# 1 Introduction

In recent decades, the number of injuries caused by high-energy trauma has increased significantly due to the greater number of severe road traffic accidents, work trauma, and also firearm and blast injuries due to local military conflicts and terror attacks. More than 75% of all injuries in modern warfare are to the extremities, with a high risk of deep wound infection and post-traumatic osteomyelitis (caused by free bone fragments stripped of their periosteum), severe covering-tissue defects, and concomitant vascular injuries [16]. In recent local regional conflicts, there were relatively fewer thoracic and abdominal injuries but more damage to the extremities, due to the use of body protective vests. In road traffic accidents, modern safety equipment, such as seat belts and airbags, has changed the pattern of injuries, protecting the head and vital organs of the trunk. However, the extremities, especially the lower ones, are exposed to injury, and often suffer complex fractures [86, 135]. The number of multi-trauma patients reaching emergency rooms alive has increased, thanks to the fact that more emergency medical and paramedic teams are trained to cope with life-threatening critical conditions, and due to the rapid evacuation of battlefield casualties and victims of terror attacks to trauma centers that provide the required care immediately.

High-energy injuries to the limbs, involving both bone and soft tissue, remain complex injuries to treat, especially when associated with life-threatening injuries [2]. This is highly relevant to war injuries, especially blast injuries, which, by their high-energy impact, cause extensive blunt soft-tissue injury due to the blast wave, multiple penetrating fragment injuries, heavy contamination of the tissues, and a high rate of compartment syndrome. According to Nechaev et al. [99], most of the injuries in the Afghanistan war were multiple and complex (59.4%–72.8%), and more than half the injured were admitted in severe and critical condition. The management of open fractures is challenging, and multiple complex surgical procedures are frequently needed to achieve soft-tissue coverage, fracture union, and restoration of function [146].

Traditionally, firearm injuries have been divided into high- and low-velocity categories, based on projectile muzzle velocity. Low-velocity missile wounds are more common in the civilian population, and are typically caused by projectiles with a muzzle velocity of less than 610 m/s or 2000 ft/s (mostly handguns). They cause less tissue destruction and generally the injury can be treated after wound excision by closed fracture principles. Tissue damage is usually more substantial with higher velocity weapons (more than 610 m/s or 2000 ft/s) [4]; for example, injuries caused by modern military rifles and mine blasts. In modern local wars, more and more wounds are caused by splinters due to blast injuries (63.4%–73.5% of the injuries in the Afghanistan war, according to Nechaev et al. [99]). Wounding potential and lethality are related to the amount of kinetic energy that the projectile is able to impart to the target. Kinetic energy can be expressed by the formula: $KE = (m \cdot v^2)/2$, where $m$ is mass and $v$ is velocity.

Tissue damage is proportional but not equal to the amount of kinetic energy deposited in the target, calculated by subtracting the amount of kinetic energy of the bullet on exit from the amount of kinetic energy on impact with the body. Although a projectile's velocity and mass are inseparable, a greater mass results only in a linear increase in kinetic energy, whereas a change in velocity affects energy exponentially to the second power [5]. The bullet velocity is a major determining factor in the production of tissue damage [86]. The greater velocity leads to magnified energy absorption, which leads to increased tissue damage [35]. Commonly, gunshot wounds in civilians (low-velocity missiles) have more focal injury patterns and usually cause limited tissue damage from the missile injury alone, and not from cavitation effects [42, 59]. The majority of patients with low-velocity gunshot wounds may be safely and economically treated non-operatively with simple local wound care (superficial irrigation and careful dressing, with or without antibiotics) on an outpatient level, while associated limb fractures can be stabilized according to the principles in use for closed limb fractures, because of their similar characteristics (but see reservations below) [3, 5, 12, 59]. Modern military high-velocity missiles produce significant cavitations and fragments during their terminal ballistic phase. If the missile strikes bone, fragmentation of the bone, of the missile, or both may occur, and the resultant secondary missiles will produce additional tissue damage [34]. Gunshot wounds and blast injuries can cause either penetrating (not exiting) or perforating (exiting) wounds. The radiological appearance of a foreign body in the tissue of an injured limb is clear evidence that all the contained kinetic energy was expended in the missile–tissue interaction. Fragmentation of bullets has also been reported to correlate with higher missile velocity and delivered energy [36]. According to Gugala and Lindsey [42], the extent of bone comminution corresponds directly to the amount of missile energy transferred, and also suggests the degree of soft-tissue injury. In contrast, only some of the kinetic energy is absorbed by the tissues in perforating wounds where bullets fragments are not detected on radiography. Limited energy transfer by high-velocity missiles produces relatively less tissue damage and, in contrast, efficient transfer of energy by low-velocity missiles can result in devastating wounds [5]. Moreover, the impact energy of low-velocity shotguns at close range is similar to that of high-velocity firearms. Therefore, simply designating gunshot injuries as low-velocity or high-velocity wounds alone does not accurately reflect the true extent of the injury severity [42]. More appropriate and more important than velocity are the designations "low-energy" and "high-energy" which are more descriptive of the extent of tissue damage. Moreover, according to Long et al. [88], who studied the accuracy of classification systems for gunshot injuries in civilians, they do not provide a true description of the weapons because more than one-quarter of patients who suffered from firearm injuries cannot identify the weapon and, in many patients, the description is unreliable. He concluded that, in deciding upon treatment without knowing the type of weapon, the clinical and radiological appearance of the injured limb dictates the treatment protocol, and patients with extensive devitalized wounds must be treated according to the protocol for patients suffering from high-energy injuries.

The condition of the soft tissue of the injured limb is a vital factor, determining the chances of limb salvage procedures and the feasibility of functional restoration. In these fractures, the injuring agent transfers significant energy to the soft-tissue envelope, traumatizing these vulnerable structures and increasing the risk of major complications. Therefore, the initial care must be minimally traumatic and maximally sparing of the already damaged soft tissues. All fractures should be stabilized as early as possible. These patients are often polytraumatized and hypotensive, and may be hypothermic and coagulopathic. The use of a temporary external fixation device allows adequate resuscitation of the patient prior to definitive fixation [47]. High-energy trauma can include neurosurgical, general surgical, maxillofacial, ophthalmologic, otolaryngological, inhalation, burns, and other injuries. Rapid skeletal stabilization in patients with multiple complex fractures allows resuscitation with minimal blood loss and operative time [47], affording time for additional diagnostic imaging and adequate preoperative planning for the definitive elective limb reconstruction. The complexity and variability of these injuries dictate that routine prescriptive management based on fixed protocols is not possible and, therefore, a flexible and individualized approach to treatment is required [63].

Even in patients who suffer from closed fractures, soft-tissue injury plays a central role in prognosis and management. Because of the possibility of further soft-tissue damage caused by unstable fractures, the main bone fragments must be stabilized without delay. Stability is a very important factor, especially when there is a combined injury. Unstable fractures cause pain, nursing problems, morbidity, and mortality. Impaired bone healing results in delayed union or even nonunion. In contrast, early and sufficient fracture stabilization improves the recovery of the overlying soft tissues and the fracture itself. This is especially so in the treatment of patients suffering from war injuries, because the great forces involved result in extensive destruction of the bone and surrounding soft-tissue envelope. Classical fixation methods of fractures, such as plaster of Paris casting and continuous skeletal traction, are not acceptable in the treatment of patients suffering from high-energy unstable fractures with severely compromised soft tissues. Massive soft-tissue damage, extensive wounds (including post-fasciotomy wounds), and extensive post-traumatic fracture blisters require intensive daily soft-tissue care and preclude the use of cast immobilization. Furthermore, such severe fractures would require a relatively long period of immobilization, and this would result in stiffness in the neighboring joints. In addition, cast fixation cannot provide sufficient stability for early weight-bearing in patients with comminuted high-energy fractures, especially with bone loss. Skeletal traction, demanding lengthy immobilization, is unacceptable for treating patients with multiple and combined injuries, who require early mobilization and active nursing care.

Heavy contamination of the injured tissues precludes the use of internal fixation methods for fracture stabilization in these patients. Interlocking intramedullary fixation provides stabilization, achieved without additional periosteal damage, with secure control of alignment and rotation of bone fragments, wide access for soft-tissue care, early mobilization of the patient, and early movement of the adjacent joints. Interlocking nails have become the treatment of choice in the management of diaphyseal fractures of the long bones, including many types of open fractures. The disadvantages of this method are the potential spread of infection throughout the medullary canal along the nail, hardware failure due to the relatively small nail size, and technical difficulties in the treatment of distal and proximal one-third fractures. A study by Henley et al. [53] demonstrated a slight advantage of the unreamed interlocking intramedullary nail over unilateral 5.0-mm half-pin external fixators in the treatment of Gustilo Type II, IIA, and IIIB open fractures of the tibial shaft. However, patients with the most complex injuries, such as Gustilo Type IIIC fractures, tibial fractures caused by firearm projectiles, and fractures with significant bone loss, were excluded from this study, thereby significantly affecting its results.

Reamed interlocking intramedullary nails have a mechanical advantage over unreamed nails, but the reaming procedure of long tubular bones causes both mechanical and thermal damage to the medullary blood supply which cannot be tolerated when the injury has stripped much of the periosteal blood supply from the bone. According to Melcher et al. [94], reaming of the medullary cavity with the attendant reduction in local vascularity and necrosis may be additional risk factors.

The method of fracture stabilization utilizing a standard plating technique requires extensive tissue dissection. Exposure of the fracture site and bone fragments should be limited, in order to retain vascularization. A precondition for performing the plating procedure is the availability of immediate and reliable coverage of the fracture site and implanted internal fixator by viable soft tissues, and this condition is frequently absent in war injuries. The concept of "biological fixation" with new plate designs and minimized bone-plate contact, bridge-plating techniques, and improved surgical techniques with percutaneously inserted plates has led to improved rates of fracture union and a decreased incidence of infection and other postoperative complications. However, even the limited local pressure of plates on bone can damage the blood supply, essential for fracture healing, to the underlying bone [50]. Furthermore, an implanted internal fixator foreign body promotes infection in the wound in cases of septic complications. Even limited contact pressure plates require safe soft-tissue coverage without any compromise. Incisions through compromised tissue can lead to wound breakdown and deep infection [135]. Thus, methods of internal fixation using intramedullary nails or plating provide fracture stabilization at the cost of disturbing the intramedullary or periosteal blood supply [19]. Based on his experience in treating war injuries to the extremities, Busic et al. [16] reported a high rate of deep infection (33%) when internal fixation was used as the primary management. Hence, an internal fixator should not be used as a method of choice in the initial stages of treatment of war injuries. Long et al. [88] observed 100 patients who underwent surgical treatment for civilian gunshot injuries to the femur. They found that the femoral fractures of 79 patients with minimal soft-tissue damage united without infection, but 8 of 21 patients with severe soft-tissue damage had deep infection.

Fracture healing depends on an adequate blood supply and sufficient stability of fixation for a successful end result. The severity of the soft-tissue injury rather than the choice of implant appears to be the predominant factor influencing rapidity of bone healing and rate of injury site infection [53].

In treating poly-traumatized patients, external fixation provides a quick and minimally invasive approach. Using external fixation as a more biological method of skeletal stabilization helps preserve tissue vascularity. The advantages of this extra-focal method of fixation also include retention of the fracture hematoma without disturbing the soft-tissue envelope at the fracture site. Using external fixation frames in the management of these patients allows both quick stabilization and realignment of shattered bones, with minimal surgical invasion and additional disruption of the mangled soft tissue. The principle behind this method is stabilization of fracture fragments by the combination of transfixion of fracture fragments and an external stable framework distanced from the wound and capable of repeated adjustments [147]. There is no need for insertion of massive foreign bodies (internal fixators) into the fracture zone, demanding an appropriate surgical approach with additional incisions and soft-tissue trauma, in addition to adequate soft-tissue coverage of the bone ends, fracture zone, and implanted internal fixators. Care must be taken not to add further surgical devascularization of the bone ends. Thus, fracture stabilization is achieved without further compromising the already damaged soft-tissue envelope. External fixation frames allow simple and quick bone stabilization, provide simplicity in nursing care, and allow earlier mobilization of patients. The wounds are easily accessed and local treatments, including necessary surgical procedures, are readily applied. This versatile method of treatment may be employed in almost any configuration, severity, and localization of fracture. Reduction and stabilization of bone fragments should be performed with minimal trauma to the tissues, avoiding additional dissection, stripping and iatrogenic devascularization of the bone fragments (*primum non nocere*). Methods of external fixation, techniques using indirect fracture reduction, and procedures that obviate the need for direct exposure of the fracture site can avoid some of the complications associated with open reduction and internal fixation of bone fragments. According to Efimenko et al. [32], the introduction of functionally stable external osteosynthesis improves the results of treatment of gunshot limb fractures. External skeletal fixation is the preferred initial treatment for stabilizing severe open missile fractures of the limbs, reducing the rate of morbidity and limb amputations [47, 140].

Modern external fixation equipment is relatively easy to use and teach. It achieves quick, effective, primary fracture stabilization. These important properties are suited to operations, often executed under emergency conditions by duty teams of orthopedic residents, in the absence of highly skilled specialists in the field of limb salvage and reconstruction.

Temporary external fixation has been recommended to provide relative bone stability while the soft tissue heals, prior to formal open reduction and internal fixation. According to Haidukewych [47], using a protocol of temporary external fixation in complex peri-articular fractures will allow time to prepare the patient for surgery, prepare the surgeon for what needs to be done, and prepare the injured extremity for surgery. The use of temporary external fixation is an attractive strategy in the staged treatment of complex fractures.

**External fixation devices provide several important advantages:**

- Extra-focal fixation technique;
- Relatively easy application technique;
- Rapid and relatively stable fracture fixation using a minimal number of parts;
- Adequate fixation frame for any fracture configuration;
- Low morbidity, minimally invasive fixation technique;
- Temporary trans-articular bridging can be performed in patients with severe intra- and juxta-articular injuries.

**The main disadvantages of external fixation are:**

- Require daily pin-tract care;
- Discomfort;
- Local pin-tract infection rate;
- Sometimes interference with soft-tissue reconstruction;
- Muscle transfixion can result in neighboring joint stiffness;
- Need for prolonged on-going orthopedic follow-up in an outpatient clinic.

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