Injury xxx (xxxx) xxx

Contents lists available at ScienceDirect

Injury

journal homepage: www.elsevier.com/locate/injury

Review

Sacral fractures: An updated and comprehensive review

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ARTICLE INFO

Article history:
Accepted 5 November 2020
Available online xxx

Keywords:
Sacral fractures
Biomechanics
Classification systems
Treatment options

ABSTRACT

Sacral fractures are often underdiagnosed but are relatively frequent in the setting of pelvic ring injury. Causes include traumatic insults and osteoporosis. Sacral fractures have become more frequent owing to the growth of the elderly population worldwide as osteoporosis is an age-related disease. Misdiagnosed and neglected sacral fractures can result in chronic back pain, spine deformity, and instability. Unfortunately, the wide range of classification systems hinders adequate communication among clinicians. Therefore, a complete understanding of the pathology, and communication within the interdisciplinary team, are necessary to ensure adequate treatment and satisfactory clinical outcomes. The aim of this manuscript is to present the current knowledge available regarding classification systems, clinical assessment, decision-making factors, and current treatment options.

Introduction

Throughout history, understanding of sacral fractures (SF) has been molded by research on pelvic ring injuries and spine surgery [1]. The development of advanced imaging tools has led to more accurate diagnosis, which has increased with the advent of CT and MRI [2]. Hence, the condition has been historically underdiagnosed, and the frequency of presentation underestimated [3]. In 24-70% of cases the diagnosis can be delayed or missed [4]. Thus, diagnosis is challenging for the clinician in the setting of acute trauma and even more in the case of insufficiency fractures. In the United States alone, a threefold increase of traumatic SF between 2002 and 2011 has been reported from 0.7 to 2.9 per 100,000 in the population [5]. Likewise, osteoporotic pelvic and sacral injuries are increasing concomitantly with the growth of the elderly population worldwide [6]. Kannus et al. presented an incidence study in Finland that revealed a fivefold increase in osteoporotic fractures related to the pelvic ring and sacrum between 1970 and 1997 [3]. Osteoporotic SF present almost exclusively in older women with increased incidence associated with other risk factors such as chronic corticosteroid therapy, rheumatoid arthritis, radiation, and other endocrine system alterations such as hyperparathyroidism. Previous spine instrumentation and fusion has been described as a risk factor for insufficiency fractures in the elderly [7].Previous work shows that SF can result from three leading causes: High energy trauma in younger patients, Low energy trauma in older osteoporotic patients, and malignant invasion of bone tissue in the setting of cancer [1,8].

The factors that hinder accurate assessment and diagnosis of SF are related to the typical trauma setting in which patients can present with loss of consciousness, associated spine injuries, severe traumatic injury, blood loss that results in hemodynamic instability, open fractures, and soft tissue involvement [9]. For these reasons, the clinician needs a high level of suspicion to make a timely diagnosis. Moreover, the classification systems for SF are numerous and this hinders proper communication among caregivers. The treatment of SF is decided on a case-by-case basis in the absence of general guidelines for management.

The relevance of SF lies in the potential clinical entities that result from the anatomical and biomechanical relationships of the sacrum to spine alignment, weight bearing, and vascular and ner-

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https://doi.org/10.1016/j.injury.2020.11.015
0020-1383/© 2020 Published by Elsevier Ltd.

vous anatomy, as discussed below. The aim of this review is to present current knowledge about SF regarding clinical assessment, classification, radiological evaluation, and treatment.

Lumbosacro-coccygeal functional unit

Given its morphology and anatomical relationships, Acevedo and Perez (2017) stated that the sacrum constitutes part of what they called the lumbosacro-coccygeal functional unit (LSCFU) [10]. This refers to the union of structures comprising the lumbar spine, sacrum, coccyx, and pelvis [10]. While the spinal unit (SU) previously described by Moroney et al. [11] included two adjacent vertebrae, the intervertebral discs, facet joints, and the spinal ligaments, the LSCFU includes the muscles, cartilage, osseous structures, and neural structures within the pelvic ring. Hence, the concept of LSCFU permits a broader and more accurate understanding of the lumbosacral spine and its relationships to the pelvic ring. Being a functional unit implies that the structures involved have a common embryological origin, anatomy-dependent function and synchronized biomechanical behavior [10].

Sacral fractures and biomechanics

The clinical ramifications of structural impairment of the sacrum can only be understood in the light of its functional aspect, for the sacrum is the anchor or keystone of the spine into the pelvic ring. It transfers and distributes biomechanical forces into the ilia and lower limbs through the hip joints [12]. Imbalance in this functional unit explains why even slight changes in spinal, sacral and pelvic morphology due to trauma or osteoporosis result in significant clinical manifestations among patients [10,13]. Persistence of back pain after surgery can be explained by facet syndrome, supporting the existence of the LSCFU [14].

It is well known that the magnitude of pelvic incidence, defined as the sacral axis related to pelvic ring, and a fixed and somehow static parameter, dramatically affects the extent of lumbar lordosis [13,15]. A mismatch above 10° between the pelvic incidence and lumbar lordosis (PI-LL), increased pelvic tilt and sagittal vertical axis, predisposes to back pain, adult spinal deformity, and kyphosis. [12,13,16] Sacrum alignment with the C7 plumb line in the sagittal plane determines sagittal alignment. Therefore, SF not only present with local anatomy-related clinical manifestations but also, when presenting with kyphotic deformity or spinopelvic dissociation, it modifies Dubousset's cone of economy resulting in chronic degenerating clinical entities, conditioning the appearance of recalcitrant neurogenic and axial somatic back pain [13]. Unsurprisingly, pelvic incidence has been proposed as a marker of success in the surgical treatment of SF [17].

Sacral fractures

As stated earlier, SF present mainly in three clinical settings: Acute high energy trauma in the case of younger patients, low energy trauma in the case of the osteoporotic elderly (insufficiency fractures), and pathologic fractures in cancer settings [1,8]. It is therefore noteworthy that SF present a bimodal distribution [5]. Although early descriptions of SF referred to it as the "suicide jumper fracture", current traumatic etiologies include motor vehicle accidents in 57%, pedestrian against vehicles in 18%, falls from heights and motorcycle accidents in 9% each, and crush injuries in 4% of cases [18]. Importantly, close to 75% of patients who present to the emergency room with SF are neurologically asymptomatic, hindering clear diagnosis [19]. Patients for whom the diagnosis of fractures is delayed continue to create chronic imbalances in the normal biomechanical disposition of the LSCFU, creating the opportunity for pathological entities [10].

The mechanisms behind sacral injuries are related to axial loading producing tensional stress, hyperflexion and hyperextension creating shear stress, and traction by the ligament insertions giving rise to avulsions. The main objective of functional assessment related to SF is the stability of the sacrum. This concept is assessed by the integrity of the joint points of the sacrum (body, facets, sacroiliac, and sacrococcygeal joints) and its stabilizing ligaments. Stability is a controversial concept, but it refers to the ability of the spine to limit the displacement of its structures when under physiological challenges [20]. Thus, the spine limits itself to avoid injury to its components while moving, providing support and protection, and preserving energy reserves. The ultimate aim of decision-making is therefore to maintain stability and achieve satisfactory neurological and clinical outcomes.

Classification systems

In general, SF can be longitudinal/vertical, transverse, avulsed, or combinations of these, leading to spinopelvic dissociation (SPD) and instability [21]. SPD accounts for 2.9% of all SF and is the most severe presentation, entailing biomechanical disconnection of the lumbar spine from the pelvic ring; it should always be treated surgically. Several classification systems have been proposed to describe the fractures according to morphology, mechanism, neurological deficit risk, or stability. Among these, the Denis classification and the modified Roy-Camille classification are the most widely used [2]. However, each system has its advantages and disadvantages. The most evident disadvantages are the lack of information regarding general and neurological clinical status, the functional integrity of the bladder and voiding systems, sexual performance, and the involvement of soft tissue in the injury. All of these are crucial for decision-making. There is therefore a need for a broader descriptive tool that would allow the clinician to communicate appropriately while providing management guidance [8,22,23]. This leads to the AO spine classification, which we will discuss in detail below. Other classification systems such as the Isler scale and the spinopelvic dissociation structural system will also be mentioned.

The Denis classification

The Denis classification system was proposed in 1988 following a retrospective analysis of 236 cases [24]. It is based on the anatomical presentation of vertical components of fractures over the sacrum anatomy divided into three major areas. The Denis classification is particularly useful for predicting the risk of neurological deficit but lacks soft tissue and instability information. Hence, it is not always suitable for decision-making when used alone (Fig. 1 and Table 1).

Denis zone I (alar zone) fractures are those that appear in the ala of the sacrum without any damage to either the foramina or spinal canal. They have a low risk of neurological deficit (< 7%), and any such deficit is related to the L5 root, which lies superior to the ala. That means clinical presentation with motor disturbances for dorsiflexion and sensory deficit relating to the lateral calf and foot. [1,24] Denis zone I fractures can be subdivided into those with and those without significant horizontal displacement [24]. Usually, such fractures do not entail instability and have a low risk of neurological deficit unless they present bilaterally, in which case the instability is sufficient to warrant surgical stabilization [9].

Denis zone II (foraminal zone) fractures present within the sacral foramina (one or more foramina). They entail neurological deficit in up to 28-30% of patients and pertain to radiculopathy not so much of L5 but more of S1-S2 [1]. Hence, fecal and bladder voiding as well as injury to the pudendal nerve are entailed,

Table 1
Denis classification system.

Type	Findings	Mechanism	Neuro deficit	Stability
Zone I	Through the ala without any damate to either the foramina or the spinal canal	Lateral compression forces, open-book deformities, and vertical shear	Low risk (<10%)	Usually stable
Zone II	Involves one or more foramina	Lateral compression forces, open-book deformities, and vertical shear	High risk (20-30%)	Usually stable
Zone III	Primarily involves the spinal canal; can also go through zones I and II	Involve a spectrum from fracture dislocations to “sacral burst” fractures	Highest risk (50%<)	Often unstable

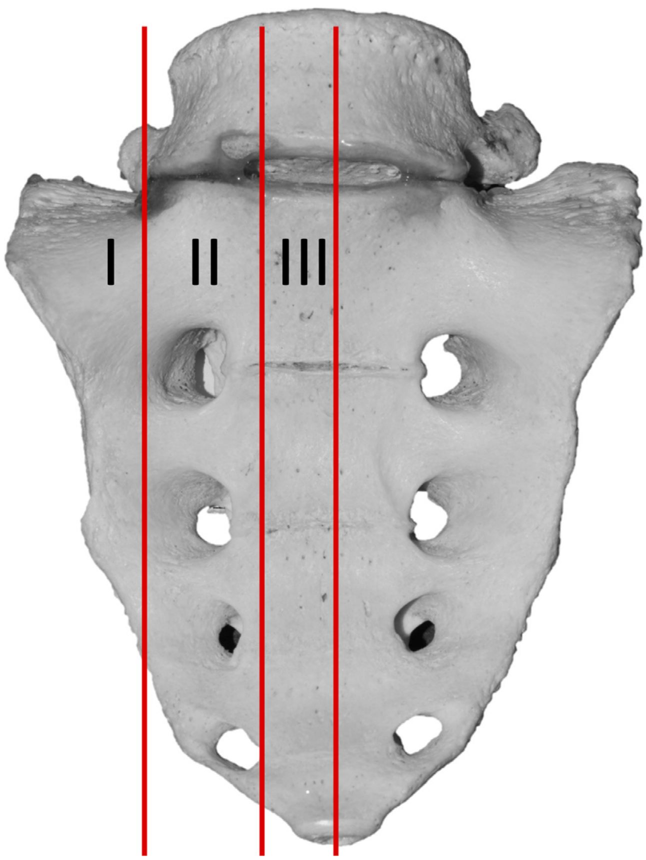

Fig. 1. Denis zones for sacral fractures (Zones I to III).

and the condition facilitates the onset of sensory disturbances in the perineum, anus, and genitalia [25].

Denis zone III (central zone) fractures involve the spinal canal. The fracture line may go through two zones. They have a risk of neurological deficit in 57% and represent the worst condition in the classification system, being related to cauda equina syndrome. Ebraheim et al. found that 87.5% of patients presenting with Denis zone III SF had loss of bowel and bladder function and 62.5% had sexual dysfunction [26]. Since this pattern almost invariably shows a transverse component, Roy-Camille proposed a subdivision of Denis zone III fractures based on the displacement of the fracture segment, initially in three types, but this was later modified by Strange–Vognsen and Lebech in 1991 who added a fourth pattern (see next section).

The modified Roy-Camille classification

The Roy-Camille classification was first proposed in 1985 [27]. However, its final version appeared after the aforementioned modifications by Strange-Vognsen and Lebech in 1991 [28]. This classification provides useful information about the morphological configuration of the fracture, the grade of ventrodorsal displacement, and the mechanism, and some degree of information about the neurological deficit risk and stability. It also provides management guidance (Fig. 2 and Table 2). However, the system still lacks clinical assessment; the involvement of adjacent soft tissues is not addressed, so again, the clinical guidance provided fails to establish the best decision-making process. In this scale, type I refers to a central SF with kyphotic deformity without displacement; type II refers to a SF presenting with kyphosis and partial retrolisthesis of the upper segment with a higher risk of neuropathy than type I. Both types I and II are produced by hyperflexion of the sacrum and present a moderate risk of instability. The type III fracture presents with sacral spondyloptosis, holding the highest risk of cauda equina syndrome with a high risk of instability. Finally, type IV, added in 1991, presents a transverse fracture without displacement and with comminution of the affected segment. It is produced by axial loading forces and has a high rate of instability [29].

Similarly, the Isler classification (Fig. 3 and Table 3) classifies Denis zone II fractures depending on the position of the fracture line in relation to the facet articulation and provides stability information: Isler type I for those lateral to the facet, type II for those that disrupt the facet directly, and type III for those extending medial to the facet joint and involving the spinal canal. It is noteworthy that type I presenting bilaterally and type III presenting unilaterally entail instability and indicate surgical treatment.

With the advent of CT, an additional system analogous to the modified Roy-Camille system was produced as a merely descriptive classification for spinopelvic dissociations. It classifies the fractures depending on the fracture line shape as: U, H, II, T and Y (Fig. 4) [9]. This system is widely used but provides little management guidance because all of these presentations are usually unstable. For that reason, the Denis classification and the modified Roy-Camille classification remain the main assessment tools worldwide.[1]

AO spine classification for sacral fractures

In 2016, a survey by the AO foundation that included 474 spine surgeons worldwide revealed a consensus: A universally accepted classification system was needed that would include clinical guidance, enhanced communication among spine professionals, global assessment regarding stability, and correlation of severity of each type of fracture [23]. On the basis of this consensus, and with the collaboration of AO spine and trauma members, the AO Spine Sacral Fracture Classification system was proposed to ameliorate the disadvantages of the earlier systems [30]. The fractures were sorted into type A (A1-A3) for lower sacrococcygeal injuries; no impact on posterior pelvic or spino-pelvic instability, type B (B1-B3) for posterior pelvic injuries; primary impact is on posterior pelvic stability, and type C (C0-C3) for spino-pelvic injuries; spino-

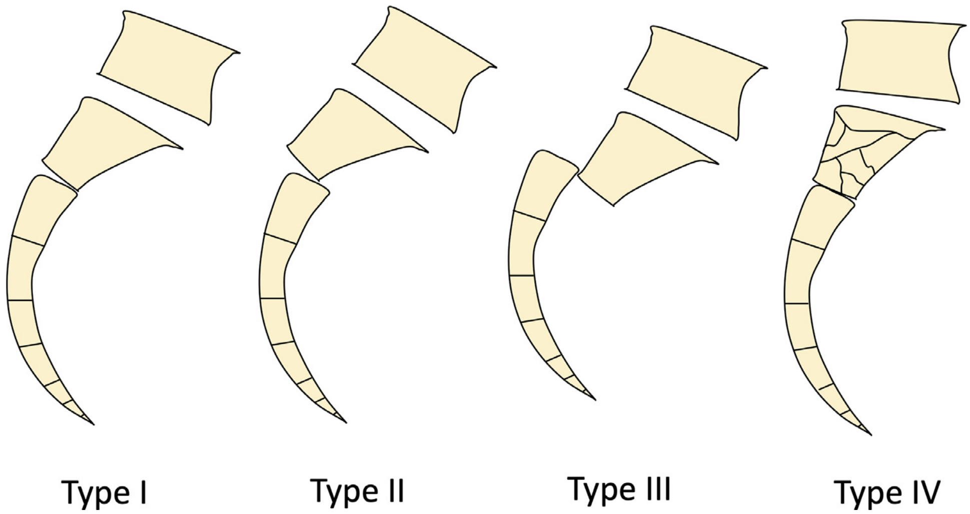

Fig. 2. Roy-Camille classification modified by Strange-Vognsen and Lebech (Types I to IV).

Table 2
Modified Roy-Camille classification system.

Type	Findings	Mechanism	Neuro deficit	Stability
Type 1	Kyphosis w/o displacement	Hyperflexion	Low risk	Potentially stable
Type 2	Kyphosis with partial Retrolisthesis	Hyperflexion	High risk	Often unstable
Type 3	Anterior displacement of the sacrum SUP BOD segment	Hyperextension	Highest risk	Always unstable
Type 4	Transverse with Conminution	Axial loading	High risk	Always unstable

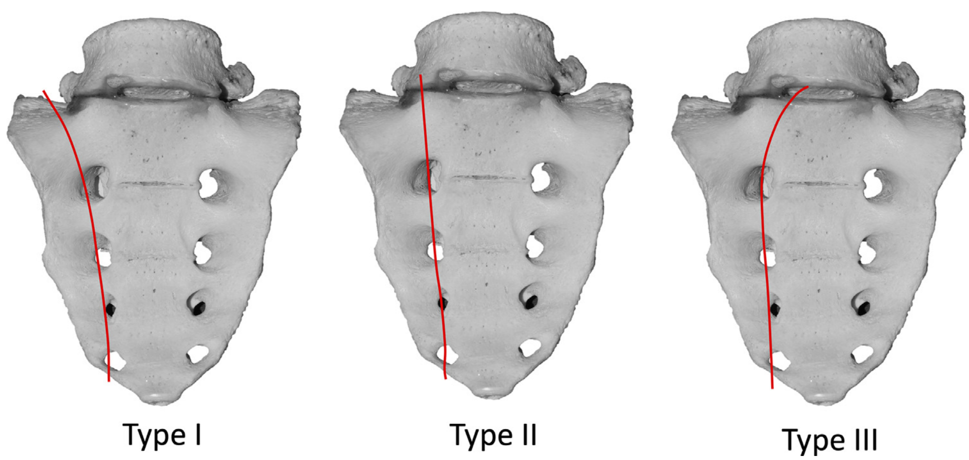

Fig. 3. Isler classification of Denis zone II sacral fractures (Types I to III).

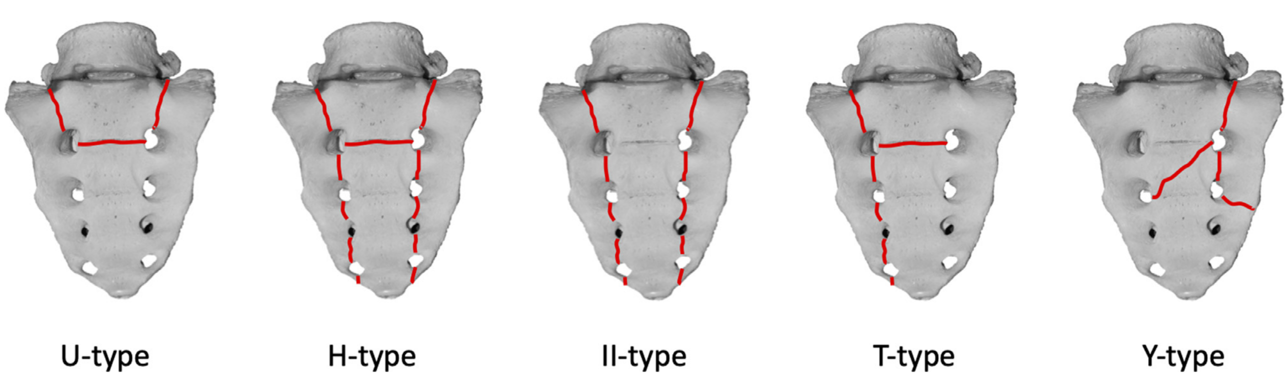

Fig. 4. Schematic depiction of the types of spinopelvic dissociation (adapted from Lehmann et al., 2012).

Table 3
Isler classification system.

Type	Findings	Stability
Type I	Fractures lateral to the facet in which the dislocating hemipelvis causes a fracture of the articular process of S1 or of the corresponding inferior articular process	Unstable when bilateral Stable when unilateral
Type II	Fractures of the lumbosacral junction that exist through the L5/S1 facet in which the dislocating hemipelvis causes a disruption at the level of the joint: (a) in the form of a fracture dislocation, if the sacral fracture passes through the articular process of S1 (b) in the form of subluxation (c) in the form of a completely locked dislocation	Higher instability
Type III	Fractures of the lumbosacral junction that exit medial to the facet where the dislocating hemipelvis causes multiple lesions along the articular pillars with resulting joint incongruencies and fractures of the articular processes, interarticular portions, laminae and pedicles	Highest instability

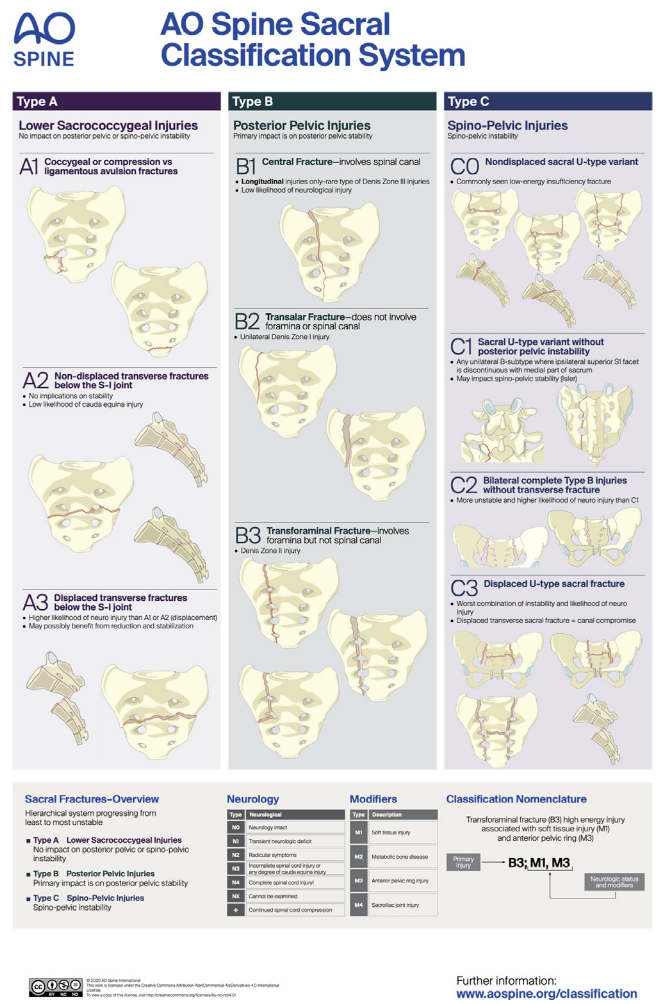

Fig. 5. AO spine sacral classification system. Reprinted from https://aospine.aofoundation.org/clinical-library-and-tools/ao-spine-classification-systems.

Table 4
The Gibbons Classification of cauda equina impairment (adapted from Beckmann and Chinapuvvula, 2017).

Type	Neurological deficit
Type I	None
Type II	Paresthesia only
Type III	Lower extremity motor deficit
Type IV	Bowel/bladder dysfunction

pelvic instability (Fig. 5). This system retains a hierarchy of increasing severity, the C type being the most severe [30]. Additionally, it addresses neurological status information, modifying Gibbonś cauda equina assessment and soft tissue modifiers (Table 4) [31].

Clinical assessment

Clinical assessment of SF is complex and challenging for the clinician because of the unique setting in which these fractures present. The multidisciplinary approach required for trauma cases enhances the patientś general clinical inspection. Since SF rarely present in isolation, the possibility of life-threatening injuries should be investigated following the advanced trauma life support (ATLS) algorithms before the sacral-focused assessment [32]. For example, associated visceral injuries were noted in 42% of cases, thoracic injuries in 37%, and closed head injuries in 21% [33]. Musculoskeletal injuries included extremities in 63%, anterior pelvic fractures in 52%, other spine fractures in 47%[33]. Spinal cord injury was noted in 16% [33].

After the achievement of hemodynamic stability and adequate resuscitation, the integrity of the pelvic ring should be evaluated first through physical examination tools and then with basic radiological assessment [34]. Through inspection, the physician can judge the symmetry of the pelvic structures, the presence of hematomas, soft tissue injuries and associated open wounds. Abnormal movement of the ilia can be elicited by manual internal and external rotation maneuvers, assessing the subcutaneous tissue for degloving (Morell-Lavallé́s lesion) [18]. Vaginal examinations provide information about open injuries. Pelvic ring injury also predisposes to vascular lesions, so it is also important to assess distal pulses [25].

The neurological assessment must include motor function, sensory function examination using a pinprick maneuver on the dermatomes of the gluteal region, anus, perineal region and external genitalia [25]. Rectal examination is necessary for evaluating the integrity of innervation to the anal sphincters, and the bulbocavernosus and cremasteric reflexes establish whether there is cauda equina injury [35].

Radiological assessment is made after the initial physical examination and evaluation of the general stability of the patientś condition. Before the advent of CT, X-Ray images were the only tool for the structural workup of the pelvic ring [2]. Because of its very low sensitivity regarding sacral fractures, plain X-Ray is not considered the best assessment tool, but sometimes it is the only available option. In such a case, the anteroposterior view, inlet, outlet, and lateral projections can increase the techniqueś receiver operative characteristics to achieve a more accurate diagnosis. A CT scan is considered the gold standard given its high sensitivity and specificity. Sagittal and coronal reconstructions are mandatory for adequate characterization of the lesions. Three-dimensional CT reconstructions can help surgeons to assess the fracture patterns prior to the surgeries. MRI techniques facilitate the assessment of soft tissue and have better receiver operating characteristics (ROC) than CT, but low availability and greater cost mean this technique is not widely used for diagnosing SF [4].

Treatment options

Management options for SF must accomplish the restoration of neurological, structural and functional outcomes while respecting the biomechanical properties of the LSCFU [10]. Consequently, the main factors to keep in mind while planning management are the fracture etiology, correct structural assessment of the fracture, neurological status represented by motor, sensitive, bowel/bladder, and sexual function, soft tissue involvement, stability, and concomitant associated injuries [36]. Given this broad spectrum of factors to consider, rigid management guidelines are difficult to conceive, and each case must be considered individually to provide the best outcome possible. The multidisciplinary approach among trauma surgeons and subspecialists provides the key to success in treating SF and its associated lesions [1].

The primary treatment should start with an adequate ATLS assessment, resuscitation, and control of associated life-threatening lesions. The use of pelvic binders and sheets in primary management has effected a statistically significant reduction in mortality and ICU length of stay and should be implemented after the clinical assessment of neurological function as mentioned above [37]. In general, the management choices are non-operative management, surgical direct or indirect decompression, minimally invasive osteosynthesis with or without navigation, external fixation, and open reduction with internal fixation techniques. Sacroplasty might be reserved for non-displaced low-grade insufficiency fractures of the sacrum although it is still controversial [38].

Non-surgical management

Conservative management is based on modification of activity, hip Spica casts, bracing, and traction techniques [9]. It is reserved for fractures without neurological deficit, preserved stability, absence of soft tissue involvement, and no displaced fragments. For instance, it is indicated for unilateral zones I and II fractures in the Denis classification, and types A1 and A2 in the AO classification. Non-operative management for fracture types A3 and B, and C0 (some equivalents to Denis zone III fractures), can be considered in individual cases where there is adequate tolerance to immobility and absence of displacement. However, Siebel et al. published a case series of sacral Denis zone III fractures treated by non-surgical management and showed that even though the fractures healed in every patient, the functional scores were always lower than in the general population, and some continued to have bladder, bowel, and sexual dysfunction and presented with chronic back pain [39]. It is noteworthy that fractures presenting below the S2 segment without displacement have a low risk of instability and, even when they present with neurological symptoms, conservative management is possible. Although conservative management has had proven good outcomes, the cases must be carefully selected and followed up for functionality.

Decompression

The term 'decompression' refers to the relief of tension/compression of neural structures entrapped or under traction after a change in the physiological structure of the surrounding tissues [40,41]. Decompression is one of the main objectives of treatment in every surgical or non-surgical intervention, so it can be achieved directly, using laminectomy or foraminotomy, or indirectly through reduction (open or closed) of the fracture segments, restoring the patency of the neural foramina and canals. Indications for these techniques are focused on the presence of neurological deficit and radiculopathies, stable fractures with little displacement, and soft tissue involvement or adverse anatomy for lumbopelvic fixation [42].

The Surgical Timing in Acute Spinal Cord Injury Study (STASCIS) [40] provided information about the importance of early decompression for achieving neurological improvements. Although the study focused on the cervical segments and compression of the spinal cord, its results have been used to support early decompression for spine traumatic injury to other neural structures; despite the fact that the nature of the compressed element (spinal cord in contrast of the cauda equina) differs greatly in terms of relative durability of nervous elements, neural perfusion, and innervation patterns which makes the validity of the comparisons unclear [40,43]. Kepler et al. in 2017 presented a systematic review of the literature that included 30 articles and 309 patients presenting with SF and comparing surgical direct vs. indirect decompression. Among these patients, 13% showed no functional recovery, 40% achieved partial recovery and 45% achieved complete recovery. The authors revealed a non-significant trend toward improvement in function using indirect decompression alone (P=0.08) and found better outcomes when decompression was performed within the first 72 hours after the clinical manifestations [44]. Complications and failure of direct decompression in monotherapy are related to patients who are poorly selected because pelvic instability and alignment are overlooked.

Sacroplasty

Percutaneous administration of stabilizing compounds into the cancellous portion of the sacrum at the level of S1-S2 segments (sacral ala) has been used since 2001, initially for metastatic pelvic lesions. [38] Since then, the procedure has proved useful for reducing pain in sacral insufficiency fractures (SIF). Frey et al. in 2017 published a prospective cohort study that included 244 patients with SIF who were treated with non-surgical management vs. sacroplasty [45]. A 10-year follow-up revealed that the sacroplasty group showed statistically significantly lower visual analog scale (VAS) scores than the non-surgical group. However, the study provided no information about the classification or stability of the fractures and did not include neurological status in the follow-up. Although it confirmed the safety and efficacy of sacroplasty for sacral insufficiency fractures, the evidence was not conclusive with respect to development of classification-based recommendations. Complications associated with this procedure include penetration of/extrusion of cement around the neural structures within the sacral plexus in up to 7.4% of cases, but usually with few clinical consequences [38]. Gupta et al. in 2014 presented a retrospective review of cases and included functional outcome assessment measured by the Functional Mobility Scale documenting a decrease from 3.0 (preoperative) to 1.0 (postoperative) ($P < 0.001$) among osteoporotic, traumatic and bilateral SF. Talmadge et al. obtained similar results [46,47]. As the biomechanical outcomes of sacroplasty have not been completely elucidated, this procedure is typically used in cases of insufficiency with non-displaced and stable fractures of the sacrum.

Minimally invasive osteosynthesis and sacroiliac fixation: posterior pelvic ring fixation

Posterior pelvic ring fixation using a sacroiliac screw (SIS) has been proposed for traumatic SF [48,49]. It involves the percutaneous placement of a 7 mm cannulated cancellous sacroiliac screw at the height of the S1 and S2 vertebrae. This can be done unilaterally or bilaterally [50]. The technique has advantages that include decreased surgical times, fewer wound-related complications and less bleeding, infection rates close to 0%, and minimal involvement of soft tissue because the technique is percutaneous. However, the reported disadvantages include persistent back pain in up to 30% of patients, and only 70-78% neurological improvement for transverse SF cases with spinopelvic dissociation; this is low compared to lumbopelvic fixation, and lacks a biomechanical basis.[51,52] SIS fixation can be contraindicated in cases of severe soft tissue involvement, sacral dysmorphism, inadequate safe entry zones, and in AO type B3 (high-grade Denis zone II) SF [4]. It can be used as supplemental hardware or alone in percutaneous or open reductions [21].

Additionally, the lack of direct visualization and limited tactile control leads to increased X-ray exposure. Complications of SIS include hardware malposition in up to 18-25% of cases, and breakages [53]. This technique has been used in Denis zone I, selected unilateral Denis zone II and non-displaced Denis zone III fractures with Roy-Camille I displacement pattern, noncomminuted U-shaped fractures,[51] fracture types B1, 2 and 3 in association with lumbopelvic fixation, or C0 in the AO spine classification for SF [54].

Lumbopelvic fixation

Lumbopelvic fixation refers to the compilation of techniques aimed at achieving functional fixation of the lumbar spine to the ilia to fix the sacroiliac joint and bypass the injured sacrumś biomechanical attachment to the lumbosacral spine and pelvic ring (Fig. 6) [33]. This treatment option is the most biomechanically robust but implies broader surgical exposure, more bleeding and longer operation times [51]. The surgical outcomes such as percentage of union and fixation over time vary depending on the specific techniques and materials used. Indications for lumbopelvic fixation include high grade spondylolisthesis; long segment fusions to the sacrum used in the setting of spinal deformity and lumbar fractures; destructive lesions to the sacrum including those caused by neoplasm, osteomyelitis, and fractures; and treatment of L5-S1 pseudoarthrosis [55]. Specifically regarding SF, the use of lumbopelvic fixation is indicated in any of the C type SF in the AO spine classification, i.e., in any fracture of the sacrum that entails instability or spinopelvic dissociation [50].

The technique was first introduced in 1950-60 with the appearance of Harrington instrumentation, a system of hooks and rods [56]. It led to pseudoarthrosis in up to 40% and high rates of complications such as flat back syndrome. Since then, several developments have been proposed such as Luqueś sublaminar wires, the Cotrel-Dubousset, and the Galveston techniques [57]. The last constitutes the basis of the current techniques; it consists of a stronger construct using contoured iliac rods, which had better biomechanical profiles than the earlier techniques but still had high rates of failure and complications. However, the technique was improved by the advent of tricortical S1, transiliac, and S2 alar-iliac screws [58]. Currently, lumbopelvic fixation can be used alone or in combination with the screws mentioned above; for example, combinations between the iliosacral and transiliac screws (triangular osteosynthesis) [59,60]. Moreover, these techniques have been performed using minimally invasive approaches with navigation systems and robotics, increasing accuracy and decreasing operative times, surgical exposure and complications [61,62].

S1 pedicular screw

The S1 pedicular screw has the most robust attachment to the cancellous bone of the sacrum. O'Brien et al. divided the pelvic structures into three areas depending on the solidity of the bony structures [63]. They defined the vertebral bodies of S1 as area 1 or the strongest, the ilia as area two and intermediate, and the lower sacrum as area 3 and less compact bone. S1 and S2 then provide the strongest anatomical corridors for hardware placement [48]. This type of hardware has three potential trajectories: Anterolateral aiming towards the ala; Anterior towards the border between the vertebral body and the ala; and Anteromedial, heading toward the sacral promontory [64]. Among these, the anteromedial trajectory represents the most biomechanically robust basis for spinopelvic constructs since it possesses the firmest bony support and because the tricortical purchase increases the overall strength [60,64].

Similarly, the S2 pedicle screw has two main trajectories: The anteromedial trajectory towards the vertebral body, and the anterolateral aiming towards the ala. Although the S2 pedicle screw has shown good surgical outcomes, it does not replace the S1 pedicle screw or the S2 alar-iliac screw described below [51].

Iliac screw (transiliac)

The transiliac screw was introduced in early 2000 to improve the biomechanical profile of the Galveston rod technique by placing large-diameter screws into the iliac column, which is a compact bony corridor between the posterior superior iliac spine (PSIS) and the anterior inferior iliac spine (AIIS) [51]. This corridor is bounded superiorly by the wing of the ilia and inferiorly by the acetabulum and the greater sciatic notch. This bony structure provides the transiliac screw with excellent biomechanical strength. Consequently, the entry point and the ideal trajectory of the screw match these anatomical boundaries [65]. As a disadvantage, the iliac screw is very prominent owing to its entry point in the PSIS, which leads to soft tissue injury and pain. Techniques to recess the screw head within the PSIS help to partially mitigate screw head prominence [60]. Also, the increased torque exerts considerable pressure on the rods connecting with the cephalic end of the construct, increasing its likelihood of breaking at this level (up to 31% of cases) [33]. Other risks include invasion of the greater sciatic notch and injury to the superior gluteal artery, leading to extensive bleeding and acute hypovolemia. In a case series presented by Bellabarba et al., up to 16% of patients had infections including methicillin-resistant staphylococcus and Gram-negative organisms [33]. This technique can be used both in open and percutaneous approaches and is one of the most widely used to fix the lumbopelvic structures [55]. Other additions to the technique have

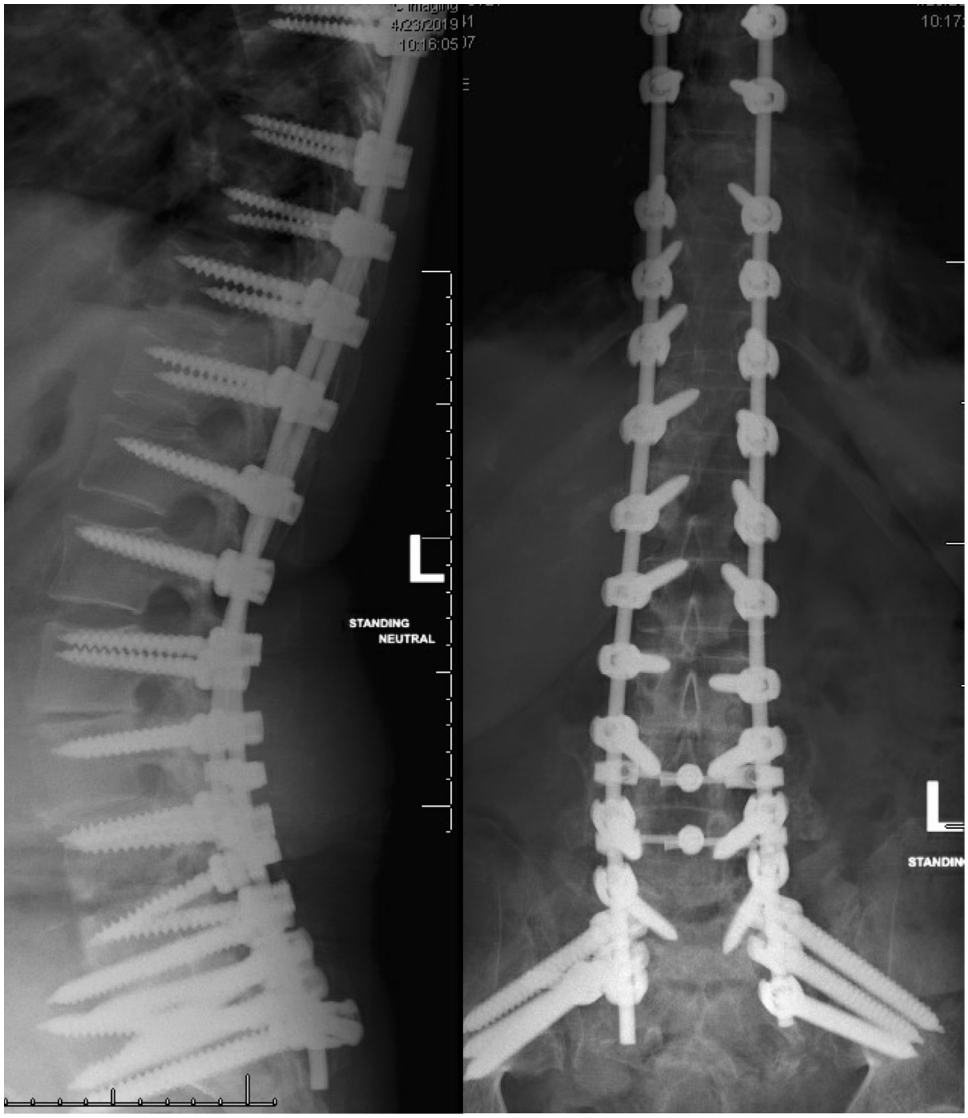

Fig. 6. A 77-year-old female patient with traumatic fracture of the T8 vertebral body, complex sacral fracture, and unstable pelvic fracture. A T6-lumbopelvic fixation was performed and post-operative radiographs are shown.

been described such as triangular osteosynthesis (using a transiliac screw simultaneously) or modifications such as the use of S2 alar-iliac screws.

Triangular osteosynthesis

Triangular osteosynthesis, introduced during the late 1990s, refers to the use of a vertical fixation component represented by a lumbopelvic construct using transiliac screws, and a horizontal part represented by a sacroiliac screw at the height of the S1 vertebral body [59]. The aim of this technique is to provide enhanced multiplanar stability of the LSCFU. It results in a statistically significantly smaller displacement and better stability than sacroiliac fixation alone [59]. Therefore, the combination of vertical and horizontal components of fixation provides additional protection against cranial migration of the injured half of the pelvic ring while sacroiliac fixation in isolation cannot resist vertical shearing loads, resulting in hardware breakage and displacement [65]. The disadvantages of triangular osteosynthesis concern the use of transiliac screws and are related to prominence, rod breakage, decubitus ulcer, infection, hematoma, and second operations [33]. Triangular osteosynthesis is contraindicated if soft tissue is compromised and indicated in unstable transforaminal Denis zone II fractures, cases with severe displacement and inadequate sacral anatomy. Notably, the presence of previous hardware can produce obstruction at the moment of fixation [66].

S2 Alar-Iliac screw (S2AI)

The S2AI emerged to combat the disadvantages of transiliac screw placement and has caused fewer complications than the previously-mentioned technique [67]. The insertion point is placed one centimeter lateral to the midline and between the S1 and S2 foramina adjacent to the sacroiliac joint [68]. The trajectory aims toward the AIIS with 30-40 degrees of lateral angulation in the transverse plane and 20-30 degrees of caudal angulation in sagittal. This entry point makes side connectors unnecessary since the screw is placed 10 to 15 mm deeper into the soft tissues and traverses three cortices to increase its fixation force and purchases both the ilia and the sacrum [69]. Its advantages include less rod breakage, fewer wound complications owing to its less prominent profile, enhanced torque strength, the option of rod construction in-line without the need to bend the rod, less paraspinal muscle dissection, and less morbidity [70]. Limitations of this technique that have been described include misplacement of hardware violating both the acetabulum (chondral lesion) and the greater sciatic foramen (neurovascular injury), injuring the superior gluteal artery, the sciatic nerve, the obturator nerve, the internal iliac vein and artery, and the lumbosacral plexus [70].

Ilyas et al. in 2015 presented a case series comparing complications of the use of S2AI versus iliac screws. They found that the S2AI had significantly fewer complications in both adult and pediatric populations [71]. There were statistically significant absolute risk reductions for acute infection (13%), loosening (18.1%), revision surgery (14.5%), late pain (18.7%), and delayed wound complications (10.8%) [72]. Regarding biomechanical rigidity, Hoernschemeyer et al. in 2017 found that S2AI invariably increased the construct stiffness but the results were not statistically significant, probably because of the small sample size [73]. These screws can be applied using a freehand technique, minimally invasive surgery, navigation guided and using robotics [58,74].

Conclusions

Fractures of the sacrum are associated with unique anatomy and biomechanics. Additionally, there is no consensus among the various classification schemes or best treatments strategies. This paper has reviewed vulnerable anatomical structures and all classification and treatment strategies for SF. Future, prospective studies are needed to assess best practices for these fractures of the vertebral column.

Funding

None.

Ethical approval

The protocol of the study did not require approval by the ethical committees or informed consent. The study followed the Declaration of Helsinki (64th WMA General Assembly, Fortaleza, Brazil, October 2013).

Declaration of Competing Interest

The authors declare that they have no conflict of interest.

References

[1] Beckmann NM, Chinapuvvula NR. Sacral fractures: classification and management. Emerg Radiol 2017;24:605–17. doi:10.1007/s10140-017-1533-3.
[2] Beckmann N, Cai C. CT characteristics of traumatic sacral fractures in association with pelvic ring injuries: correlation using the Young-Burgess classification system. Emerg Radiol 2017;24:255–62. doi:10.1007/s10140-016-1476-0.
[3] Kannus P, Palvanen M, Niemi S, Parkkari J, Järvinen M. Epidemiology of osteoporotic pelvic fractures in elderly people in Finland: sharp increase in 1970-1997 and alarming projections for the new millennium. Osteoporos Int 2000;11:443–8. doi:10.1007/s001980070112.
[4] Kuklo TR, Potter BK, Ludwig SC, Anderson PA, Lindsey RW, Vaccaro AR. Radiographic measurement techniques for sacral fractures consensus statement of the Spine Trauma Study Group. Spine 2006;31:1047–55 (Phila Pa 1976). doi:10.1097/01.brs.0000214940.11096.c8.
[5] Bydon M, De la Garza-Ramos R, Macki M, Desai A, Gokaslan AK, Bydon A. Incidence of sacral fractures and in-hospital postoperative complications in the United States. Spine 2014;39:E1103–9 (Phila Pa 1976). doi:10.1097/BRS.0000000000000448.
[6] Wagner D, Ossendorf C, Gruszka D, Hofmann A, Rommens PM. Fragility fractures of the sacrum: how to identify and when to treat surgically? Eur J Trauma Emerg Surg 2015;41:349–62. doi:10.1007/s00068-015-0530-z.
[7] Cook C, Yoder K, Long C, Averell K, McBride E, Bartsokas J. Risk factors associated with sacral stress fractures: a systematic review. J Man Manip Ther 2014;23:84–92. doi:10.1179/2042618613y.0000000055.
[8] Bakker G, Hattingen J, Stuetzer H, Isenberg J. Sacral insufficiency fractures: How to classify? J Korean Neurosurg Soc 2018;61:258–66. doi:10.3340/jkns.2017.0188.
[9] Lehmann W, Hoffmann M, Briem D, Grossterlinden L, Petersen JP, Priemel M, et al. Management of traumatic spinopelvic dissociations: Review of the literature. Eur J Trauma Emerg Surg 2012;38:517–24. doi:10.1007/s00068-012-0225-7.
[10] Acevedo Gonzalez JC, Perez Rodriguez JC. Unidad lumbosacrococcígea. Desarrollo conceptual. Rev Colomb Ortop Traumatol 2017;21:55–62. doi:10.1016/j.rccot.2017.03.002.
[11] Moroney SP, Schultz AB, Miller JAA, Andersson GBJ. Load-displacement properties of lower cervical spine motion segments. J Biomech 1988;21:769–79. doi:10.1016/0021-9290(88)90285-0.
[12] Lindado Pacheco CA, Gutierrez S, Acevedo González JC. Factores pronósticos para artrodesis lumbar. Univ Médica 2018;60:1–8. doi:10.11144/Javeriana.umed60-1.artr.
[13] Ames CP, Smith JS, Scheer JK, Bess S, Bederman SS, Deviren V, et al. Impact of spinopelvic alignment on decision making in deformity surgery in adults. J Neurosurg Spine 2012;16:547–64. doi:10.3171/2012.2.SPINE11320.
[14] Acevedo J. Síndrome facetario lumbar. Nuevo signo de diagnóstico clínico. Rehabilitación 2004;38:168–74. doi:10.1016/S0048-7120(04)73452-0.
[15] Le Huec JC, Thompson W, Mohsinaly Y, Barrey C, Faundez A. Sagittal balance of the spine. Eur Spine J 2019;28:1889–905. doi:10.1007/s00586-019-06083-1.
[16] Merrill RK, Kim JS, Leven DM, Kim JH, Cho SK. Beyond pelvic incidence–lumbar lordosis mismatch: the importance of assessing the entire spine to achieve global sagittal alignment. Glob Spine J 2017;7:536–42. doi:10.1177/2192568217699405.
[17] Hart RA, Badra MI, Madala A, Yoo JU. Use of pelvic incidence as a guide to reduction of H-type spino-pelvic dissociation injuries. J Orthop Trauma 2007;21:369–74. doi:10.1097/BOT.0b013e31806dd959.
[18] Rodrigues-Pinto R, Kurd MF, Schroeder GD, Kepler CK, Krieg JC, Holstein JH, et al. Sacral fractures and associated injuries. Glob Spine J 2017;7:609–16. doi:10.1177/2192568217701097.
[19] Bydon M, Frederickson V, De la Garza-Ramos R, Li Y, Lehman RA, Trost GR, et al. Sacral fractures. Neurosurg Focus 2014;37:E12. doi:10.3171/2014.5.FOCUS1474.
[20] Smith JS, Shaffrey CI, Lafage V, Schwab F, Scheer JK, Protopsaltis T, et al. Comparison of best versus worst clinical outcomes for adult spinal deformity surgery: a retrospective review of a prospectively collected, multicenter database with 2-year follow-up. J Neurosurg Spine 2015;23:349–59. doi:10.3171/2014.12.SPINE14777.
[21] Pearson JM, Niemeier TE, McGwin G, Manoharan R, Spinopelvic S. Dissociation: comparison of outcomes of percutaneous versus open fixation strategies. Adv Orthop 2018;2018:1–6. doi:10.1155/2018/5023908.
[22] Lehman RA, Kang DG, Bellabarba C. A new classification for complex lumbosacral injuries. Spine J 2012;12:612–28. doi:10.1016/j.spinee.2012.01.009.
[23] Schroeder G, Kurd MF, Kepler CK, Chapman JR, Vaccaro AR, Sagi HC, et al. The development of a universally accepted sacral fracture classification: a survey of AOSpine and AOTrauma members. Glob Spine J 2016;6 s-0036-1582908-s-0036-1582908. doi:10.1055/s-0036-1582908.
[24] Denis F, Davis S, Comfort T. Sacral fractures: an important problem. Retrospective analysis of 236 cases. Clin Orthop Relat Res 1988;227:67–81.
[25] Brazis PW, Masdeu JC. Localization in clinical neurology. Sixth. Philadelphia PA: Lippincott Williams & Wilkins; 2011.
[26] Ebraheim NA, Biyani A, Salpietro B. Zone III fractures of the sacrum. A case report. Spine 1996;21:2390–6 Phila Pa 1976.
[27] Roy-Camille R, Saillant G, Gagna G, Mazel C. Transverse fracture of the upper sacrum. Suicidal jumper's fracture. Spine 1985;10:838–45 Phila Pa 1976.
[28] Strange-Vognsen HH, Lebech A. An unusual type of fracture in the upper sacrum. J Orthop Trauma 1991;5:200–3.
[29] Bishop JA, Dangelmajer S, Corcoran-Schwartz I, Gardner MJ, Routt MLC, Castillo TN. Bilateral sacral ala fractures are strongly associated with lumbopelvic instability. J Orthop Trauma 2017;31:636–9. doi:10.1097/BOT.0000000000000972.
[30] Kleweno CP, Kepler CK, Schnake KJ, Kandziora F, Oner FC, Krieg JC, et al. The AOSpine sacral fracture classification. Glob Spine J 2016;6 s-0036-1582696-s-0036-1582696. doi:10.1055/s-0036-1582696.
[31] Nonne D, Capone A, Sanna F, Busnelli L, Russo AL, Marongiu G, et al. Suicidal jumper's fracture – sacral fractures and spinopelvic instability: a case series. J Med Case Rep 2018;12:186. doi:10.1186/s13256-018-1668-1.
[32] Rozo OL. Condiciones de salud y trabajo asociadas a dolor lumbar inespecífico en los operarios de la línea de ensamble de superpolo S. A UNIVERSIDAD NACIONAL DE COLOMBIA; 2009.
[33] Bellabarba C, Schildhauer TA, Vaccaro AR, Chapman JR. Complications associated with surgical stabilization of high-grade sacral fracture dislocations with spino-pelvic instability. Spine 2006;31:S80–8 (Phila Pa 1976). doi:10.1097/01.brs.0000217949.31762.be.
[34] Rommens PM, Hofmann A. Comprehensive classification of fragility fractures of the pelvic ring: recommendations for surgical treatment. Injury 2013;44:1733–44. doi:10.1016/j.injury.2013.06.023.
[35] Rommens PM, Wagner D, Hofmann A. Surgical management of osteoporotic pelvic fractures: a new challenge. Eur J Trauma Emerg Surg 2012;38:499–509. doi:10.1007/s00068-012-0224-8.
[36] Haroun HS. Clinical anatomy of the splanchnic nerves. MOJ Anat Physiol 2018;5:87–90. doi:10.15406/mojap.2018.05.00169.
[37] Hsu S, Chen C, Chou Y, Wang S, Chan D. Effect of early pelvic binder use in the emergency management of suspected pelvic trauma: a retrospective cohort study. Int J Environ Res Public Health 2017;14:1217. doi:10.3390/ijerph14101217.

[38] Frey ME, Warner C, Thomas SM, Johar K, Singh H, Mohammad MS, et al. Sacroplasty: a ten-year analysis of prospective patients treated with percutaneous sacroplasty: literature review and technical considerations. Pain Physician 2017;20:E1063–72.
[39] Siebler JC, Hasley BP, Mormino MA. Functional outcomes of Denis zone III sacral fractures treated nonoperatively. J Orthop Trauma 2010;24:297–302. doi:10.1097/BOT.0b013e3181ccb645.
[40] Fehlings MG, Vaccaro A, Wilson JR, Singh A, Cadotte W, Harrop D, et al. Early versus delayed decompression for traumatic cervical spinal cord injury: results of the surgical timing in acute spinal cord injury study (STASCIS). PLoS One 2012;7:e32037. doi:10.1371/journal.pone.0032037.
[41] Schildhauer TA, Bellabarba C, Nork SE, Barei DP, Frcs C, Routt LC, et al. Decompression and lumbopelvic fixation for sacral fracture-dislocations with spino-pelvic dissociation. J Orthop Trauma 2006;20:447–57.
[42] Sasso RC, Vaccaro AR, Chapman JR, Best NM, Zdeblick TA, Harris MB. Sacral fractures. Instr Course Lect 2009;58:645–55.
[43] Hollern DA, Kepler CK, Chapman JR, Schroeder GD, Dvorak M, Fehlings MG, et al. Do formal laminectomy and timing of decompression for patients with sacral fracture and neurologic deficit affect outcome? J Orthop Trauma 2017;31:S75–80. doi:10.1097/bot.0000000000000951.
[44] Kepler CK, Schroeder GD, Hollern DA, Chapman JR, Fehlings MG, Dvorak M, et al. Do formal laminectomy and timing of decompression for patients with sacral fracture and neurologic deficit affect outcome? J Orthop Trauma 2017;31:S75–80. doi:10.1097/BOT.0000000000000951.
[45] Onen MR, Yuvruk E, Naderi S. Reliability and effectiveness of percutaneous sacroplasty in sacral insufficiency fractures. J Clin Neurosci 2015;22:1601–8. doi:10.1016/j.jocn.2015.03.039.
[46] Gupta AC, Chandra RV, Yoo AJ, Leslie-Mazwi TM, Bell DL, Mehta BP, et al. Safety and effectiveness of sacroplasty: a large single-center experience. Am J Neuroradiol 2014;35:2202–6. doi:10.3174/ajnr.A4027.
[47] Talmadge J, Smith K, Dykes T, Mittleider D. Clinical impact of sacroplasty on patient mobility. J Vasc Interv Radiol 2014;25:911–15. doi:10.1016/j.jvir.2014.02.007.
[48] Dilogo IH, Satria O, Fiolin J. Internal fixation of S1-S3 iliosacral screws and pubic screw as the best configuration for unstable pelvic fracture with unilateral vertical sacral fracture (AO type C1.3): a biomechanical study. J Orthop Surg 2017;25:1–7. doi:10.1177/2309499017690985.
[49] Zhao Y, You L, Lian W, Zou D, Dong S, Sun T, et al. Anatomical relation between S1 sacroiliac screws' entrance points and superior gluteal artery. J Orthop Surg Res 2018;13:15. doi:10.1186/s13018-018-0713-5.
[50] Salmon J, Davey S, Kanlic E, Abdelgawad AA, Gurusamy P. Ilio-sacral (IS) screw fixation for sacral and sacroiliac joint (SIJ) injuries in children. J Pediatr Orthop 2015;36:117–21. doi:10.1097/bpo.0000000000000416.
[51] Bederman SS, Hassan JM, Shah KN, Kiester PD, Bhatia NN, Zamorano DP. Fixation techniques for complex traumatic transverse sacral fractures. Spine 2013;38:E1028–40 Phila Pa 1976. doi:10.1097/BRS.0b013e318297960a.
[52] Nork SE, Jones CB, Harding SP, Mirza SK, Routt MLC. Percutaneous stabilization of U-shaped sacral fractures using iliosacral screws: technique and early results. J Orthop Trauma 2001;15:238–46. doi:10.1097/00005131-200105000-00002.
[53] Moscote-Salazar L, Alcala-Cerra G, Alvis-Miranda H, Farid-Escorcia H, Castellar-Leones S. Sacroiliac screw fixation: a mini review of surgical technique. J Craniovertebr Junction Spine 2014;5:110. doi:10.4103/0974-8237.142303.
[54] König MA, Jehan S, Boszczyk AA, Boszczyk BM. Surgical management of U-shaped sacral fractures: a systematic review of current treatment strategies. Eur Spine J 2012;21:829–36. doi:10.1007/s00586-011-2125-7.
[55] Wang MY, Ludwig SC, Anderson DG, Mummaneni PV. Percutaneous iliac screw placement: description of a new minimally invasive technique. Neurosurg Focus 2008;25:E17. doi:10.3171/FOC/2008/25/8/E17.
[56] Pecina M, Dapic T. More than 20-year follow-up Harrington instrumentation in the treatment of severe idiopathic scoliosis. Eur Spine J 2007;16:299–300. doi:10.1007/s00586-006-0223-8.
[57] Allen BL, Ferguson RL. The galveston technique of pelvic fixation with L-rod instrumentation of the spine. Spine 1984;9:388–94 Phila Pa 1976. doi:10.1097/00007632-198405000-00011.
[58] Bederman SS, Hassan JM, Shah KN, Kiester PD, Bhatia NN, Zamorano DP. Fixation techniques for complex traumatic transverse sacral fractures. Spine 2013;38:E1028–40 Phila Pa 1976. doi:10.1097/BRS.0b013e318297960a.
[59] Schildhauer TA, Ledoux WR, Chapman JR, Henley MB, Tencer AF, Chip Routt JL. Triangular osteosynthesis and iliosacral screw fixation for unstable sacral fractures: a cadaveric and biomechanical evaluation under cyclic loads. J Orthop Trauma 2003;17:22–31. doi:10.1097/00005131-200301000-00004.
[60] Kebaish KM. Sacropelvic fixation: techniques and complications. Spine 2010;35:2245–51 Phila Pa 1976. doi:10.1097/BRS.0b013e3181f5cfae.
[61] Hu X, Lieberman IH. Robotic-guided sacro-pelvic fixation using S2 alar-iliac screws: feasibility and accuracy. Eur Spine J 2017;26:720–5. doi:10.1007/s00586-016-4639-5.
[62] Ohya J, Vogel TD, Dhall SS, Berven S, Mummaneni PV. Technique and nuances of an S-2 alar iliac screw for lumbosacral fixation in patients with transitional and normal anatomy. Neurosurg Focus 2016:41 Video:1. doi:10.3171/2016.2.FocusVid.1690.
[63] Sasaji T, Imaizumi H, Murakami T. Usefulness of sacral sublaminar wire for low transverse sacral fractures: two cases' report.. Case Rep Orthop 2017;2017:1–6. doi:10.1155/2017/7396564.
[64] Katsuura Y, Lorenz E, Gardner W. Anatomic parameters of the sacral lamina for osteosynthesis in transverse sacral fractures. Surg Radiol Anat 2018;40:521–8. doi:10.1007/s00276-017-1955-3.
[65] Schildhauer TA, McCulloch P, Chapman JR, Mann FA. Anatomic and radiographic considerations for placement of transiliac screws in lumbopelvic fixations. J Spinal Disord Tech 2002;15:199–205. doi:10.1097/00024720-200206000-00005.
[66] Laratta JL, Lin JD, Shillingford JN, Hardy NE, Reddy H, Lehman RA. Obstructed spinopelvic fixation in the setting of a triangular titanium sacroiliac fusion implant: a case description. J Spine Surg 2017;3:732–5. doi:10.21037/jss.2017.11.11.
[67] Elder BD, Ishida W, Lo SFL, Holmes C, Goodwin CR, Kosztowski TA, et al. Use of S2-Alar-iliac screws associated with less complications than iliac screws in adult lumbosacropelvic fixation. Spine 2017;42:E142–9 Phila Pa 1976. doi:10.1097/BRS.0000000000001722.
[68] Yilmaz E, Abdul-Jabbar A, Tawfik T, Iwanaga J, Schmidt CK, Chapman J, et al. S2 Alar-Iliac screw insertion: technical note with pictorial guide. World Neurosurg 2018;113:e296–301. doi:10.1016/j.wneu.2018.02.009.
[69] Burns CB, Dua K, Trasolini NA, Komatsu DE, Barsi JM. Biomechanical comparison of spinopelvic fixation constructs: iliac screw versus S2-Alar-Iliac screw. Spine Deform 2016;4:10–15. doi:10.1016/j.jspd.2015.07.008.
[70] Park Y-S, Hyun S-J, Kim H-J, Jahng T-A, Kim K-J, Park J-H. Radiographic and clinical results of freehand S2 Alar-Iliac screw placement for spinopelvic fixation. Clin Spine Surg 2018;30:E877–82. doi:10.1097/bsd.0000000000000520.
[71] Ilyas H, Place H, Puryear A. A comparison of early clinical and radiographic complications of iliac screw fixation versus S2 Alar Iliac (S2AI) fixation in the adult and pediatric populations. J Spinal Disord Tech 2015;28:E199–205. doi:10.1097/BSD.0000000000000222.
[72] Ilyas H, Place H, Puryear A. A comparison of early clinical and radiographic complications of iliac screw fixation versus S2 Alar Iliac (S2AI) fixation in the adult and pediatric populations. J Spinal Disord Tech 2015;28:E199–205. doi:10.1097/BSD.0000000000000222.
[73] Hoernschemeyer DG, Pashuck TD, Pfeiffer FM. Analysis of the s2 alar-iliac screw as compared with the traditional iliac screw: does it increase stability with sacroiliac fixation of the spine? Spine J 2017;17:875–9. doi:10.1016/j.spinee.2017.02.001.
[74] Bederman SS, Hahn P, Colin V, Kiester PD, Bhatia NN. Robotic guidance for S2-alar-iliac screws in spinal deformity correction. Clin Spine Surg 2017;30:E49–53. doi:10.1097/BSD.0b013e3182a3572b.