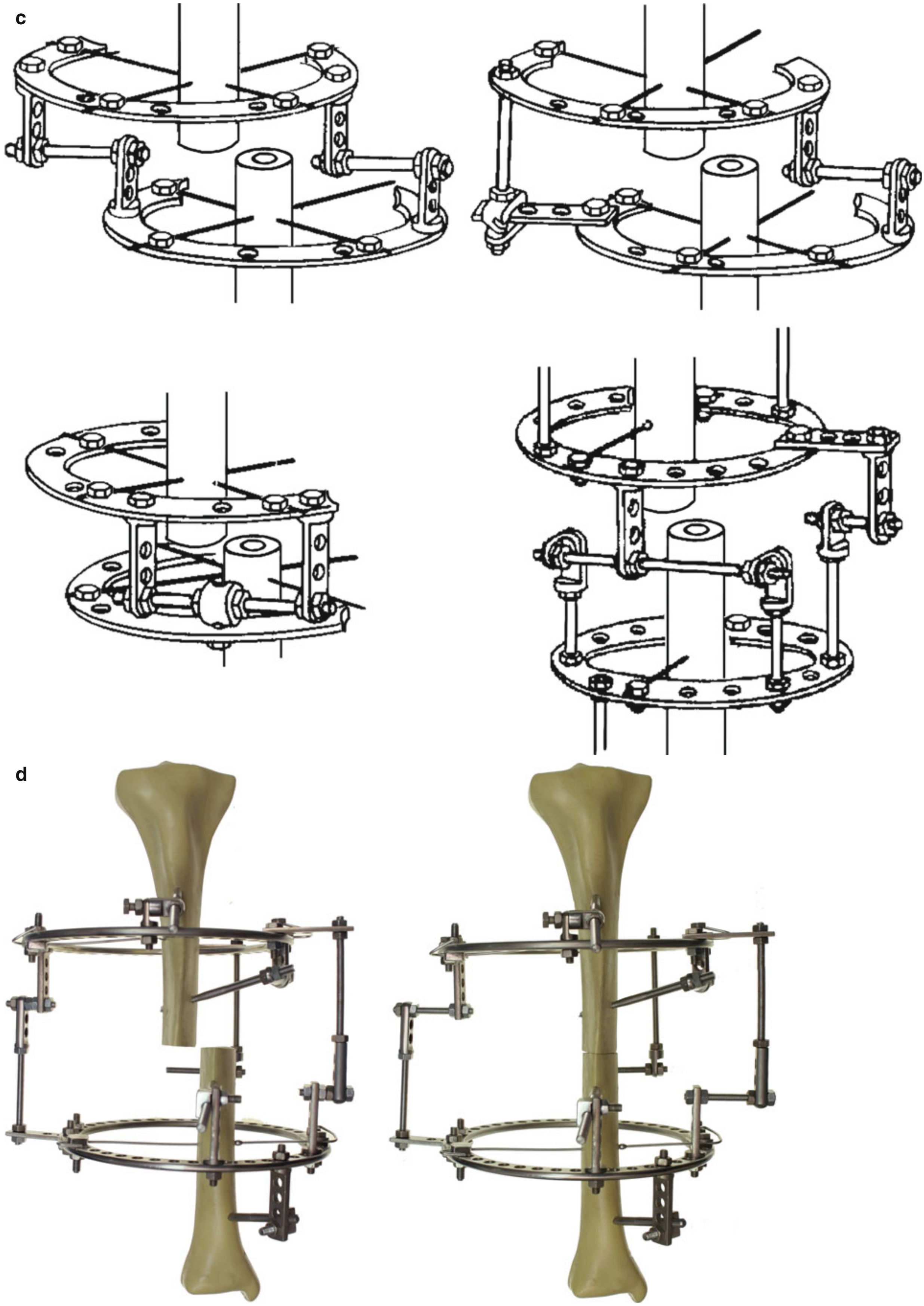


Fig. 2.5 (continued)

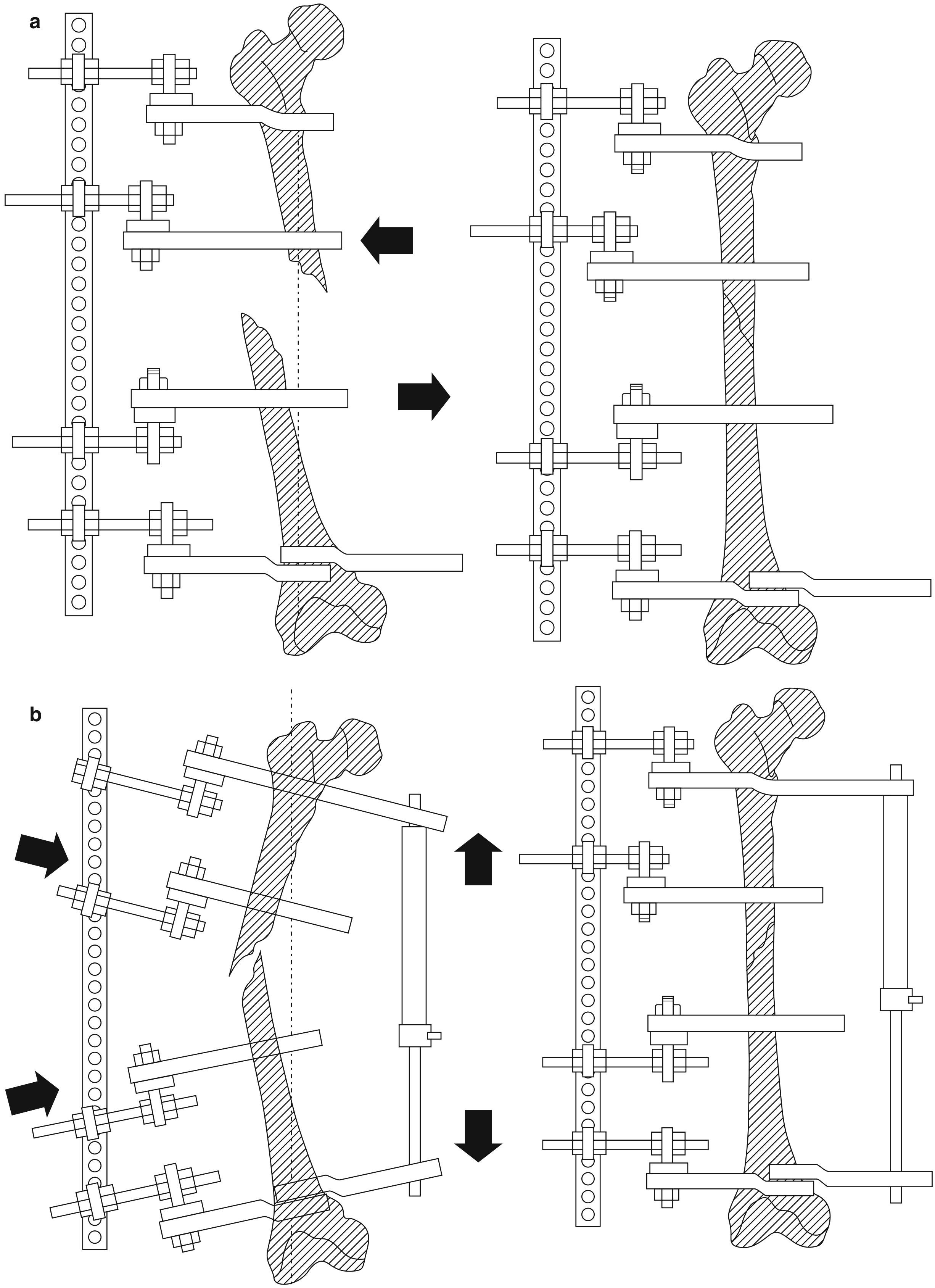


Fig. 2.6 In the combination of transverse fragment displacement with angular deformation, the reductionally fixing supports are transferred using trailing bars (From [10])

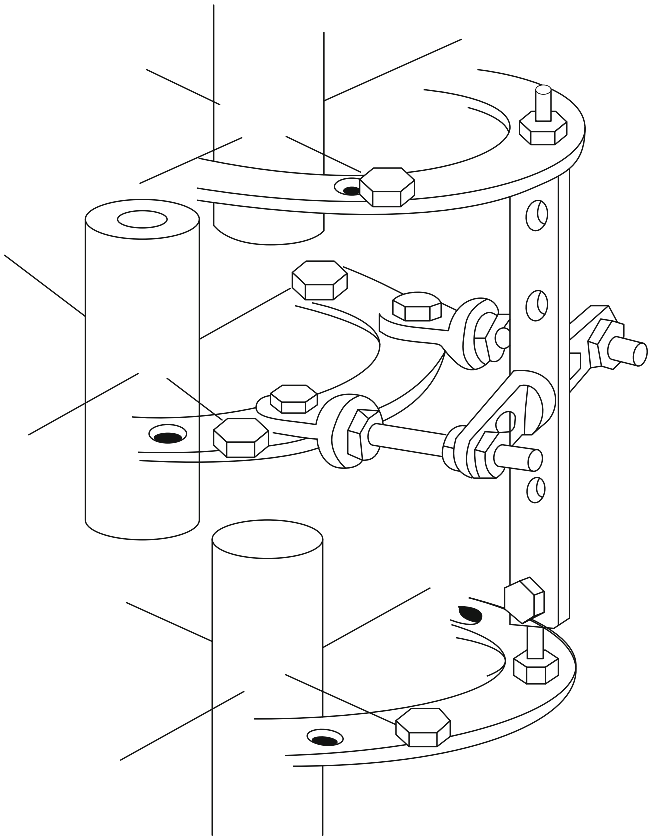


Fig. 2.7 Intermediate fragment reduction

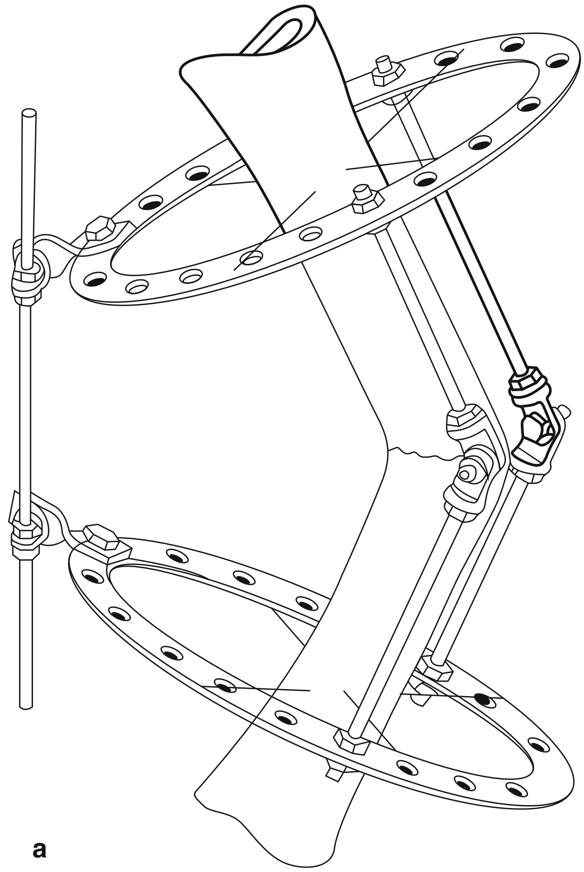


Fig. 2.8 (**a**, **b**) In the correction of angular deformation, transosseous modules fixing the bone fragments are connected with a hinge subsystem. For further details on Ilizarov hinges, see Chap. 16

Fig. 2.8 (continued)

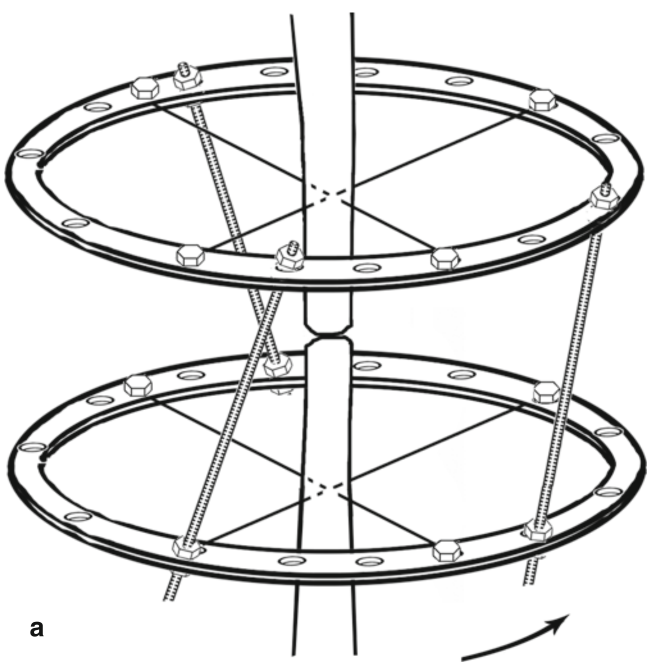
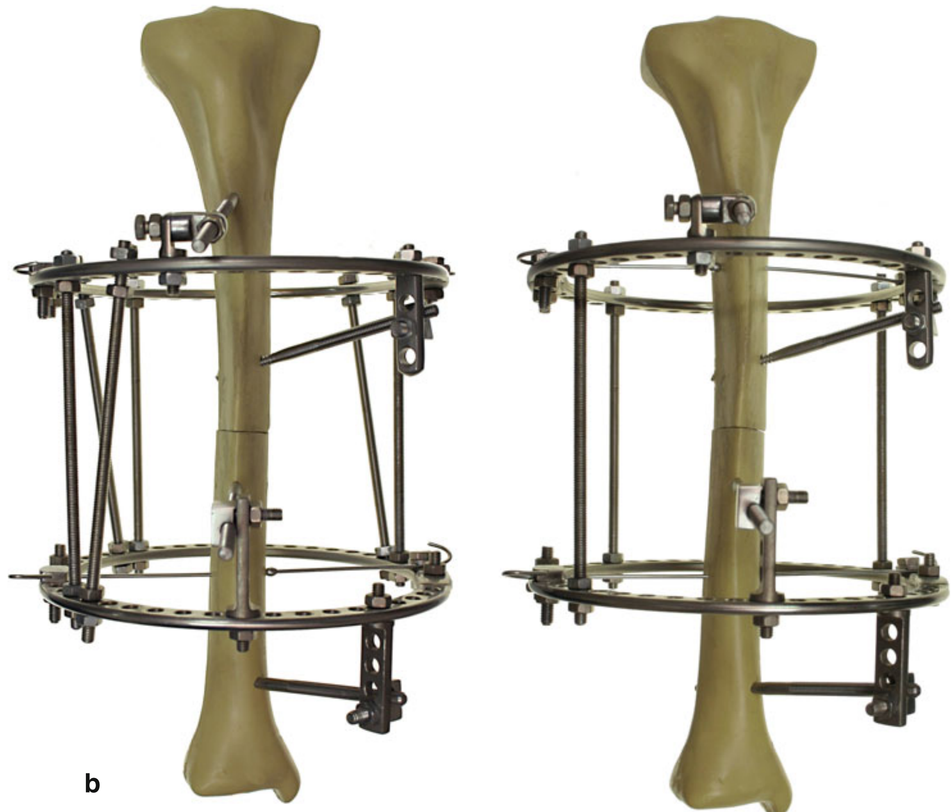
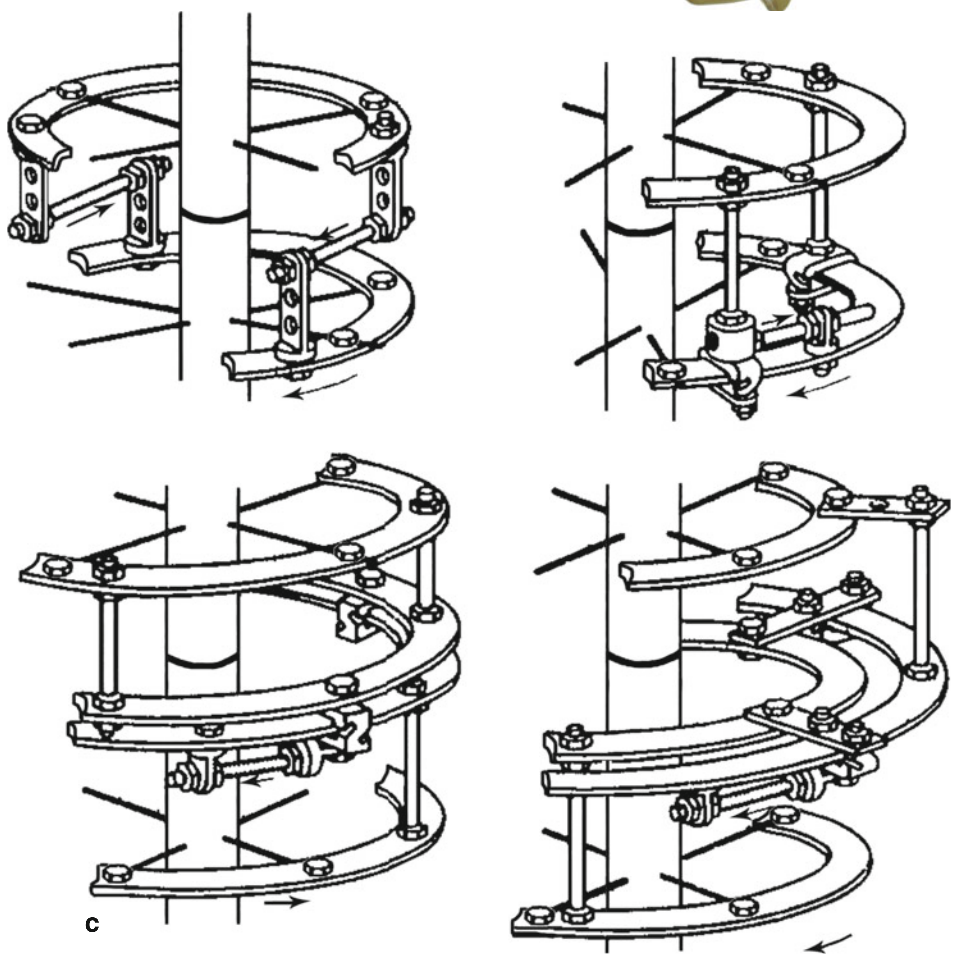


Fig. 2.9 The rotational transference (torsion) of fragments is achieved with the aid of a sloped arrangement of the connective half-pins (**a**, **b**) or using assemblies of uniform derotation nodes (**c**, **d**). Additional information is given in Chap. 16

Fig. 2.9 (continued)



b



c

Fig. 2.9 (continued)

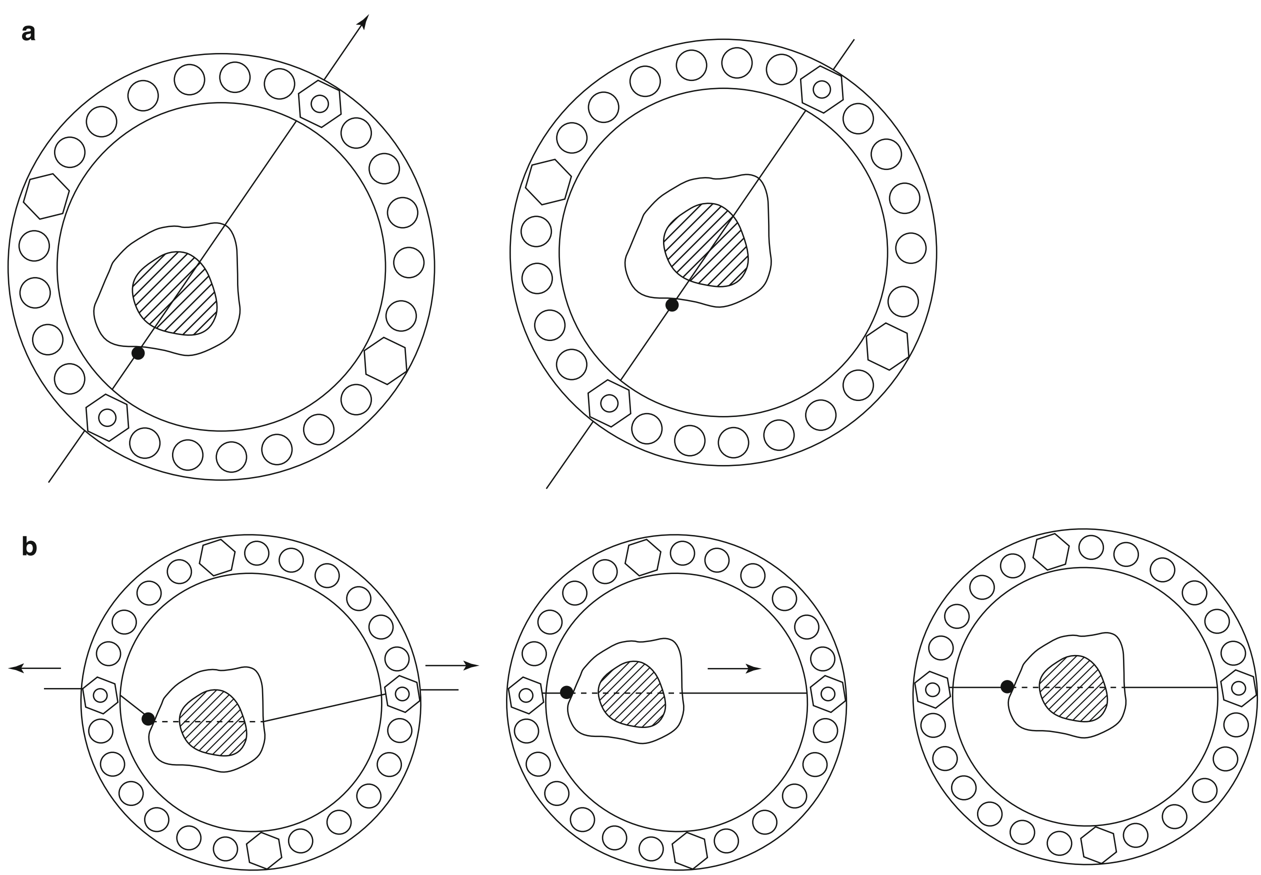


Fig. 2.10 The use of bent wires and/or wires with stops is a classic approach in external fixation and, owing to its high efficacy, the one that is most often used for repositioning in fractures (**a**). To achieve maximum proficiency in the method of external fixation, wires inserted for repositioning in the frontal plane should be used (**b**). For traction, both wire pullers and traction clamps are recommended. These simplify repositioning and facilitate maintenance of the wire pull in the postoperative period

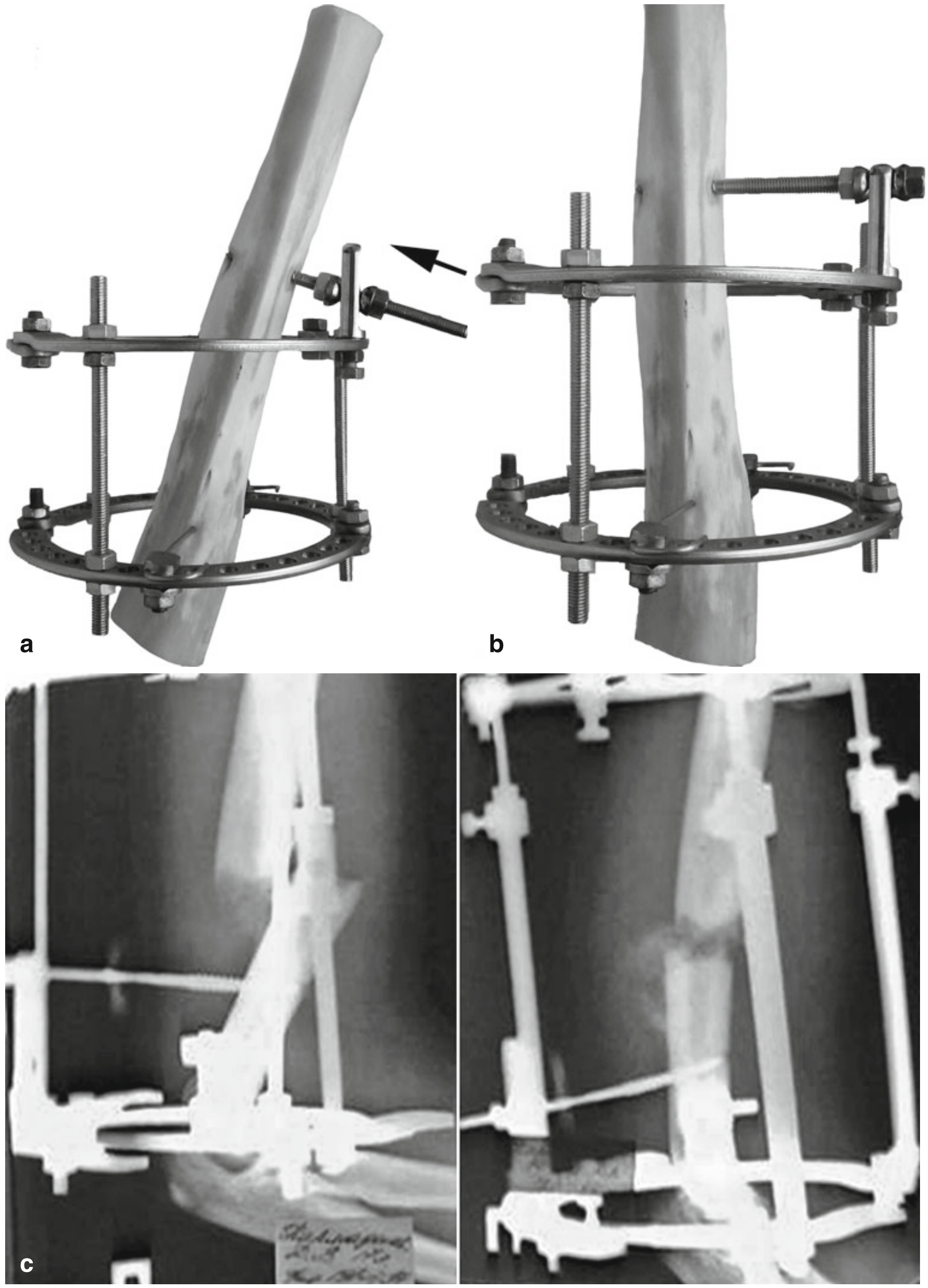
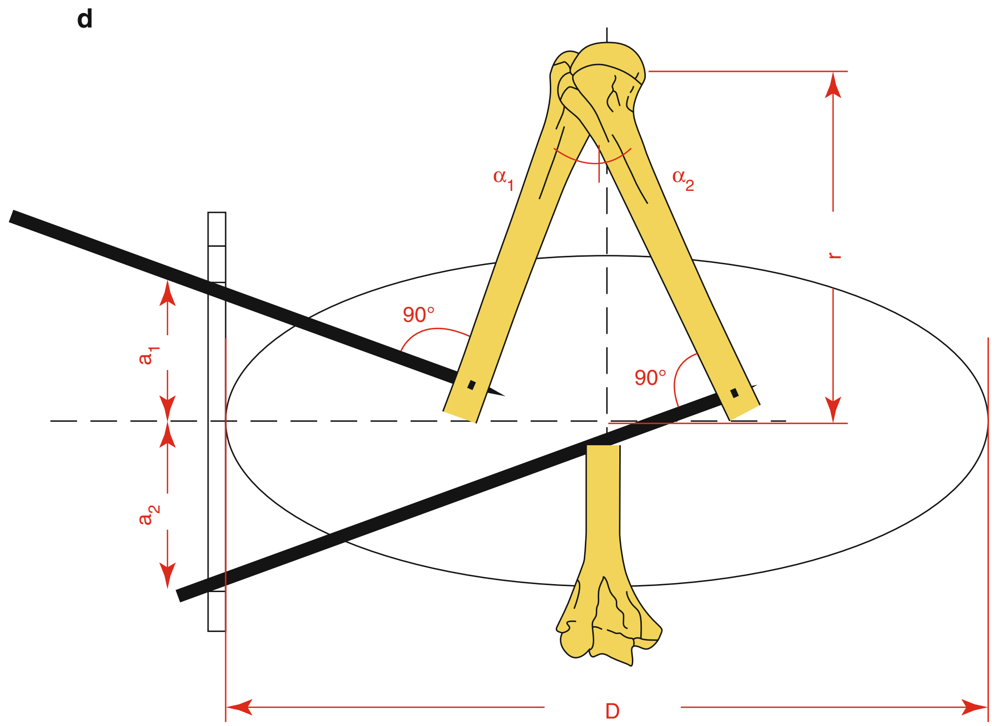


Fig. 2.11 (**a–c**) To eliminate transverse displacement of a fragment, a half-pin can be used as the "pusher" or "puller." Note that the female posts must have a longitudinal slit (see Table 1.2) and the nuts must be complemented with hemispherical washers. Moving the half-pin in the slotted post during reduction avoids its Z-shaped deformation

Fig. 2.11 (continued) (**d**) Movement calculation scheme for a half-pin bone fragment



$a_1 = (0.5D\text{-}r\ \mathrm{Sin}\alpha_1)\ \mathrm{tg}\alpha_1 + r\ (1+\mathrm{Cos}\alpha_1)$

$a_2 = 0.5D\ \mathrm{tg}\alpha_2 + r\ (1/\mathrm{Cos}\alpha_2 - 1)$

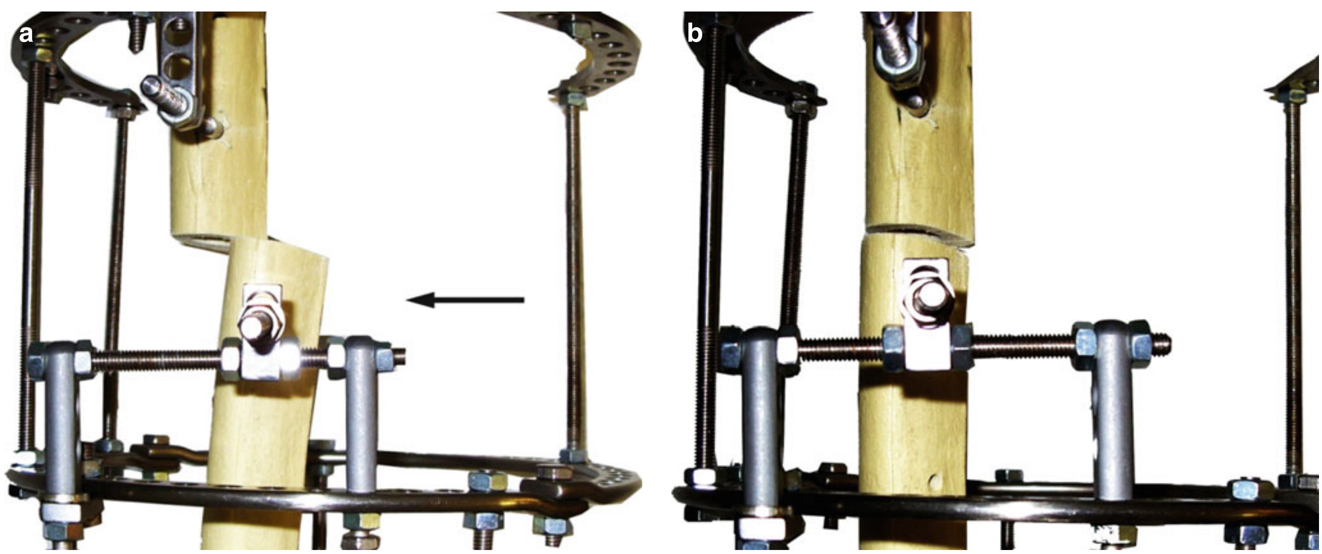
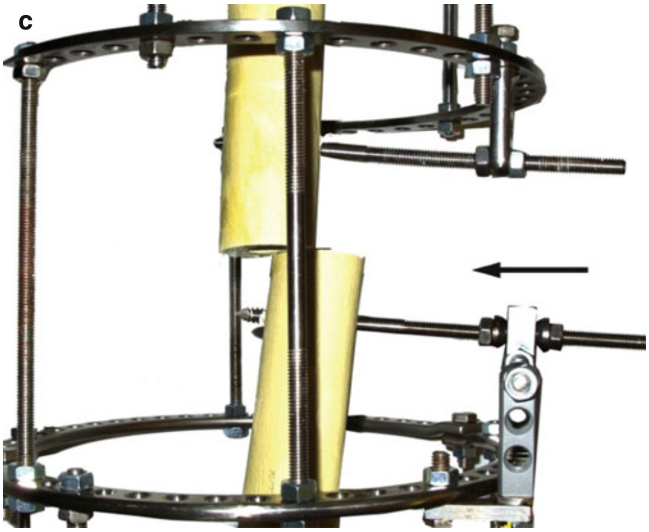


Fig. 2.12 This device (see Table 1.2) enables the bone fragment to be moved in two planes. For transference of the fragment in the plane perpendicular to the plane of insertion of the half-pin, the device is moved along the threaded rod attached to the device ring (**a**, **b**)



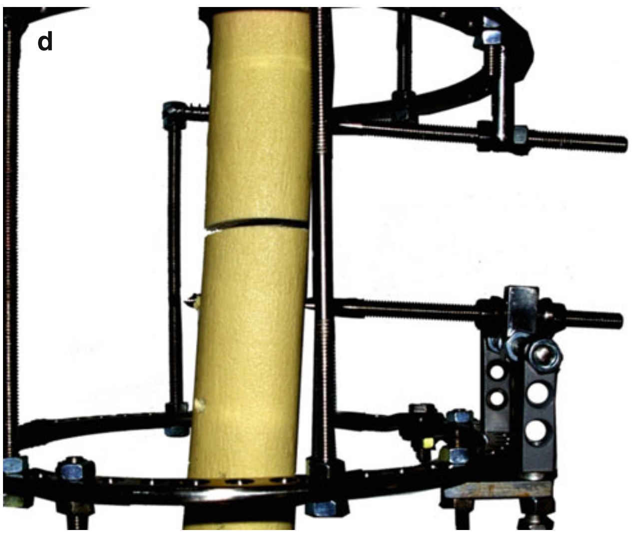


Fig. 2.12 (continued) In addition, the half-pin can be used as a "pusher" or "puller" (**c**, **d**) as described in Fig. 2.11. In this device, there is no need to use hemispherical washers

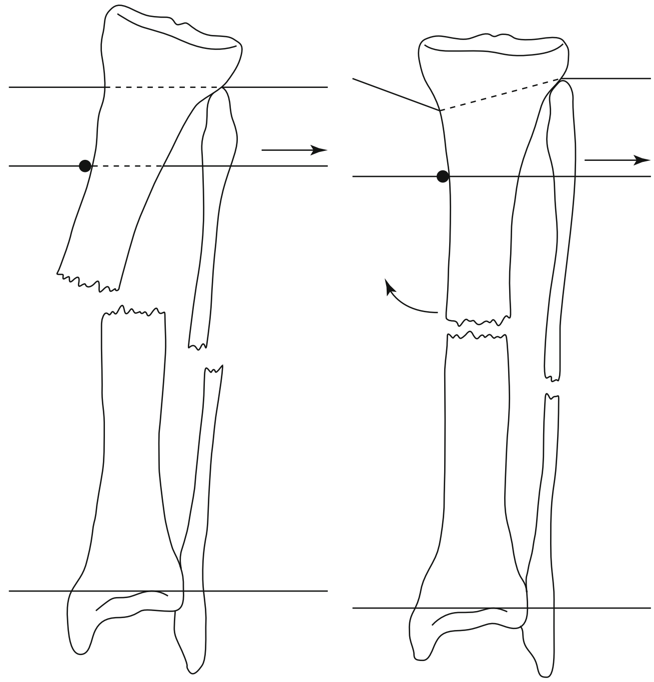


Fig. 2.13 In the transference of the transosseous elements relative to the external supports for repositioning, the following points should be kept in mind: If the basic transosseous elements are not perpendicular to the bone's long axis, then changing the spatial orientation of the bone fragment with the repositioning/fixation wire (half-pin) will induce a Z-like deformation of the basic wires (as shown in the diagram) or of the basic half-pins. In this case, the bone fragment is subjected to the actions of two differently directed forces: the repositioning force induced by the action of the reductionally fixing transosseous element and the force occurring from elastic deformation of the basic transosseous element. The latter acts to return the bone fragment to the initial position, reducing the rigidity of the osteosynthesis and increasing the threat of a secondary displacement. Deformation of the repositioning/fixation wire is not shown. An analogous situation arises in transference of the reductionally fixing supports (Fig. 2.6)

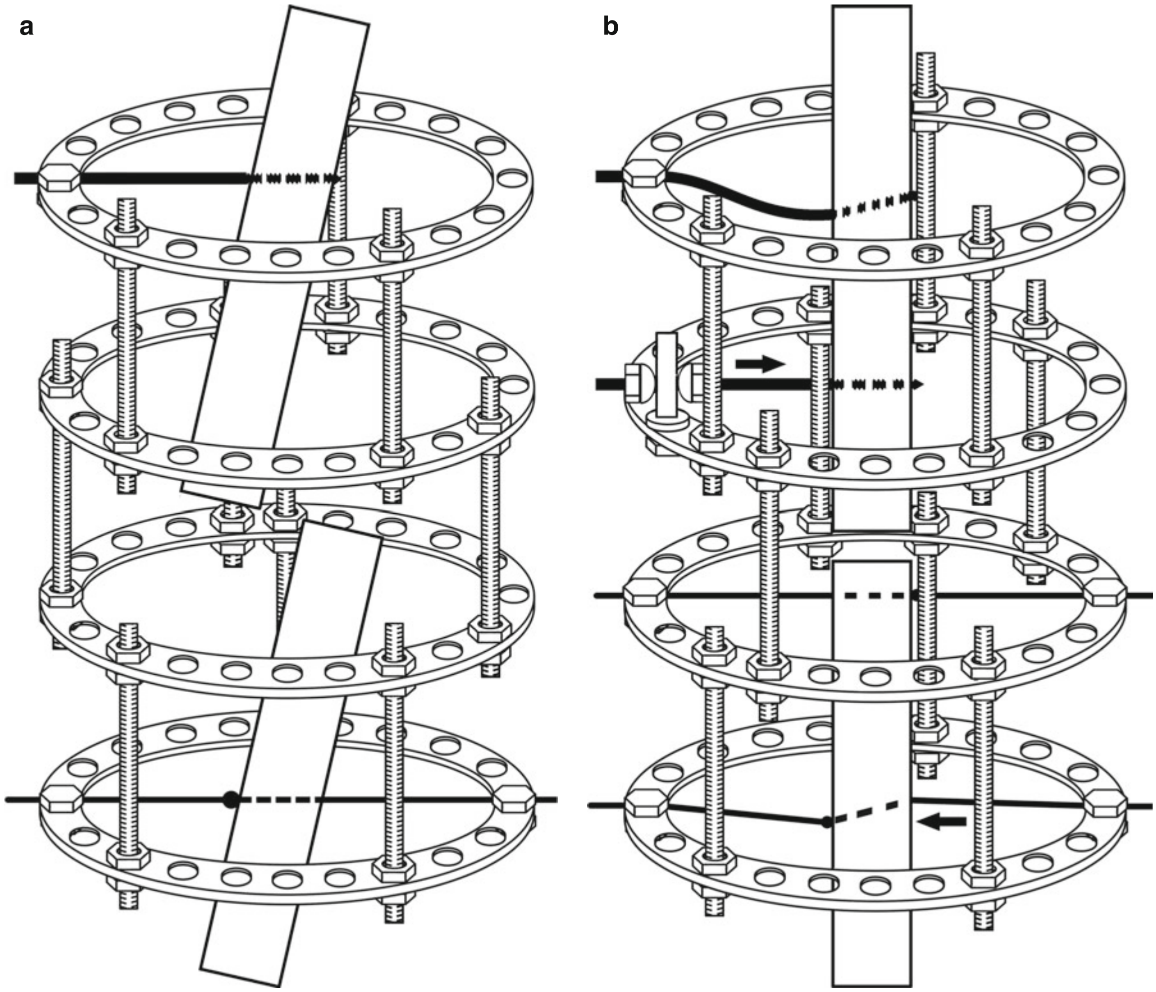


Fig. 2.14 If after reduction of the bone fragments there is deformation of the basic transosseous elements (**a**, **b**)

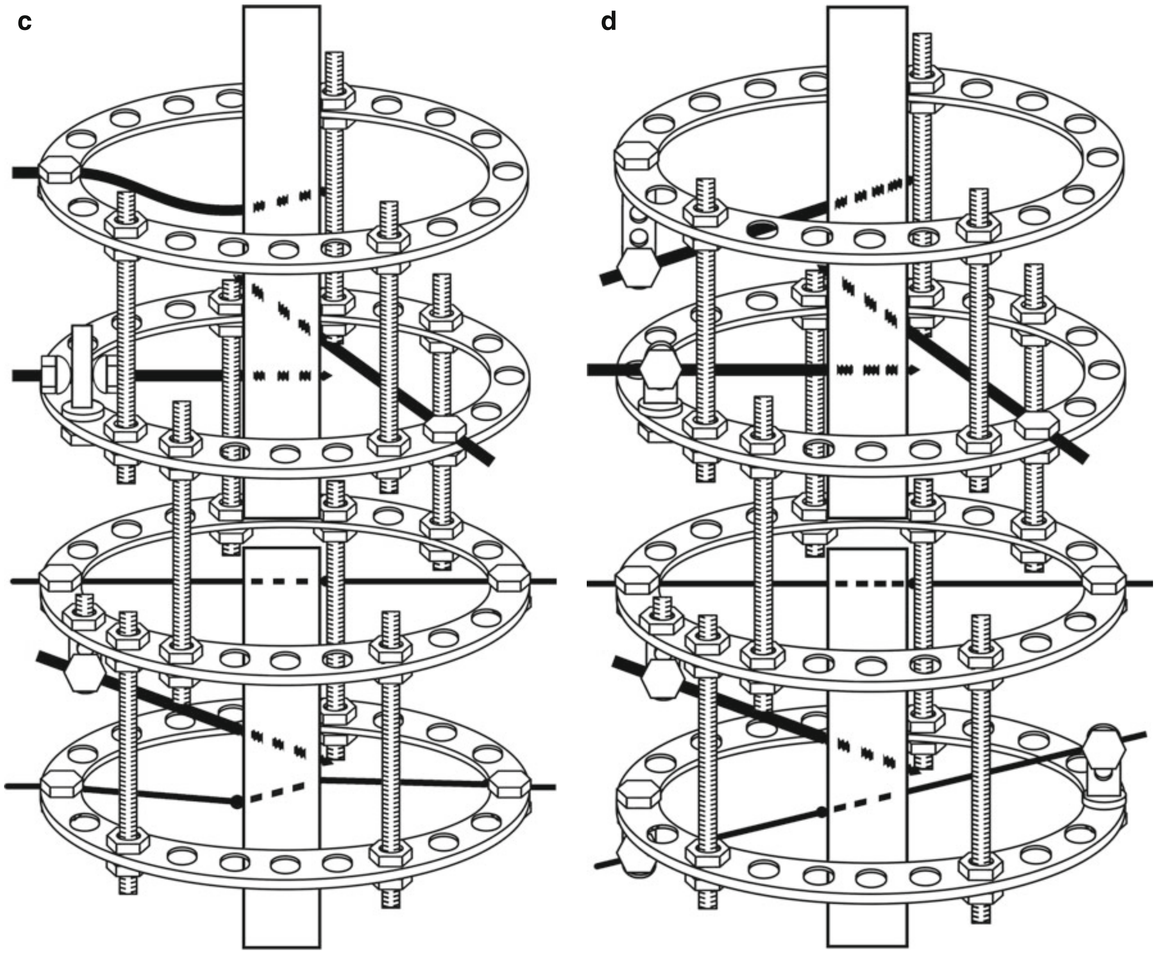


Fig. 2.14 (continued) Additional stabilizing wires or half-pins must be inserted and fixed to the supports (**c**). This allows detachment of the deformed basic transosseous elements from the support and the opportunity to fix them again to the corresponding support, avoiding deformation (**d**)

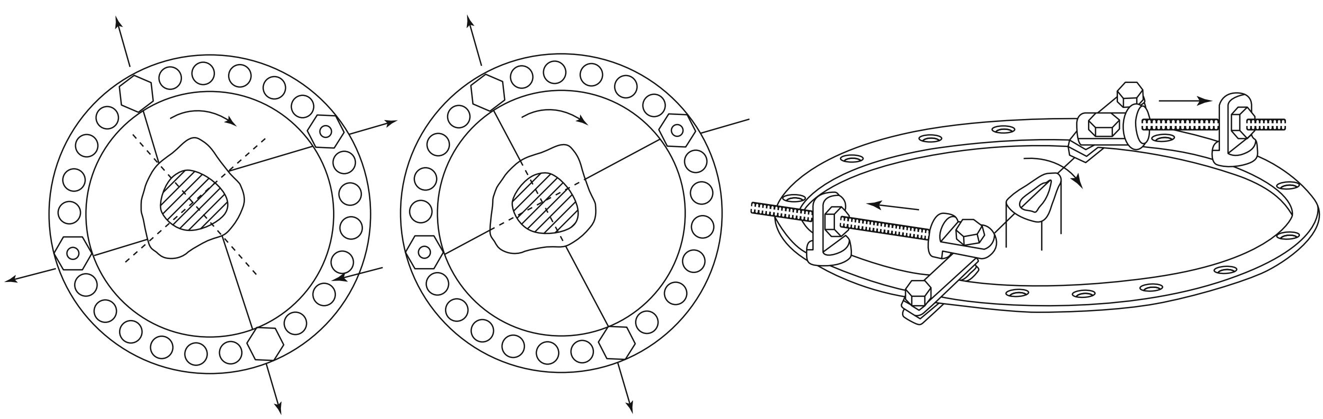


Fig. 2.15 Rotation of the bone fragment can be achieved by moving the wire ends in the support (From [9])

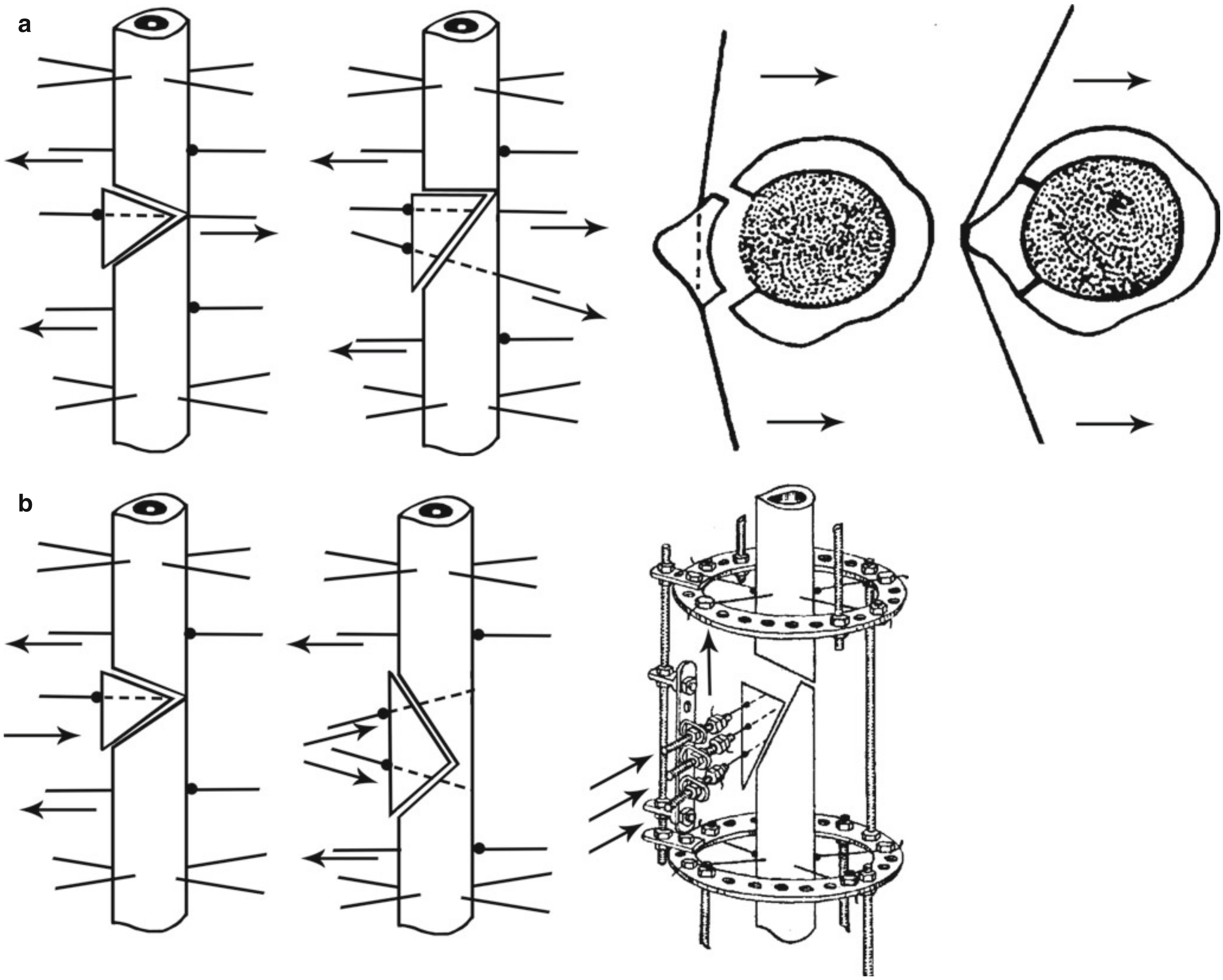


Fig. 2.16 Repositioning of the bone fragments with the aid of Kirschner wires (**a**) and console wires (**b**) (From [11, 12])

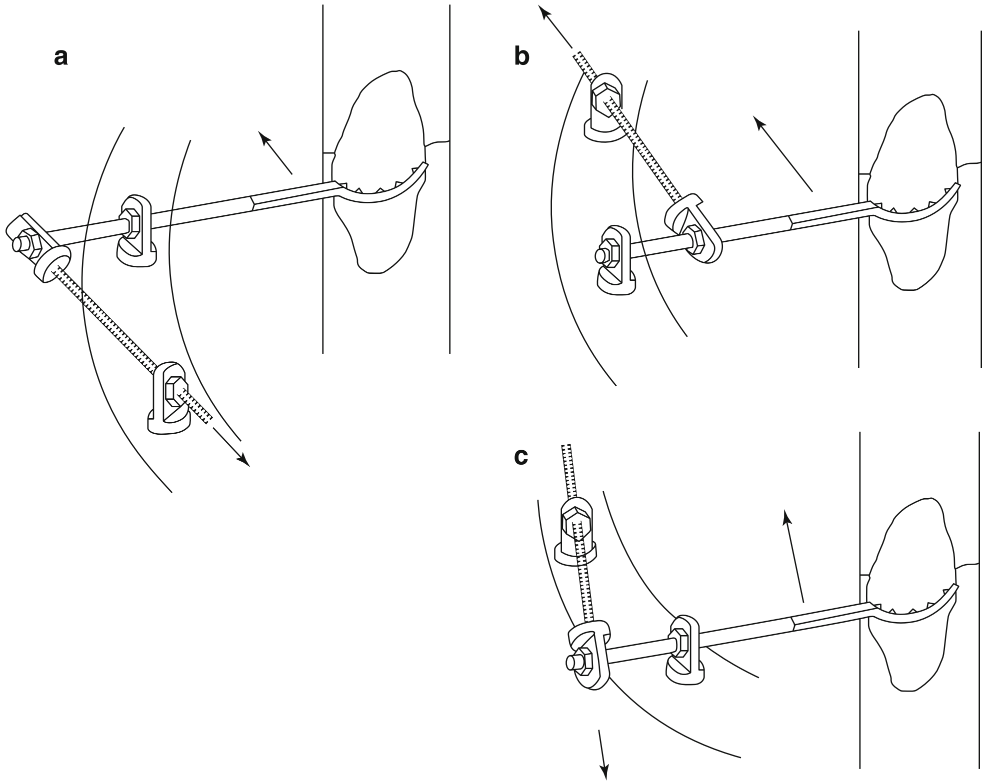


Fig. 2.17 (**a–c**) Situations may arise in which the use of wires and console wires for fragment repositioning is impossible (e.g., in the proximity of main vessels and nerves) or inadvisable (extreme soft-tissue thickness). Most often, such circumstances occur if the fragment is located at the internal, posterior surface of the middle third of the humerus or femur or in the interbone space of the ulna/radius or tibia/fibula. In these cases, a fork-shaped half-pin is employed (Table 1.2). When this device is used on the forearm, the diameter of the repositioning wire is 2–3 mm. For example, when the bone fragment is located along the posterior surface of the femur, the device is inserted from the external side of the segment (there are no main vessels or nerves here, and soft-tissue displacement is relatively small during movement of the hip and knee joints). If both longitudinal displacement and transverse transference are required, a fork-like half-pin with a longitudinal channel in the shank end is used. In the first stage, the fragment is pressed with its fork-like curvature into the main bone fragment. A 1.5-mm wire is inserted in the half-pin canal and the bone fragment is then drilled with this wire, thus providing its fixation to the half-pin. The fragment is then relocated in the desired direction

2.3 Control of Bone Fragment Rigidity

Several parameters influence the rigidity of bone fragment fixation and are relevant for all types of transosseous devices; these are discussed below.

The more rigid the material used in the manufacture of the external fixation device's components, the stronger the rigidity of the bone fragment fixation. Along with stainless steel, titanium alloys and chromium-cobalt-molybdenum alloys are used (Fig. 2.18). The durability of these alloys is three-fold higher, whereas their mass is two-fold lower. Synthetic polymer materials suitable for use in the transosseous device frames are currently under development.

As the transosseous elements are more elastic than the external supports and the bars connecting them, the rigidity of the transosseous synthesis to a considerable extent depends on the principles guiding the insertion and use of the transosseous elements.

Fig. 2.18 Composite and aluminum alloy supports

2.3.1 Number of Transosseous Elements

The greater the number of transosseous elements inserted into each bone fragment, the greater the rigidity of the transosseous synthesis. One should remember, however, that a greater number of interventions leads to a proportional increase in the degree of trauma and an increase in the risk of pin-induced joint stiffness.

2.3.2 Diameter and Type of Transosseous Elements

In clinical practice, transosseous elements 1.5–6 mm in diameter are most commonly used. Increasing the diameter of the transosseous elements will lead to an increase in the rigidity of the bone fragment fixation. However, the dilemma is that along with the increase in element thickness there is an increase in both the mechanical injury to the tissues and the rigidity of the bone–device block. Reducing the diameter of the elements reduces the rigidity, but enhancement of the tension in the bone leads to its resorption, which to some extent may be compensated for by using supports and stopper tubes or by altering the tension of the wire (Fig. 2.19).

Transosseous elements with an angular thread provide good rigidity of the bone–metal block. For similar diameters, trans-segmental transosseous elements offer greater rigidity than console elements.

2.3.3 Wire Tension

Insufficient tension of the wires reduces the rigidity of the bone fragment fixation. The reference force of the wire strain in the ring is 900–1100 N, and in the unclosed support 500–700 N.

2.3.4 Levels of Transosseous Element Insertion

The greater the distance between the level of insertion of the basic and reductionally fixing transosseous elements of each bone fragment (Fig. 2.20), the greater the distance between the level of insertion of the basic and stabilizing transosseous elements (Fig. 2.21), and the greater the rigidity of the osteosynthesis. Therefore in the fixation of stabilizing half-pins it is necessary to use four-hole posts. This does not necessarily involve insertion of the wire and half-pins through the joint cavity and within 1–3 cm from the pathological focus.

2.3.5 Plane of Orientation of the Transosseous Elements

The "neutral" angle for crossing of the wires in the support is 60°. With a wider angle, the wires will exert a mutual pulling action, and with a narrower angle a weakening action (Fig. 2.22). If it is possible to use an angle <45°, the external support should be oriented by an angle of 45° to the most displacing forces. However, to increase support rigidity, it is necessary to insert additional transosseous elements at some distance from the support (Fig. 2.23).

If the transosseous elements are placed perpendicular to each other, the system will respond "universally" to possible displacing forces. The topographic-anatomic specifics of the majority of extremity segment levels, which govern the localization of the RPs, in the majority of cases will predetermine this universal response if console transosseous elements (half-pins and console wires) are used.

The expedience of inserting a half-pin at an angle to the displacing force has been confirmed. It is partly explained by the increased distance between a support and the level of insertion of a half-pin into a bone. Thus, the greatest rigidity

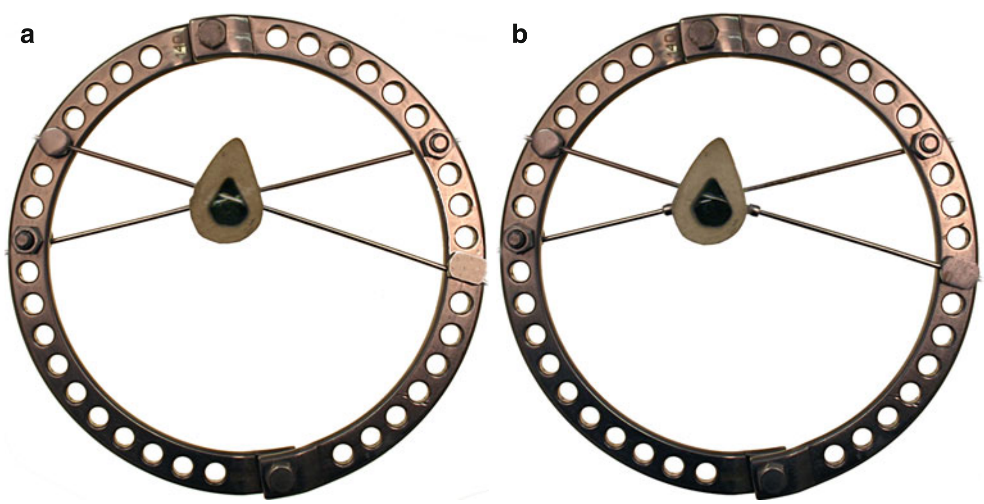


Fig. 2.19 (**a**, **b**) Increased osteosynthetic rigidity using wires fitted with a stopper. The wires are inserted "in the passer's" direction

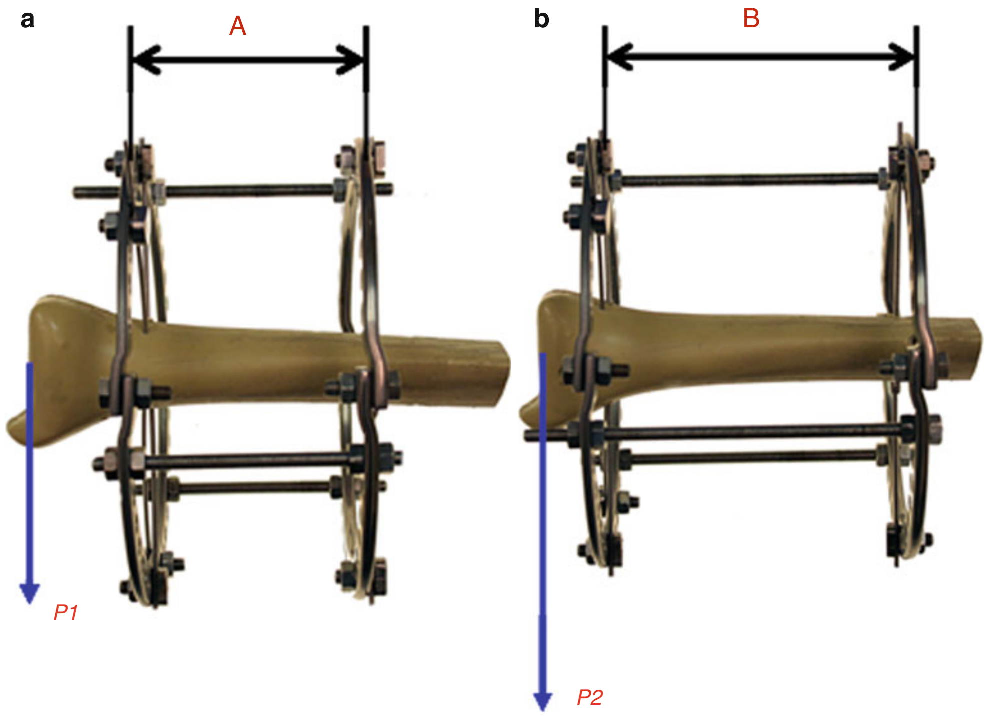


Fig. 2.20 (**a**, **b**) The greater the distance between the level of insertion of the basic and reductionally fixing transosseous elements, the greater the rigidity of the osteosynthesis: A < B, P1 < P2

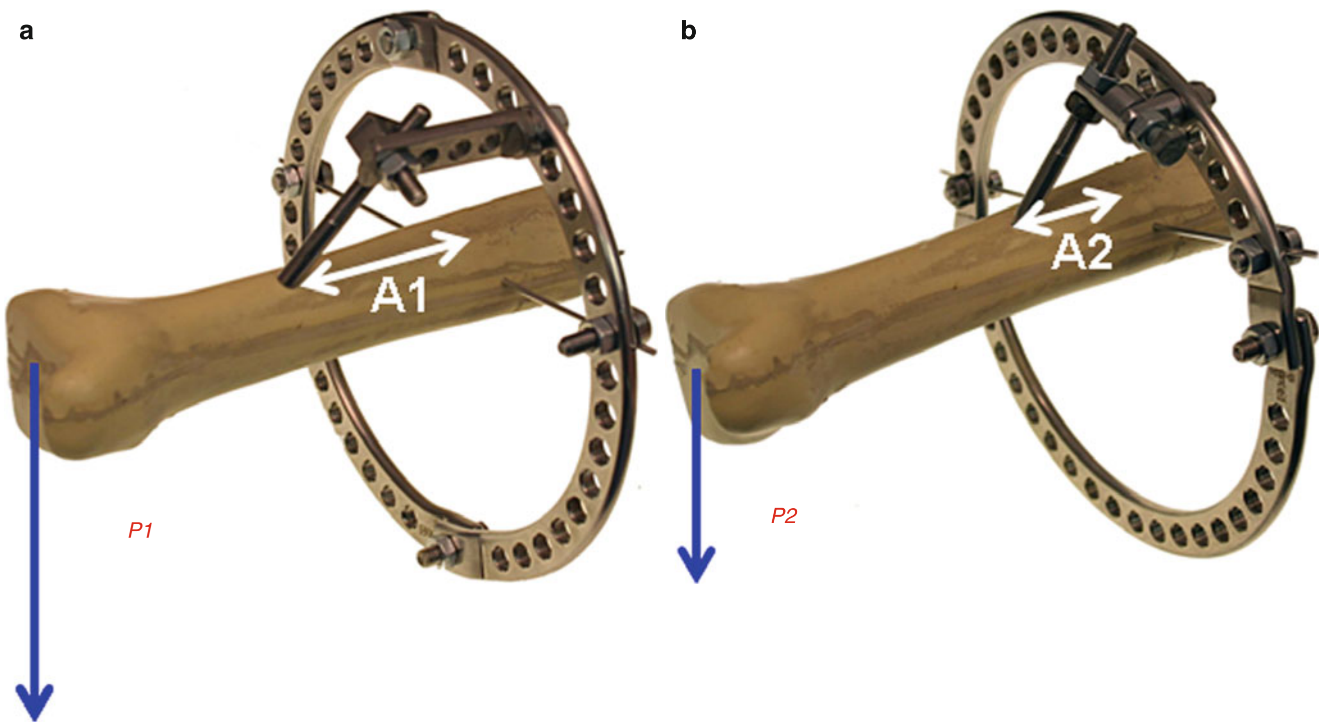


Fig. 2.21 (**a–c**) The greater the distance between the level of insertion of the basic and stabilizing transosseous elements, the greater the rigidity of the osteosynthesis: A1 > A2 > A3, P1 > P2 > P3

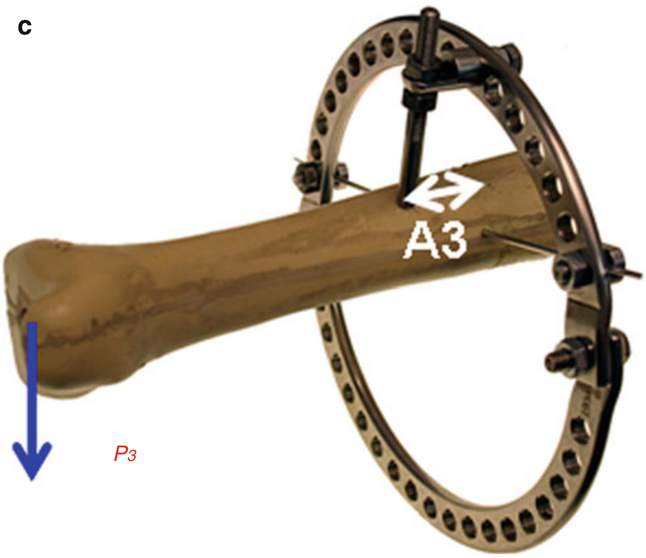


Fig. 2.21 (continued)

will be provided with a support to which a half-pin to be inserted at an angle to a bone fragment is fixed by means of a four-hole post (Figs. 2.24 and 2.25).

2.3.6 Distance from the Bone to the External Support

The shorter the distance, the greater the rigidity provided by the construction (Fig. 2.26). To avoid compression of swollen soft tissues, it is necessary to provide a certain clearance between the skin and the support's internal rim. The rim has to be established individually for each segment and type of pathological condition operated upon and should be 1.5–5 cm.

2.3.7 External Support Geometry

There is a direct dependence between the magnitude of segment coverage at each insertion level of the transosseous elements and the rigidity of the external fixation. Therefore, the trend of increasing bone fragment fixation rigidity proceeds from the type V device (circular) in the direction of the type I device (Table 1.1). The use of closed external supports enables the wire to be optimally stretched, providing a wider range of possible transosseous element insertion angles.

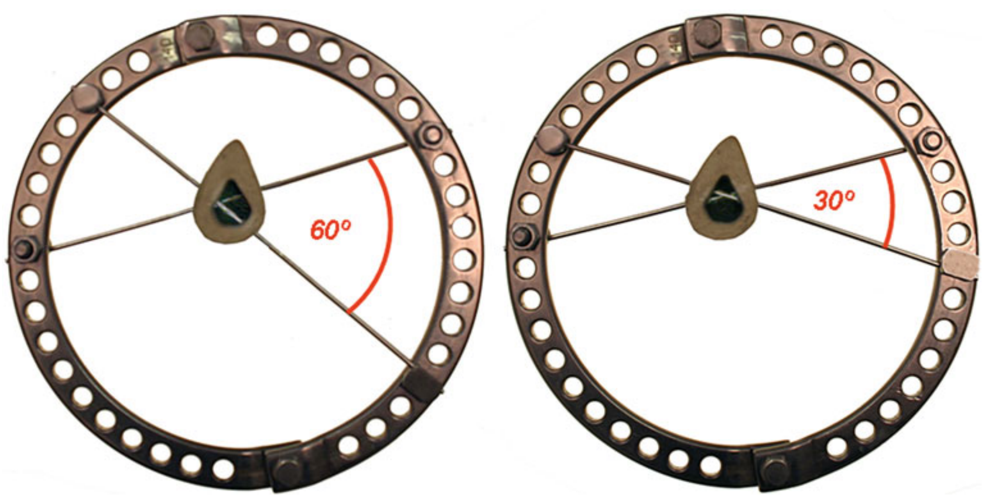


Fig. 2.22 The "neutral" angle for wires crossing in the support is 60°

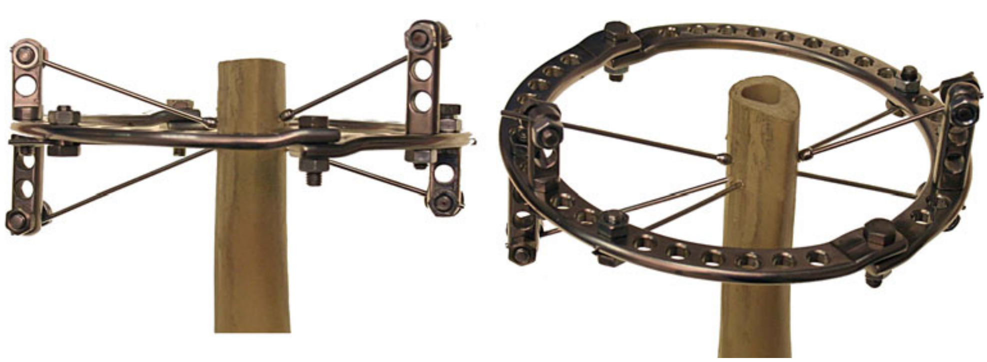


Fig. 2.23 To increase support rigidity, additional transosseous elements must be inserted at some distance from the support

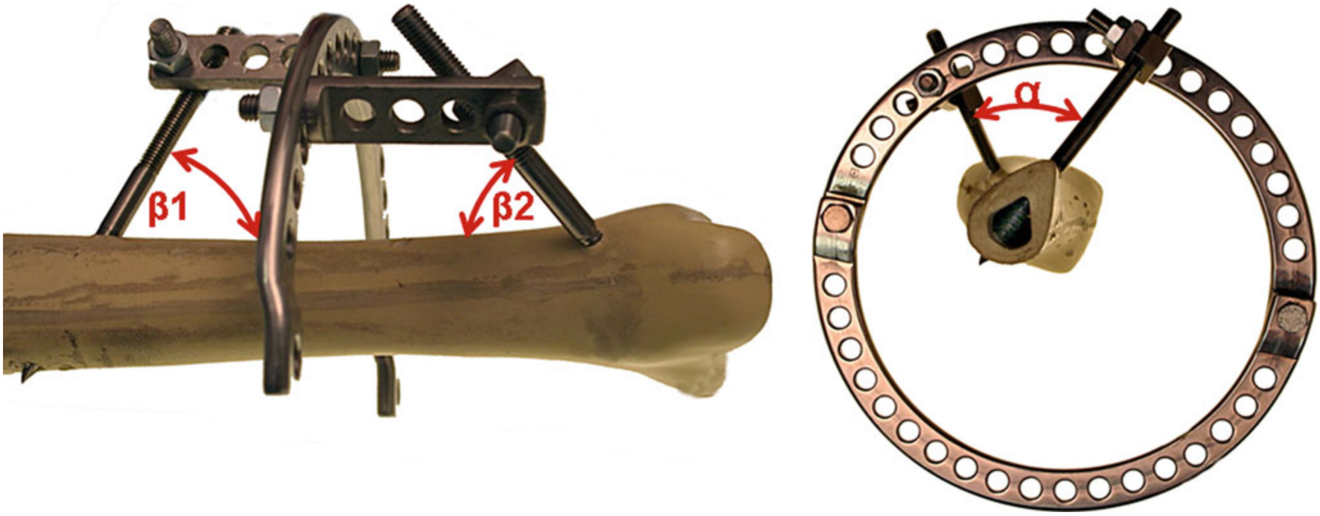


Fig. 2.24 To provide the greatest rigidity of bone fragment fixation when a half-pin-based module is used, the half-pins should be inserted at corresponding angles: $\beta1 = 120° \pm 10°$, $\beta2 = 70° \pm 10°$, $\alpha = 60° \pm 10°$

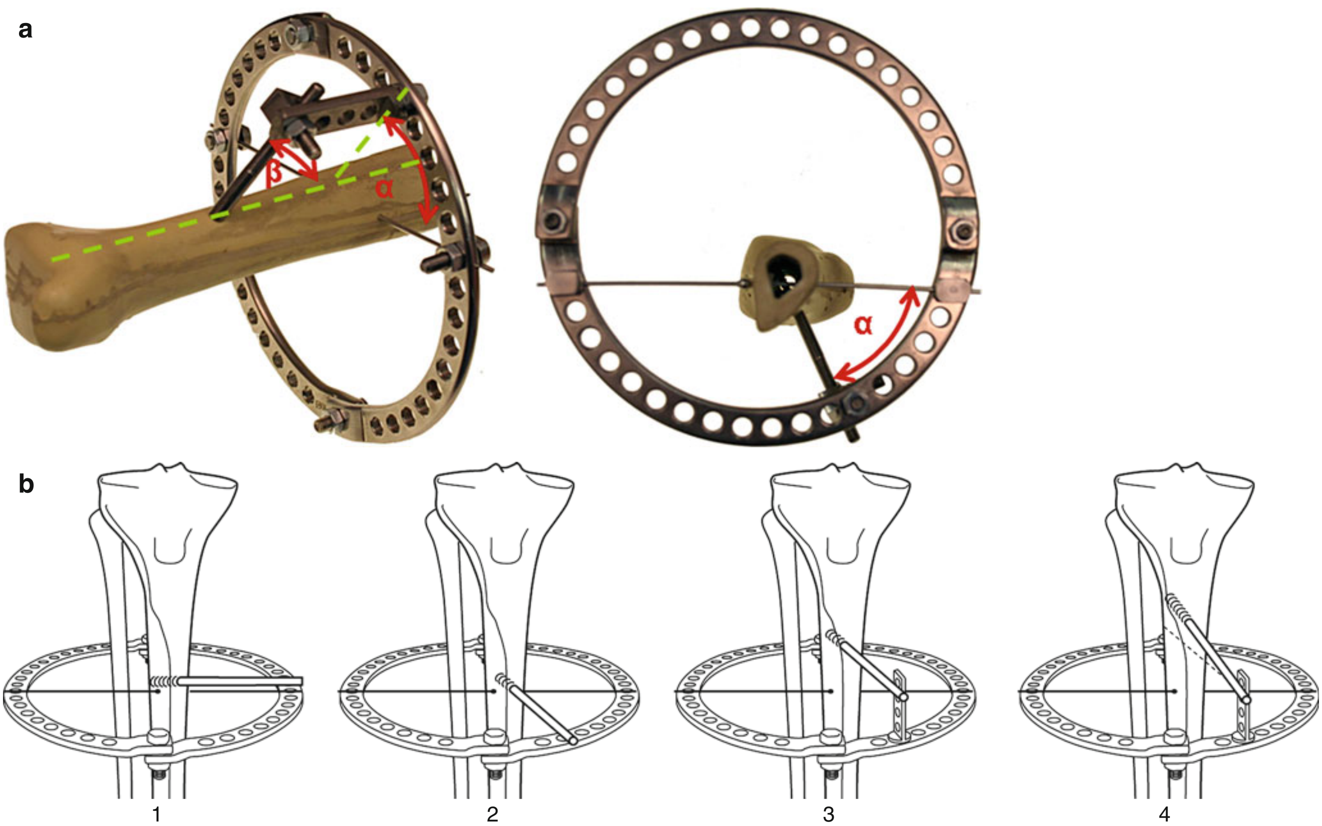


Fig. 2.25 Rigidity of a combined (hybrid) support. (**a**) To obtain the greatest rigidity of bone fragment fixation using a combined (hybrid) support, angle α (between the wire and half-pin insertion planes) should be 60° (75° ± 15°) and angle β (angle between the half-pin insertion and the longitudinal axis of the bone fragment) 70° (70° ± 10°). (**b**) Thus, the support with wire and half-pin positions provides different bone fragment fixation rigidities: 4 > 3 > 2 > 1

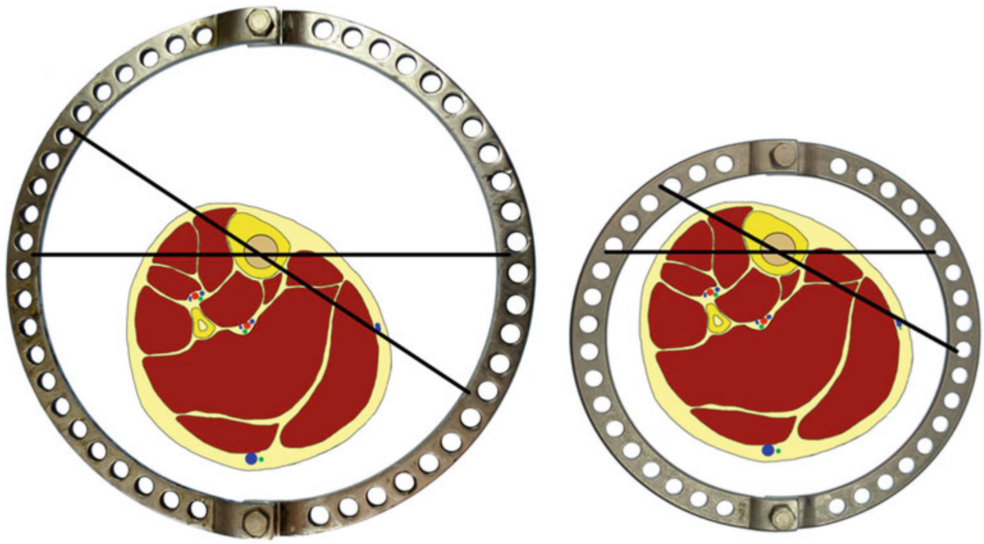


Fig. 2.26 The shorter the distance between the bone and the external support, the greater the rigidity of the bone fragment fixation

2.3.8 Number of Connecting Rods

The closed (ring) supports and reductionally fixing (intermediate) and basic supports should be connected by three rods. Use of a fourth connecting rod does not increase osteosynthetic rigidity. If one or both reductionally fixing (intermediate) supports are of the open type (one-third, two-thirds or three-quarter rings), use of a fourth connecting rod increases osteosynthetic rigidity by 18–22% (Fig. 2.27). An obligatory condition for this purpose is the uniform distribution of connecting rods on all supports; grouping the connecting cores in the next holes will reduce fixation rigidity.

Conflicts often arise between the biomechanical requirements of each component of the external fixation (and other requirements of the external fixation device) because of the contradictory requirements that must be fulfilled to achieve an optimal solution. In these situations, one should be guided by the priorities of the osteosynthesis tasks to arrive at a compromise that will maximize the efficiency factor of each transosseous element and each external support (see Chap. 3).

As in the case of the biomechanics involved in changing the spatial orientation of the bone fragment, the multiple factors affecting bone fragment fixation rigidity in the external fixation serves as a basis for determining the directions for optimizing the assembly of the transosseous devices.

Most clinical studies of the biomechanics of external fixation involve stand tests of external fixation models. The importance of the results obtained in such experiments by many researchers in different countries cannot be overestimated. However, apart from the natural limitations associated with experiments involving models, both the interpretation of the data and their use in practice emphasize the fact that there is no single commonly accepted method for carrying out a stand test. At present, there are a number of devices that differentiate among the "original" carcass, the nodes of the model fixation, the force-generating elements, and the movement transducers. The models are assembled using native or artificial bone, wooden or plastic cylinders, or metal tubes. The model can be fixed in the carcass in different ways, the displacing force applied in different ways, the transducers allocated in different ways, and the algorithm for carrying out the experiment may also be different. Therefore, an objective comparison of the results of studies by the various authors is hardly possible. Moreover, the number of such studies seems to increase yearly. Chapter 36 presents a method for rigidity testing of an external fixation construct.

In addition to stand tests, external fixation devices can be optimized through mathematical modeling using computer software especially designed or adapted for the tasks that need to be resolved. The efficacy of the finite element method is now recognized [2, 8, 9, 13, 29–32]. However, studies aimed at defining the optimal parameters for bone fragment fixation rigidity at all stages of healing currently remain the most relevant, and methods objectifying the durability of bone mechanical restoration on the basis of biomechanical, laboratory, optical, electrophysiological, radiological, and other types of monitoring are being intensively developed [8, 33–40], Unfortunately, at the time of this writing, not one of these methods, for various reasons, has been widely applied in clinical practice. Furthermore, there is as yet no unanimous opinion as to what the bone fragment fixation rigidity should be at each stage of bone anatomy restoration.

We conclude this chapter by noting that biomechanics is a rapidly evolving field of knowledge. There is a relatively large number of published works dedicated to the biomechanics of osteosynthesis (including the biomechanics of external fixation). It can thus be reasonably expected that a solution to the above-stated problems will be found in the relatively near future.

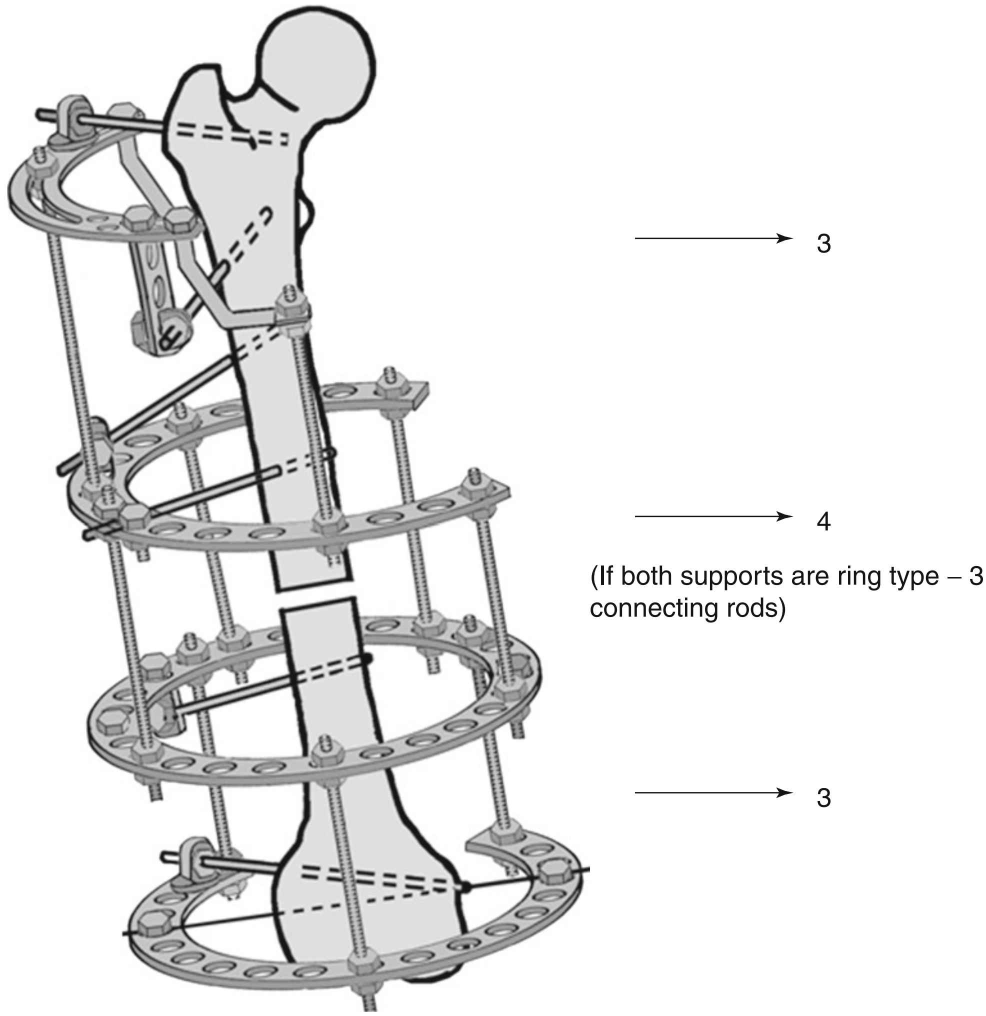


Fig. 2.27 Optimum number of connecting rods