

# Biomechanics of External Fixation

## A Review of the Literature

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### Abstract

*External fixation for the purpose of bony realignment has been in practice since the early 1900s and is widely used today. External fixators are primarily used for trauma but may also be used for deformity correction and arthrodesis, among other applications. The advantages of external fixation over open reduction and internal fixation and intramedullary nailing include simplicity of application, adjustability of the construct, and increased access for wound care and wound monitoring after fixation is achieved. Frame design requires a combination of pins, wires, clamps, rings, and rods to ultimately form a stable construct that can apply compressive, distractive, or neutral forces on bone.*

External fixation is a method of aligning or realigning bones using a combination of pins, wires, clamps, and bars or rings. This type of fixation was first employed by Lambotte in the early 20th Century.<sup>1</sup> Anderson and Hoffman modified Lambotte's device by developing an adjustable pin clamp that allowed manipulation of the fracture in all three planes—a precursor to many of the modern devices in use today.<sup>1</sup>

Allied forces used external fixation during World War II, only to encounter countless complications and nonunions, earning the technique the nickname of “the nonunion ma-

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chine.”<sup>2</sup> External fixation quickly fell out of favor. After much clinical and biomechanical research, external fixation came back into use in North America, in the 1970s, and is now commonly used in fracture fixation, deformity correction, and other surgical procedures.

Ring fixators were first described by Professor Gavril A. Ilizarov, from Siberia, in 1952.<sup>3</sup> These systems can expand the indications and uses of external fixation, but are subject to the same basic biomechanical principles that apply to conventional external fixators.

In certain fractures, external fixation is advantageous compared to other means of fixation, such as open reduction and internal fixation (ORIF) and intramedullary (IM) nailing. This is particularly true with high-energy polytrauma patients, who may have open wounds, massive soft tissue injury, bony comminution, or bone loss unsuitable for acute ORIF or IM nailing. Application of an external fixation construct is quick, with relatively low risk and minimal blood loss. The adjustable frame allows for fracture alignment and realignment; wounds and soft tissues around the fracture are easily accessible for examination and care. In such examples, external fixation may provide temporizing or definitive fixation.

Frame constructs consist of percutaneous pins or wires, clamps, sidebars or rings, and struts. These elements can be constructed to form unilateral, bilateral, circular, or hybrid external fixation frames. Each system has specific indications, advantages, and disadvantages.

### Pins and Wires

Pins and wires connect sidebars and clamps to bone and are a critical link in the stability of external fixation. Pins and wires are available in numerous shapes, sizes, and materials. The bone-pin or bone-wire interface is vital in attaining a stable construct for fracture fixation and healing.

Transfixion pins and wires traverse the axial plane of

the limb, with the two shanks of the pin or wire protruding from opposite sides of the bone. Each protruding pin shank or wire end can then be connected to a sidebar or ring, creating bilateral external fixation. Transfixion pins and wires provide a rigid construct, creating bilateral or circular fixation. Improper placement of transfixion pins may jeopardize muscles, tendons, and neurovascular structures (Fig. 1).

Half pins protrude from the bone and soft tissue of the limb on only one side but are anchored in both cortices of bone. The protruding shank can then be connected to a sidebar, creating a unilateral external fixation construct that is less bulky and puts fewer anatomic structures at risk than the bilateral frame. Half pins are more commonly used today.

Use of thin wires is increasing with the growing popularity of ring fixators and hybrid fixators. Thin wires are always bilateral, because they must be under constant tension to provide stability between the fracture and frame.<sup>4</sup> They carry the advantage of creating smaller defects in soft tissue and bone; however, as they are bilateral, care must be taken to avoid injuring underlying anatomic structures.

When placing an external fixator, preoperative planning is essential. Damage to existing anatomic structures, including muscles, tendons, nerves, and vessels, must be avoided or minimized. Anatomic safe zones for pin insertion are suggested to avoid such damage. Usually, the safe zone is in the area of bone that is most superficial, with the fewest number of neurovascular structures in the vicinity.

For maximum stability in a four-pin construct, ideally, the location of the pins is such that one pin is as close to the fracture as possible, and the other pin is as far from the fracture as possible. This pin construct is replicated on the opposite side of the fracture.<sup>1,5</sup> When planning pin place-

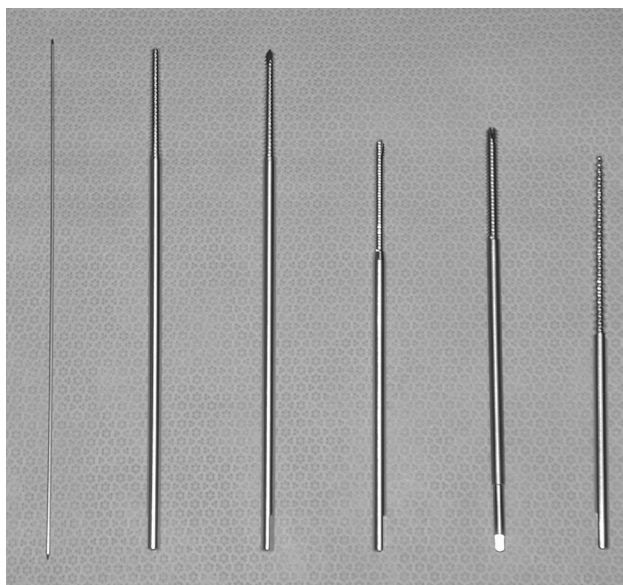
ment in an open fracture, contamination from the wound must be taken into account, and care must be taken to avoid pin placement through open wounds. Subsequent treatment options, such as IM nailing, ORIF, bone grafting, or skin grafting, should also be considered when placing pins.

Increasing the number of pins distributes the force among the pins and increases the stiffness of the overall construct. However, additional pins can increase the risk of damaging anatomic structures, and provide portals for infection.

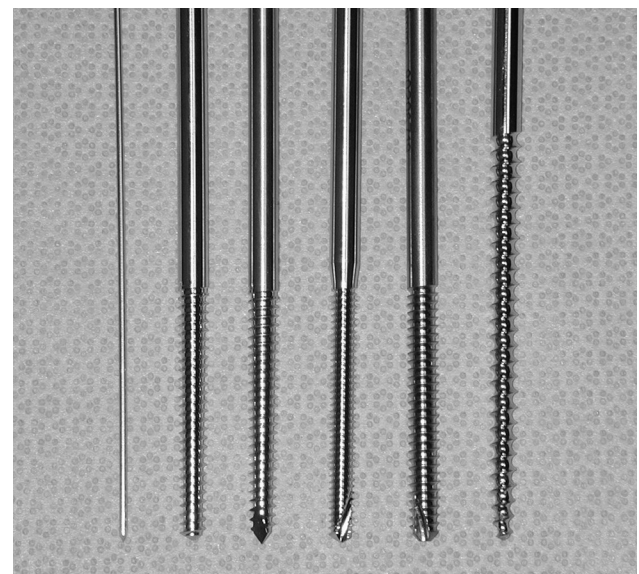
As the core diameter of a pin increases, the torsional strength increases at a rate proportional to the radius to the fourth power. A 6 mm pin is five times stiffer than a 4 mm pin.<sup>5</sup> Huiskes and associates<sup>6</sup> found that the less stiff the pin the more stress there is at the bone-pin interface. Thus, to maximize construct stiffness, the largest core diameter pins should be used,<sup>7</sup> taking care not to exceed one-third of the bony diameter in order to minimize the risk of pin-hole fractures.<sup>4</sup> The weakest point of a pin is at the thread-shank junction. Sinking the shank of the pin into the proximal cortex improves stiffness by up to two times.<sup>5</sup> This technique also decreases soft tissue irritation and inflammation by the threads.

Halsey and coworkers<sup>8</sup> found no statistical differences in pullout strength related to different thread profiles ("V" versus buttress) or varied thread pitch. There was a significant increase in pullout strength with decreased core diameter, likely due to larger interference between the pin threads and the bone. The advantage of increased pullout strength must be balanced with the substantial decrease in pin torsional strength associated with decreased core diameter.

With conventional pins, a mismatch between the threads and bone surface is possible, thereby providing a source



**Figure 1** Examples of various pin types. From right to left: Transfixion wire, tapered cortical half-pin, trocar-tip tapered half-pin, self-drilling tapered half-pin, self-drilling cylindrical half-pin, and cancellous tapered half-pin.



**Figure 2** Close up of pin tips.

for decreased stiffness and potential loosening. The advent of conical pins was intended to eliminate this potential mismatch, ultimately increasing stiffness at the bone-pin interface.

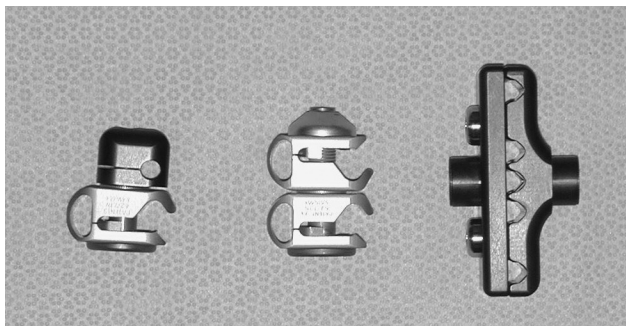
The fixation strength of tapered versus bicylindrical HA-coated external fixation pins in sheep tibiae was studied by Moroni and colleagues.<sup>9</sup> After six weeks, both types of pins were well fixed and osteointegrated histologically. However, the tapered pins demonstrated a higher extraction torque by two- to three-fold.

Loosening and infection, the two most common complications of external fixation, are thought to be related to thermal necrosis of bone.<sup>10</sup> Bone necrosis is attributed to high temperatures attained during pin insertion, and mechanical properties of bone are reported to be irreversibly altered at temperatures greater than 50° C.

Matthews and associates<sup>11</sup> tested three different drill speeds in bone (hand drilling, 300 rpm, and 700 rpm) and found that drilling at 300 rpm resulted in statistically significantly lower temperatures. However, in all three drilling methods, the temperature required to thermally necrose osteoblasts (55° C.) was exceeded at a distance of 2 mm from the drill.

These investigators also examined five types of pin tips: trochar, spade or diamond tip, Hoffmann, half drill, and modified half drill. The half drill and modified half drill produced lower average maximum temperatures at all measured distances than all other tested drill bits. They surmised that the lower temperatures associated with the half drill and modified half drill bits were due to the pin tip design that allowed elimination of hot bone chips and fragments from the drilled hole (Fig. 2). For all pin types, temperatures recorded during pin insertion into predrilled holes were significantly lower than temperatures for pins inserted into bone without predrilling.

Moroni and coworkers<sup>11</sup> compared the torques required for extraction of HA-coated pins, titanium-coated pins, and uncoated tapered half pins in sheep tibiae. Six weeks after insertion, the extraction torque was approximately 5% of the insertion torque for the uncoated pins, and 45% of the insertion torque for the titanium-coated pins. The HA-coated



**Figure 3** Left to right: Pin to bar clamp, bar to bar clamp, and modular clamp.

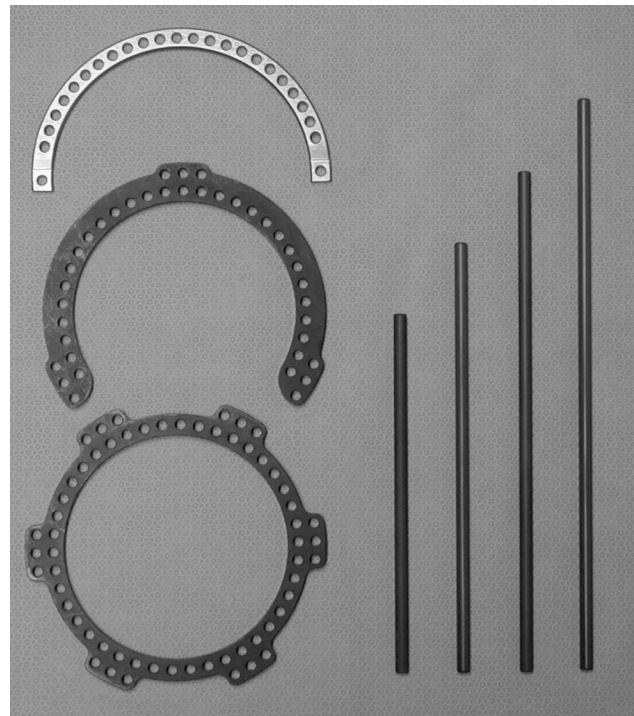
pins showed no statistical differences between insertion and extraction torques.

A similar study by Moroni and colleagues<sup>12</sup> was performed in human subjects with tibial shaft fractures. Median extraction torque of the tapered uncoated pins was approximately 8% of the insertion torque. For the HA-coated pins, extraction torque increased by 62% over the insertion torque. All fractures united without major complication; however, three of seven patients with uncoated pins developed pin tract infections, whereas no patient out of the seven with HA-coated pins developed infection.

Pettine and associates<sup>13</sup> examined the mechanism of pin loosening using in vivo canine tibiae under various loading conditions. They found that pins may loosen under static or dynamic loads, but pins fixing an unstable fracture (greater than or equal to a 2 mm gap) had more loosening. They suggested that in unstable fracture patterns, protected weightbearing should be enforced to minimize pin loosening. In addition, they found a distinct relationship between initial pin insertion torque and rate of loosening. Sixty-nine percent of pins with an initial torque resistance of less than 68 Ncm became grossly loose, compared to only 9% gross loosening if the initial torque resistance was greater than 68 Ncm.

### Pin Clamps and Rings

Clamps link a pin or wire to a rod or ring. Simple clamps connect one pin to a rod, whereas modular clamps may connect multiple pins to a rod. In addition, clamps are con-



**Figure 4** Left: Half ring, 270° ring, full ring. Right: Various sizes of connecting bars.



structed with varying degrees of freedom, depending upon their intended purpose and manufacturing specifications (Fig. 3). Drijber and Finlay,<sup>14</sup> examined Hoffman clamps, studying slippage as a result of the rate that a load is applied to a clamp-bar construct. They concluded that joint slippage is a function of the magnitude of the load and not related to the rate of load application. Aro and coworkers<sup>15</sup> analyzed the Hoffmann and Orthofix modular clamps, both of which accommodate five pins within a single clamp. In testing the Hoffmann clamp, total torque resistance was highest using two and three clamps in a symmetric configuration and decreased as more pins were used, and with asymmetric configurations. The Orthofix clamp achieved maximum torque resistance using two pins in a symmetric configuration, and steadily decreased with more pins, and with asymmetric configurations.

### Sidebars

Connecting rods, or sidebars, provide a bridge between the pin clamps and rings, unifying the bony fragments in the external fixator construct. Sidebars, traditionally, have been composed of stainless steel, aluminum alloy, or carbon fiber, and have been constructed in an array of cross-sectional geometries. An ideal sidebar is stiff, lightweight, and radiolucent for radiographic evaluation (Fig. 4).

Stainless steel tubes were compared to carbon fiber rods in a study by Kowalski and colleagues.<sup>16</sup> They found that, during bending, the carbon fiber rods were 15% stiffer than the stainless steel tubes. The stainless steel tubes deformed without breaking when subjected to a 250 Nm bending moment.

The carbon rods maintained their elastic stiffness throughout the testing. They concluded that carbon fiber rods were able to sustain higher loads without failing when compared to stainless steel tubes. In addition to higher stiffness, carbon fiber connecting rods have the advantage of being radiolucent.

### Overall Construct Stability

Stability of the external fixation is necessary to maintain alignment at the fracture site. Failure to maintain alignment could cause loss of reduction, potentially leading to malunion, nonunion, or catastrophic failure. The amount of motion at the fracture site can profoundly influence the rate of bone healing.

The two major classes of conventional external fixation configurations are unilateral frames, encompassing less than 90° of a limb sector in the axial plane, and bilateral frames, involving greater than 90° of a limb sector. Unilateral frames utilize half-pins and can generally be safely applied within a limb's "safe zones," avoiding vulnerable neurovascular structures. Bilateral frames use transfixion pins, traversing the diameter of the limb, potentially jeopardizing soft tissue structures. In addition, bilateral frames are more cumbersome than unilateral frames, providing an inherently stiffer

construct, but also potentially limiting access to the soft tissues.

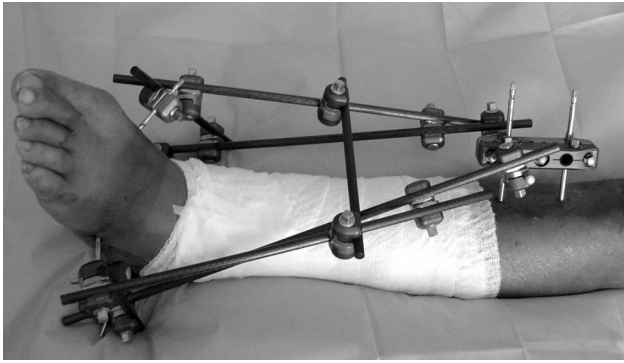
Both unilateral and bilateral frames can be assembled in one- and two-plane configurations. Converting a one-plane frame to a two-plane frame requires assembling an entirely new external fixator on the same limb, but in a different plane, usually 90°, to the existing frame. One-plane frames are not as obstructive as two-plane frames, but are approximately four- to seven-times weaker when bent in the plane orthogonal to the plane of the pins.<sup>5</sup> Unilateral, one-plane frames are most commonly used today. Behrens and associates<sup>5</sup> showed that methods to increase stiffness of unilateral frames include using stiffer components, increasing the distance between pins within a bony fragment, decreasing the sidebar to bone distance, incorporating an additional sidebar, creating a bilateral system, and aligning the plane of the pins with the major bending axis of the bone. Decreasing the distance between the sidebar and the bone from 80 mm to 25 mm and increasing the distance between pins within the same bony fragment from 44 to 90 mm significantly increased bending stiffness in all loading modes. Adding a second unilateral frame increased coronal bending stiffness, but had little effect on sagittal bending stiffness, the plane to which the most stress is applied. The one-plane unilateral frame was found to most closely mimic physiologic bending ratios in the sagittal and coronal planes (3:1 to 5:1).

Podolsky and Chao<sup>17</sup> examined the biomechanical properties of circular external fixators and found that factors that increase stiffness in conventional frames also apply to circular frames. In both circular and conventional systems, increased stiffness could be achieved by increasing wire or pin diameter, increasing the distances between the wires or pins, and decreasing the bone to ring or bone to sidebar distance. Features unique to circular frames that increase stiffness include increasing the wire tension and positioning the proper wire-crossing angle. Fixators with wires crossing at 90° had significantly higher stiffness to axial compression when compared to systems with wires crossed at 45°.

### Clinical Applications

External fixation can be used for a wide range of clinical applications, utilizing compressive, distractive, or neutralization forces on bone. Compressive forces can be used to fix transverse long bone fractures, AP II pelvic fractures, or in joint arthrodesis<sup>18</sup> and congenital pseudoarthrosis<sup>19</sup> surgery.

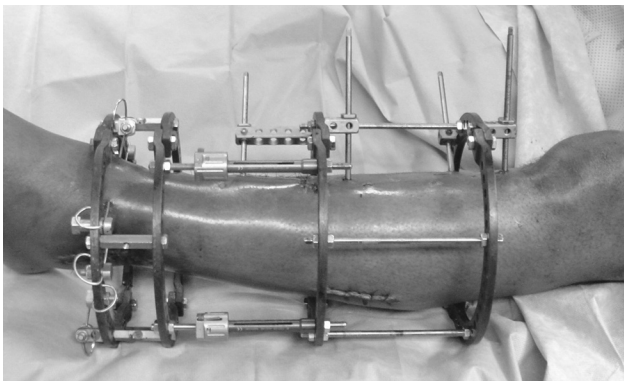
Distraction external fixation can be used to span intra-articular fractures. Distractive forces are used, for example, with ligamentotaxis to treat distal radius fractures, pilon fractures, and tibial plateau fractures (Figs. 5 and 6). Distractive forces may also be used to span comminuted long bone fractures, functioning as "portable traction." The principles of distraction are also employed in limb lengthening, distracting in graduated increments over an extended period of time.<sup>20</sup> In addition, distraction external fixation may



**Figure 5** Treatment of a pilon fracture using “delta” external fixation frame construct.



**Figure 6** Saw-bone model of external fixation spanning the knee joint for injuries such as multiligamentous injury or high-energy tibial plateau fractures.



**Figure 7** Ilizarov frame for bone transport of the tibia.

be applied to decrease joint contact forces, such as in the treatment of Legg-Calve-Perthes disease. Bone transport for large bony defects simultaneously employs distractive and compressive forces<sup>21</sup> (Fig. 7).

Angular deformities, including Blount’s disease or recurrent club foot, can be corrected using circular fixators, such

as spatial frames or Ilizarov frames, or conventional pin-bar constructs, providing a scaffold for bony realignment.<sup>22,23</sup> Circular fixators are more frequently used for multiplanar corrections, whereas pin-bar constructs are more commonly employed for uniplanar deformity.

**Summary**

Two major classes of external fixators, pin-bar and wire-ring, have been developed, each with advantages and disadvantages in specific applications. In addition, hybrid external fixators, using a combination of pin-bar and wire-ring systems, extend the applications of external fixation. Regardless of the type of system used, the same principles apply regarding pin and wire insertion, bone-wire interface pins, clamps, rings, and sidebars.

Different applications of external fixators are based upon various characteristics of each frame construct. For example, pin-bar external fixators are more commonly used to temporarily span injuries in the acute fracture setting, due to simplicity of application, relative safety of half pins, and accessibility to underlying soft tissues after application. Wire-ring fixators are more commonly applied in deformity correction because of their ability to apply high levels of compression and control distraction and orientation in three dimensions.

When the orthopaedic surgeon chooses to employ external fixation as a means of bony alignment, it is important to take into account the advantages and disadvantages of each system available, the extent of soft tissue damage, and the nature of the fracture or bony realignment that is to be addressed in order to most effectively treat the limb and benefit the patient.

*Disclosure Statement*

None of the authors have a financial or proprietary interest in the subject matter or materials discussed, including, but not limited to, employment, consultancies, stock ownership, honoraria, and paid expert testimony.

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