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Hip joint of cats and dogs: anatomy and biomechanics, fractures and treatment methods

Merve BAKICI [1,a*]**, *Barış KÜRÜM*** [1,b]

[1] *Kırıkkale University, Faculty of Veterinary Medicine, Department of Surgery, Kırıkkale, Türkiye*

0000-0001-8833-3499 [a]*; 0000-0002-5559-7815* [b]

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ABSTRACT

Fractures of the proximal femur and acetabulum, which together constitute the hip joint in cats and dogs, are typically severe injuries resulting from high-energy trauma. These injuries are often accompanied by concomitant orthopedic damage and, due to their anatomical location, intrapelvic organ damage may also be encountered. Surgical treatment is recommended rather than conservative treatment because long-term complications such as osteoarthritis and chronic pain may occur in intra-articular fractures. The primary objectives of surgical management are to restore extremity function, achieve precise anatomical reduction, and ensure rigid fixation of the fracture fragments within the shortest possible timeframe to minimize the risk of adverse outcomes. In young animals, preservation of the vascular supply to the proximal femur and protection of the growth plates are critical factors in surgical planning. For acetabular fractures, an understanding of the biomechanical forces acting on the region is essential for appropriate implant selection and effective stabilization. Equally important is an in-depth knowledge of the biomechanical characteristics of the implants themselves, including their respective advantages and limitations. This understanding directly influences implant choice and postoperative outcomes. Detailed knowledge of the vascular anatomy of the proximal femur, as well as the localization of the sciatic nerve, which lies in close proximity to the acetabulum, is imperative to minimize iatrogenic complications and ensure optimal surgical approach. Differentiating traumatic fractures from underlying pathological conditions is critical in the diagnostic process. Accurate identification of pre-existing disorders not only aids in planning the surgical approach but also allows for better prediction and management of potential postoperative complications. This review aims to provide a comprehensive overview of the current principles and considerations in the surgical management of proximal femur and acetabular fractures in cats and dogs, emphasizing the integration of biomechanical, and anatomical knowledge for successful outcomes.

Kedi ve köpeklerin kalça eklemi: anatomi ve biyomekanik, kırıklar ve tedavi yöntemleri

ÖZET

Kedi ve köpeklerde kalça eklemini oluşturan proksimal femur ve acetabulum kırıkları, genellikle yüksek enerjili travmalar sonucu oluşan ciddi yaralanmalardır. Bu yaralanmalara genellikle eş zamanlı ortopedik hasarlar eşlik eder ve anatomik konumları gereği intrapelvik organ hasarları ile de karşılaşılabilir. Eklem içi kırıklarda osteoartrit ve kronik ağrı gibi uzun vadeli komplikasyonlar oluşabileceği için konservatif sağaltımdan ziyade cerrahi sağaltım önerilir. Cerrahi sağaltımın primer hedefleri, ekstremite fonksiyonunu geri kazandırmak, tam anatomik redüksiyon elde etmek ve olumsuz sonuçları en aza indirmek için kırık fragmentlerinin mümkün olan en kısa sürede rijit bir şekilde sabitlenmesini sağlamaktır. Genç hayvanlarda, proksimal femurun vasküler beslemenin ve büyüme plakalarının korunması cerrahi planlamada kritik faktörlerdir. Acetabular kırıklar için, bölgeye etki eden biyomekanik kuvvetlerin anlaşılması, uygun implant seçimi ve etkili stabilizasyon için esastır. Aynı derecede önemli olan, implantların kendi avantajları ve sınırlamaları dahil olmak üzere, biyomekanik özelliklerinin derinlemesine bilinmesidir. Bu anlayış, implant seçimini ve postoperatif sonuçları doğrudan etkiler. Proksimal femurun vasküler anatomisinin ve acetabuluma yakın mesafede bulunan siyatik sinirin lokalizasyonunun ayrıntılı bilgisi, iatrojenik komplikasyonları en aza indirmek ve optimum cerrahi yaklaşımı sağlamak için zorunludur. Travmatik kırıkları altta yatan patolojik durumlardan ayırt etmek, tanı sürecinde kritik öneme sahiptir. Önceden var olan bozuklukların doğru bir şekilde tanımlanması, yalnızca cerrahi yaklaşımın planlanmasına yardımcı olmakla kalmaz, aynı zamanda olası postoperatif komplikasyonların daha iyi tahmin edilmesine ve yönetilmesine de olanak tanır. Bu derlemenin amacı, kedi ve köpeklerde proksimal femur ve acetabular kırıklarının cerrahi tedavisinde güncel prensipler ve değerlendirmeler hakkında kapsamlı bir genel bakış sunmak ve başarılı sonuçlar için biyomekanik ve anatomik bilginin bütünleştirilmesinin önemini vurgulamaktır.

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* *Sorumlu Yazar e-posta adresi / Corresponding Author e-mail address:* merve.blsy@gmail.com

1. Anatomy of The Hip Joint

The hip joint is composed of the hemispherical-shaped acetabular fossa and the caput ossis femoris, which articulates within it. The primary stabilizers of the hip joint include the ligamentum capitis ossis femoris, the joint capsule, the dorsal acetabular rim, and the ligamentum transversum acetabuli, the latter of which completes the acetabular fossa ventrally. The ligamentum capitis ossis femoris arises from the acetabular fossa and inserts into the fovea capitis of the femur, contributing significantly to the joint's stability. The joint capsule extends from the acetabular rim to the base of the femoral neck (1, 2).

The medial wall of the acetabulum is formed by the ilium, ischium, and acetabular bone. Notably, the pubis is not part of the acetabular wall. Radiographic studies on the closure times of acetabular physis in juvenile animals are limited, with the ilioischial physis being the only one reported. In cats, the closure occurs between 20-25 weeks, while in dogs, this occurs between 18-20 weeks (3). Due to the superposition femoral head, the ilioacetabular, ischioacetabular, and puboacetabular physes are not visible on standard radiographs, making the closure time for these regions difficult to determine. As a result, definitive data regarding the closure of the ilioischial and iliopubic acetabular physes are lacking (4).

The proximal femur initially grows as a single physis until around 2-3 months of age, after which it divides into the capital and trochanteric physes, as a result of the pull of the muscles attached to the region. The capital physis is responsible for approximately 30-40% of the longitudinal growth of the femur in animals. In transverse cross-section, the capital physis exhibits an L-shaped profile, which confers resistance to both shear and rotational forces encountered during growth (5). The growth plate of the greater trochanter contributes to the overall development of the proximal femur but does not influence its longitudinal growth (6). In cats, the capital physis typically closes between 30-40 weeks (7), whereas in dogs, this closure occurs between 6-12 months (8).

The vascular supply to the proximal femur can be categorized into extraosseous, intracapsular, and intraosseous vessels. The extraosseous vessels, in order of importance, include the lateral and medial circumflex femoral arteries, the caudal and cranial gluteal arteries, and the iliolumbar artery. These vessels contribute to the formation of an extracapsular vascular ring located at the base of the femoral neck, which gives rise to the intracapsular and intraosseous vascular networks. This vascular ring enters the joint capsule distally and spreads toward the epiphysis, where it forms an intracapsular ring near the capital physis. Branches from this ring penetrate the physis and develop into an intraosseous arcuate network that supplies both the epiphysis and proximal femoral neck (5, 6, 9, 10).

Since these arteries originate from a single ring, any traumatic damage to the region may disrupt the blood circulation of the femoral neck and head. This is especially concerning in juvenile animals, where incomplete bone development may predispose them to vascular damage. Such disruption, whether due to trauma or surgical intervention, can result in complications such as abnormal femoral head and neck development, femoral head resorption, and the onset of degenerative joint disease (5).

In young cats, in addition to the vascular network surrounding the femoral neck, the femoral head receives blood supply from a branch of the medial circumflex femoral artery, which traverses from the acetabulum to the femoral head alongside the ligamentum capitis ossis femoris (11). In contrast, this artery does not contribute to the femoral head's blood supply in dogs, making them more susceptible to avascular necrosis of the femoral head and neck following trauma compared to cats (8, 12).

2. Classification of Fractures

Acetabular fractures are classified as cranial, central and caudal. If the fracture line includes the area in front of the acetabular notch, it is called "cranial", if it includes the area behind the acetabular notch, it is called "caudal", and if it includes the acetabular notch on both sides, it is called "central" fracture (13) (Figure 1A).

Proximal femur fractures are generally classified as intracapsular or extracapsular according to the location of the fracture in relation to the joint capsule. Intracapsular fractures include epiphyseal, physeal, subcapital, and transcervical fractures (Figure 1B). Ekstracapsular fractures include cervical, intratrochanteric, subtrochanteric fractures. This classification system is related to the vascular supply of the femoral head and neck. Accordingly, it has been stated that intracapsular fractures are more likely to result in avascular necrosis and that the classification system can potentially be used as a prognostic indicator (5).

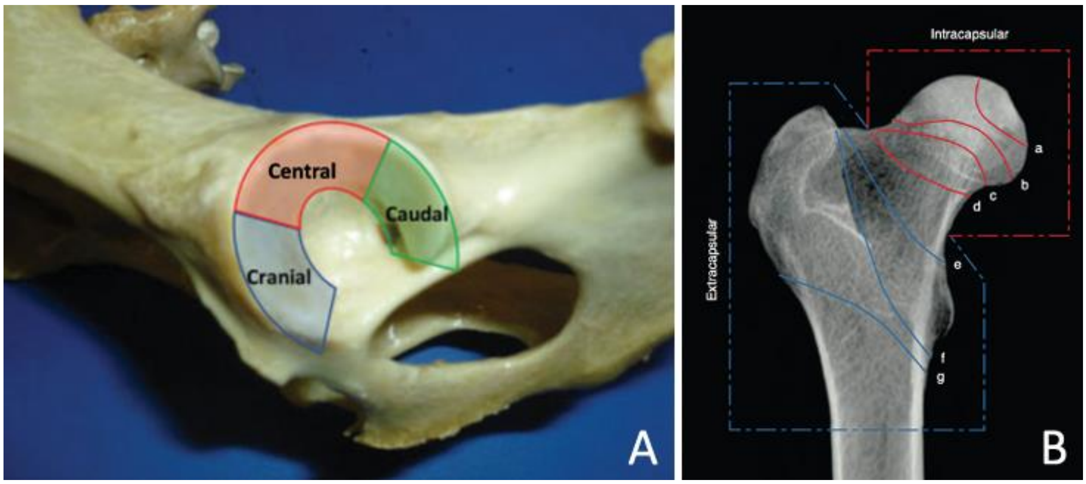

Figure 1: (A) Classification of acetabular fractures (14). (B) Classification of proksimal femoral fractures. Intracapsular fractures include epiphyseal (capital) (a), physeal (b), subcapital (c) and transcervical (d) fractures (5).
Şekil 1: *(A) Acetabular kırıkların sınıflandırılması (14). (B) Proksimal femoral kırıkların sınıflandırılması. İntrakapsüler kırıklar epifizeal (capital) (a), fizeal (b), subcapital (c) ve transcervical (d) kırıkları içerir (5).*

3. Incidence of Acetabular And Proximal Femoral Fractures

Acetabular fractures represent the lowest incidence among pelvic fractures and typically occur unilaterally (15). Pelvic fractures as a whole account for approximately 25% of all fractures in dogs, with acetabular fractures constituting 12–20% of these cases (16, 17, 18). In cats, pelvic fractures comprise 20–22% of all fractures, with acetabular fractures contributing 17.5–26% of these pelvic fractures (15, 19).

The development of acetabular fractures is often attributed to the force generated during trauma. This force may originate laterally at the greater trochanter or from the extremity in extension, with energy being transmitted proximally along the femur. Therefore, acetabular fractures are frequently observed alongside other pelvic fractures (17, 20). Unlike stress fractures, which occur in racing greyhounds due to repetitive or excessive microtrauma to the musculoskeletal system, trauma-induced acetabular fractures are typically associated with significant displacement of bone fragments. Stress fractures, by contrast, are limited to the acetabulum and exhibit minimal displacement, as they arise without external trauma (21).

Proximal femur fractures constitute approximately 25% of femur fractures. In young animals, the majority of proximal femur fractures (70%) are capital physeal fractures. Although rare, capital epiphyseal fractures involve the avulsion of the epiphyseal fragment, which often remains attached to the ligament of the femoral head (5). In cats, proximal femur fractures predominantly involve the femoral neck until the first 6 months of age, while between 6-10 months they mostly occur in the epiphysis of the femoral head. This transition reflects differences in bone strength during growth, as the femoral neck is more susceptible to fracture in younger animals. After the closure of the growth plates, which typically occurs by one year of age, epiphyseal fractures of the femoral head become uncommon (22). Physeal fractures of the proximal femur are most often classified as Salter-Harris types I and II and represent 16% of all physeal fractures. Proximal femur fractures may also occur spontaneously as a result of pathological disorders (23).

Capital physeal dysplasia, also referred to as spontaneous capital physeal fractures, is characterized by the unilateral or bilateral separation of the femoral head epiphysis from the proximal femoral metaphysis along the physeal growth plate, occurring in the absence of trauma. These lesions, commonly associated with acute epiphysiolysis observed radiographically, predominantly affect cats under two years of age. Differentiating these fractures from trauma-induced physeal injuries can be challenging due to their radiographic similarities (14). Although more frequently reported in cats, this condition has also been documented in dogs (24).

The condition is most prevalent in young (<2 years old), neutered, obese male cats (6, 25, 26). The underlying cause is multicentric chondrocyte disorder (dysplasia) in the physis, leading to physeal separation (10). Androgens, which play a critical role in initiating and terminating physeal closure and growth. In males, androgens, predominantly testosterone, are produced in the Leydig cells of the testicles, while in females, this androgen is mainly produced in the zona reticularis region of the adrenal cortex. Following neutering in males, the removal of the testicles significantly reduces androgen levels, resulting in delayed physeal closure when compared to intact males or neutered females (27). This hormonal deficiency slows cartilage maturation and prolongs the period during which the physis remains open, making it structurally weaker and more susceptible to mechanical forces (28, 29, 30). As the dysplastic growth plate fails to tolerate biomechanical stresses, it separates from the femoral neck. Over time, remodeling and sclerosis occur, eventually leading to pseudoarthrosis formation (26, 28, 31). Neutering is also associated with secondary physiological changes, including elevated insulin levels, which have been implicated in weight gain (32). Additionally, obesity is exacerbated by increased caloric intake and reduced energy expenditure. As a result, obesity is a frequently observed comorbidity in cats diagnosed with capital physeal dysplasia (33).

Metaphyseal osteopathy represents another pathological condition affecting the proximal femur. It remains unclear whether this condition constitutes an independent pathology or arises secondary to a primary fracture, followed by subsequent new bone formation. Some authors propose that initial bone loss, as observed in Legg-Calvé-Perthes disease in dogs, may predispose to secondary femoral neck fractures (2).

Increased or decreased vascularization in the metaphysis (such as Legg Calve Perthes) can result in necrosis, collapse or fracture of the femoral neck. Radiographic features of this condition often include osteolysis and remodeling of the femoral neck (11). Interestingly, in cats, changes in metaphyseal circulation do not typically affect the epiphysis, as the epiphysis receives additional vascular support from the ligamentum capitis ossis femoris. This contrasts with the vascular anatomy of dogs, where the epiphysis lacks such auxiliary support, leading to different pathological outcomes (2). Chronic fractures can often be differentiated from acute traumatic ones based on the presence of metaphyseal remodeling and the typically older age of affected patients (14).

Both capital physeal dysplasia and metaphyseal osteopathy of the femoral neck result from conditions such as dysplasia of the physis or impaired vascularization in the proximal femur. These pathological disorders share common radiographic findings, including sclerosis, osteolysis, and remodeling, which can make distinguishing between them challenging, particularly in chronic cases (2). Accurate differentiation of these pathological fractures from trauma-induced fractures is critically important. Pathological fractures occur in structurally compromised bone, increasing the likelihood of complications such as nonunion following surgical intervention. In contrast, traumatic fractures typically carry a lower postoperative risk of nonunion due to the relatively healthier bone structure (14).

4. Biomechanics of The Hip Joint

Healthy bone tissue possesses inherent material properties and is resistant to specific force modalities. As long as the applied forces remain below the bone's resistance threshold, fractures do not occur. Instead, the bone absorbs the load, undergoes elastic deformation, temporarily alters its shape, and reverts to its original form once the force is removed. Under normal physiological conditions, such as those imposed by gravity and routine movements, healthy bone tissue can withstand these forces without fracturing. When subjected to repetitive forces, bones adapt through a dynamic process involving bone resorption and subsequent new bone formation. However, if the magnitude and duration of stress on the bone exceed the remodeling capacity, excessive resorption may occur. Without sufficient time for remodeling, stress fractures can develop (21). This process represents an adaptive mechanism wherein the organism attempts to strengthen the bone by deconstructing and reconstructing it under persistent stress. However, this destruction-reconstruction cycle relies on a delicate balance. If adequate rest periods are not provided to allow for the necessary reconstruction, bone tissue weakens, increasing the risk of fractures even under normal physiological loads. Studies in humans have demonstrated that individuals undergoing continuous training subject their bones to repetitive stress, leading to plastic deformation and structural changes in the musculoskeletal system (34).

Biomechanical analysis of the canine hip has revealed that during running, the primary forces transmitted from the extremities to the hip act within the horizontal plane and are directed cranially (35). Based on this, some authors have hypothesized that caudal acetabular fractures occur in areas subjected to minimal force, making non-displaced fractures potentially amenable to conservative management (13, 36, 37, 38). In an experimental study, canine acetabulum were divided into cranial, central, caudal and axial, middle, abaxial regions and subjected to load testing. Results showed that the cranial and caudal one-third portions of the acetabulum bore loads 7.9 and 13.1 times greater, respectively, than the central region. Similarly, the abaxial and middle portions of the acetabulum carried loads 72.4 and 351 times greater than the axial portion, respectively (39). A similar study on cat acetabulum divided the acetabulum into cranial, central, and caudal segments, filled the regions with fast-setting alginate, and subjected them to load testing. The findings indicated that the central and caudal regions bore significantly higher loads than the cranial region, though the cranial portion still contributed to load-bearing (40).

Given these findings, it has been argued that the fracture location does not significantly influence treatment options, as all acetabular regions contribute to weight-bearing (40, 41). This supports the recommendation that no acetabular fracture should be treated conservatively (36). However, conservative management may be suitable for stable, minimally displaced, or non-displaced fractures that do not involve the facies lunata, especially in young dogs. Even in such cases, stabilization using an Ehmer sling is advised (17).

The femoral neck provides structural support to the femoral head and aligns the diaphysis laterally to the body wall, allowing for a wide range of motion in the hip joint. However, this configuration also exposes the femoral neck to significant bending stresses during daily activities. The proximal femur's trabecular architecture is specifically adapted to withstand these forces and is reinforced cranially by the linea transversa, a bony ridge extending from the femoral head base to the greater trochanter (17).

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5. Complication of Acetabular and Proximal Femoral Fractures

Osteonecrosis and nonunion are significant complications following femoral neck fractures, with osteonecrosis occurring in approximately 20% of cases (42, 43, 44). In animals with incomplete bone development, outcomes such as femoral neck shortening and hip joint instability may result after repairing femoral neck fractures or epiphyseal separations, potentially leading to hip joint dysplasia. Radiographically, narrowing of the collum femoris, often described as an "apple core" shape, occurs in about 70% of cases undergoing internal fixation. However, this rarely leads to collapse of the femoral neck (45, 46).

It was previously thought that Salter-Harris type I fractures occur in the hypertrophic zone of the growth plate, allowing continued growth if the epiphyseal blood supply remains intact. However, more recent histopathological studies show that in over 75% of traumatic fractures, the fracture line traverses the physis, separating the reserve zone from the epiphysis (8). This is critical since the proliferative zone's vascular networks are limited, and the hypertrophic zone is avascular. Damage to the epiphyseal blood supply or proliferative cells may lead to premature growth plate closure, ossification, and the formation of nonunion or pseudoarthrosis (23, 47).

Prompt surgical intervention is generally believed to reduce the risk of osteonecrosis in femoral neck fractures, though evidence from randomized controlled trials is lacking (48, 49). Although early surgery does not appear to have a beneficial effect on mortality or function in patients with a hip fracture alone, early surgery has been associated with less pain, shorter hospital stay, and fewer postoperative complications in stable patients (50). Delayed fracture repair can lead to fibrous adhesions and muscle contractions, making fracture reduction more difficult and increasing morbidity (51). deally, surgical treatment should be performed within 24 hours, provided the patient's condition permits (46).

In human studies, the incidence of postoperative avascular necrosis varies widely, ranging from 3-47%. Factors such as screw placement within the epiphysis, the number of screws used, fracture displacement, and difficulty in reduction significantly affect the risk of avascular necrosis. There is a strong correlation between the degree of epiphyseal displacement and the likelihood of necrosis. Reduction during the operation increases the likelihood of avascular necrosis by causing the vessels that adapt to the fracture area to stretch. Interestingly, patients with bilateral fractures exhibit lower rates of avascular necrosis, likely due to decreased mobility compared to those with unilateral fractures (52).

Postoperative complications usually manifest within six weeks and may include transient demineralization or slight narrowing of the femoral neck, though the final outcome of the femoral head and neck may take up to six months to evaluate fully. In cases of coxofemoral luxation, epiphysiolysis, or femoral neck fractures, narrowing of the femoral neck is common but rarely leads to functional issues (46).

Conservative management of proximal femur fractures is often associated with chronic pain, lameness, muscle atrophy, secondary osteoarthritis (OA), and hypertrophic pseudoarthrosis. Several factors complicate surgical repair, including vascular trauma, residual growth potential in the capital physis, eccentric loading of the femoral head, limited bone stock for stabilization, and potential for joint locking (5).

In animals with open acetabular physes, premature physeal closure due to trauma can result in reduced acetabular depth, sclerosis, and subluxation of the femoral head (4). Although conservative management of acetabular fractures may be appropriate in skeletally immature animals due to their greater bone remodeling capacity and higher healing potential, surgical intervention is typically indicated for all types of acetabular fractures in skeletally mature animals (53).

Pelvic fractures, in the absence of accompanying thoracic or cranial trauma, are infrequently fatal. Nonetheless, these injuries are associated with significant morbidity, primarily due to soft tissue damage. Critical structures, such as the urinary bladder or the intrapelvic urethra, are particularly vulnerable, leading to complications such as rupture (41). Mortality from high-energy trauma involving the pelvis typically arises from secondary systemic effects, including multi-organ failure and sepsis (54).

Acetabular fractures, as intra-articular injuries, are inherently predisposed to long-term complications, most notably osteoarthritis (OA), regardless of the quality of anatomical reduction achieved (17). This inevitability is attributed to the high kinetic energy absorbed by both osseous and cartilaginous structures during trauma. However, early anatomical reduction has been shown to attenuate the progression of OA (55, 56). Despite this benefit, surgical intervention may be delayed in the presence of life-threatening injuries, which complicates and often precludes achieving optimal reduction (20). Notably, the extent of fragment displacement—a parameter reflecting the trauma's severity—plays a more critical role in prognosticating outcomes than the timing of surgical intervention (17).

The development of degenerative joint disease (DJD) following acetabular trauma stems from two primary mechanisms. The first is direct mechanical damage to the joint at the time of injury, while the second involves a progressive deterioration of articular cartilage due to abnormal pressure distributions caused by joint incongruity (36). Malalignment within the joint leads to accelerated wear of articular cartilage and irregular intra-articular pressure gradients. As such, the primary surgical objective in acetabular fractures is to restore joint congruity. Conservative management, while potentially alleviating symptoms temporarily, fails to stabilize the joint adequately, thus perpetuating intra-articular incongruity and exacerbating the risk of OA. Consequently, surgical intervention significantly lowers the incidence of OA compared to non-operative approaches (17, 57, 58).

Cats' lower body weight and efficient locomotor system may make them more amenable to conservative treatment of acetabular fractures. However, even in such cases, long-term complications, including a painful hip joint and muscle atrophy, may occur (59). Recent studies have revealed that only 50% of cats diagnosed with acetabular fractures undergo surgical intervention, despite the clear indication for surgery in these cases (15). Displaced fractures necessitate surgical intervention to prevent severe complications, such as narrowing of the pelvic canal, constipation, or degenerative joint disease (4, 46 60).

Pelvic fractures typically result from high-energy traumatic events, necessitated by the robust protective role of the surrounding musculature. The extensive muscle masses that envelop the pelvic region act as a buffer, absorbing lower-energy impacts and thereby reducing the likelihood of fractures under normal circumstances. However, the high energy required to breach this protective mechanism often produces significant comorbidities alongside the pelvic fracture itself. Research conducted in 2002 identified that between 59% and 72% of patients with pelvic fractures also presented with non-orthopedic injuries. These injuries most commonly involved the urinary system and neurological structures, underscoring the systemic implications of pelvic trauma (61). Among the structures at heightened risk in pelvic trauma are the urinary bladder and the urinary tract. Their vulnerability can be attributed to their anatomical position and relative exposure during high-energy impacts (37). Studies have consistently demonstrated that urethral injuries are disproportionately prevalent in male patients, a phenomenon that may be explained by the unique anatomical configuration of the male urethra. Specifically, the *urethra masculina* is anatomically tethered to the ischial structures via the *ischiocavernosus* and *ischiourethralis* muscles, which creates a biomechanical predisposition to injury under high-impact conditions (62).

Sciatic nerve injury, although more commonly associated with ilial fractures and sacroiliac luxations, can also occur in acetabular fractures. The nerve is highly susceptible to compression from fracture fragments or manipulation during reduction, as it closely contacts the medial surface of the ilium. Anatomical reduction and rigid internal fixation can minimize callus formation and reduce the risk of secondary nerve compression (60, 63). Neurological evaluation in animals with pelvic fractures may be challenging, but absence of withdrawal reflex or deep pain perception can indicate significant sciatic nerve damage, negatively affecting the prognosis for limb function recovery (38).

6. Fixation Methods

The surgical management of acetabular fractures necessitates meticulous anatomic reduction, rigid and stable fixation, and the restoration of joint surface congruity to prevent secondary complications such as degenerative joint disease. Achieving these objectives minimizes the risk of callus formation through primary bone healing mechanisms. Among the fixation implants available, plates are uniquely capable of providing the structural conditions required for optimal outcomes (14, 64, 65, 66).

Fixation methods for acetabular fractures

Plates: The standard approach for repairing acetabular fractures involves securing an acetabular plate along the dorsal surface of the acetabulum (46). However, the inherently curved anatomy of the acetabulum poses challenges to achieving accurate plate contouring. Inadequate shaping of the plate can lead to poor bone-implant contact, compromising the reduction and potentially resulting in a loss of stability during screw tightening (64). The caudal acetabulum is particularly vulnerable due to limited bone stock in this region, increasing the likelihood of screw loosening in fractures affecting the caudal fragment. In such cases, extending the implant toward the ischium can enhance stabilization by securely anchoring the caudal fragment (67). Reconstruction plates are preferred over standard veterinary acetabular plates for their adaptability in these complex scenarios.

The primary implants used in acetabular fracture management include standard reconstruction plates, "String of Pearl" (SOP) plates, and “C”-shaped veterinary acetabular plates (VAP). Although dynamic compression plates (DCP), screw-wire-polymethylmethacrylate (VTP) constructs, and external fixators have been historically used, their application is now generally limited to situations where the aforementioned implants are unavailable or due to the surgeon’s familiarity with alternative methods.

Locking plates, which function biomechanically as internally placed external fixators, offer significant advantages in certain fracture patterns. These plates reduce the need for precise shaping—a critical challenge in acetabular fracture repair—and provide enhanced stability in comminuted fractures. By avoiding compression between the bone and plate, locking systems preserve periosteal blood flow and reduce the risk of vascular compromise (68). Additionally, locking systems distribute axial forces through the screws, minimizing the stress on individual screws and reducing the risk of screw loosening or failure (69). Comparative studies have shown no significant differences between locking and non-locking plate systems in terms of achieving and maintaining anatomic reduction or structural strength. However, these findings may be influenced by the fact that both plate types were precisely contoured to the bone in the study designs. In cases where ideal plate-bone congruency cannot be achieved, locking plates demonstrate superior biomechanical performance, particularly in osteoporotic or osteopenic bone models (68).

Veterinary acetabular plates, with their characteristic “C” shape, are specifically designed to conform to the dorsal acetabular surface, simplifying their application. However, achieving anatomic reduction remains a challenge, and reduction loss can occur during screw tightening (41, 46). Locking versions of these plates may provide additional stability in cases where ideal contact between the implant and bone is less feasible. While C-shaped plates require less contouring than straight implants, they may not be suitable for fractures extending cranially along the *corpus ossis ilium*, caudal acetabular fractures, or comminuted patterns. These plates are most effective for treating fractures confined to the middle one-thirds of the dorsal acetabular surface (60). In veterinary practice, acetabular plates are more commonly utilized in dogs compared to cats. This disparity is attributed to anatomical and size differences between the two species. The broader adoption of these implants in canine patients highlights their utility in accommodating the unique biomechanical demands of larger species (70).

String of Pearl Plates (SOP) plate system represents a versatile locking plate design, characterized by a series of spherical components (“pearls” or “nodes”) interconnected by cylindrical segments (“internodes”). This unique geometry allows the SOP plates to be contoured in three planes without compromising their locking capability. Specifically, these plates can tolerate bending up to 40° and rotation up to 20° along their longitudinal axis while maintaining structural integrity and mechanical locking properties. This adaptability makes SOP plates particularly suitable for securing fixation on the irregularly curved dorsal surface of the acetabulum (65). A significant advantage of SOP plates is their relatively narrow profile compared to conventional plate systems, simplifying their placement on the limited dorsal width of the acetabulum (67).

A significant advantage of SOP plates is their relatively narrow profile compared to conventional plate systems, simplifying their placement on the limited dorsal width of the acetabulum. Furthermore, SOP plates demonstrate superior bending strength in vitro compared to commonly used implants such as Limited Contact Plates (LCP), Dynamic Compression Plates (DCP), and Limited Contact Dynamic Compression Plates (LC-DCP). Research suggests that SOP plates retain their mechanical strength and rigidity after shaping, performing comparably to unshaped, conventional DCPs in terms of resistance to bending forces (71). Despite their favorable bending characteristics, SOP plates may be less effective under torsional forces compared to locking compression plates (LCP). In static and cyclic load testing, LCPs demonstrated superior torsional strength, while SOP plates exhibited higher resistance to bending forces (72). This disparity could have clinical implications, as certain acetabular fractures are prone to failure due to ventrolateral rotation of the caudal segment (65, 73).

A biomechanical comparison of SOP plates with Veterinary Tension Plates (VTP) and Veterinary Acetabular Plates (VAP) revealed that SOP plates offer superior load-bearing capacity. Specifically, SOP plates demonstrated 16% and 30% greater flexural strength compared to 3.5 mm LCPs and LC-DCPs, respectively (74). However, it is noteworthy that the failure loads in these studies exceeded physiologic forces encountered in vivo, suggesting that all systems would be sufficient to maintain fracture reduction in clinical scenarios (75).

Reconstruction plate, crafted from relatively less rigid materials, are characterized by “V”-shaped grooves positioned between the screw holes. Due to these features, they are relatively easy to shape to fit irregular and curved bone surfaces, but due to these same features, they are weaker than similarly sized dynamic compression plates. These plates are designed to be used in less load-bearing bones such as the pelvis and mandible (5, 76). When 3.5 mm reconstruction plates were compared to 2.7 mm acetabular plates, the latter provided superior performance in terms of ease of shaping and precision of fracture fragment reduction. While the reconstruction plate showed no measurable stiffness advantage, the acetabular plate was inherently better suited for achieving and maintaining accurate reduction in complex acetabular fractures (77, 78).

Recent developments in minimally invasive plate osteosynthesis (MIPO) have introduced novel techniques for managing acetabular fractures. One such approach utilizes preoperative 3D modeling to optimize implant design and placement. In this technique, computed tomography (CT) scans are used to generate a three-dimensional model of the intact acetabulum, enabling precise pre-contouring of locking compression plates. During surgery, the pre-shaped plates are introduced through an epiperiosteal tunnel created via small incisions at the ilium and ischium. This method minimizes surgical exposure, preserves soft tissue integrity, and potentially reduces perioperative complications associated with extensive surgical dissections (57).

Other Methods: The use of a Type IA external fixator (EF) has been reported in the management of acetabular fractures in animals with unclosed physeal plates (3). This approach offers several advantages, including minimally invasive application, reduced disruption to surrounding tissues, and a lower risk of infection, which collectively contribute to faster healing times (53). However, evidence regarding whether EF provides definitive benefits over alternative fixation methods remains inconclusive and requires further investigation.

The Screw/Wire/Polymethylmethacrylate (SWP) technique involves a systematic approach to stabilize acetabular fractures. Following anatomic reduction of the fracture fragments, Kirschner wires (K-wires) are strategically placed within the fragments to maintain alignment. Screws are subsequently positioned in the cranial and caudal acetabular fragments. A cerclage wire, typically arranged in a figure-of-eight configuration, is then passed around these screws and tensioned to neutralize tensile forces along the dorsal acetabular margin. The screws and cerclage wire are subsequently encased in polymethylmethacrylate (PMMA), enhancing fixation strength and stability (78). The dorsal acetabulum is suitable for tension band application because it is a tension surface. However, this technique is less appropriate for oblique fractures, as the tension bands may inadvertently draw fragments together, resulting in fragment overlap (4).

This fixation method can be used with or without composite (PMMA), but naturally the use of composite significantly enhances fixation quality. In biomechanical studies comparing constructs with and without PMMA, the non-composite group demonstrated stability against ventral distraction forces alone. Conversely, constructs incorporating PMMA displayed additional resistance to rotational, dorsal, medial, and lateral distraction forces. This increase in stabilization was attributed to the rotational and distraction forces being absorbed and eliminated by PMMA (73).

In acetabular fractures, the caudal fragment is frequently displaced caudally, ventrally, and medially, primarily due to the mechanical pull exerted by the biceps femoris, semitendinosus, and semimembranosus muscles. To counteract these forces and prevent reduction loss, it has been recommended to insert 2-3 Kirschner wires before the application of PMMA (65). While increasing the number of K-wires enhances stabilization, the placement of additional wires poses technical challenges due to the limited space and potential for interference with other implants (58). Biomechanical analyses have shown that even a single K-wire contributes significantly to stabilization after PMMA application. However, the placement of multiple K-wires can complicate screw positioning and increase the risk of implant conflicts (65).

The SWP technique is associated with several potential complications, including, abduction deformities caused by contact between the femoral head and PMMA, restricted joint range of motion, penetration of K-wires into the pelvic canal, ventrolateral bending of K-wires, fracture or failure of PMMA, thermal damage to adjacent tissues during the exothermic polymerization of PMMA, challenges in removing PMMA in cases of infection, impaired radiographic evaluation of fractures due to PMMA opacity (4, 58, 65, 73, 78).

Plate luting, an alternative fixation method, involves the application of PMMA between the plate and bone or between the screw heads and plate. This technique increases the contact area between the implant and the underlying bone, facilitating precise fracture reduction and minimizing implant movement during screw tightening. Consequently, plate luting helps maintain anatomic alignment and enhances stabilization (64).

Fixation methods used in proximal femur fractures

Conservative treatment of fractures in the proximal femur is generally associated with a high incidence of complications, including nonunion, malunion, pseudoarthrosis, and secondary osteoarthritis (OA). These outcomes underscore the importance of surgical intervention for fractures in this region. Surgical approaches are broadly classified into primary repair techniques and salvage procedures, with the choice of method depending on factors such as the patient's age, the time between trauma and treatment, vascular supply to the area, fracture location, and the surgeon's expertise. In cases where pre-existing hip joint arthritis is present, primary repair is typically unnecessary, and salvage methods such as total hip replacement (THR) or femoral head and neck excision arthroplasty are recommended (5, 23).

Open reduction and internal fixation (ORIF) has historically been a preferred method for managing femoral head and neck fractures. This technique typically involves the use of multiple Kirschner wires (K-wires), pins, or screws to stabilize the fracture fragments. However, ORIF carries potential complications, particularly in young animals. These include premature closure of the proximal femoral physis, femoral head or neck deformities, loss of reduction, resorption of the femoral neck, and the progression of degenerative joint disease (79). To maximize mechanical strength and minimize interference with normal growth, K-wires should ideally be placed parallel to each other. This configuration not only ensures greater stability but also allows for continued physeal growth in young animals (14). Parallel pin placement also distributes mechanical forces evenly between the pins, thereby reducing the likelihood of implant failure. In contrast, divergent pin placement may impair physeal growth by creating a locking effect on the growth plate, potentially resulting in premature closure of the physis. Divergent pinning also unevenly distributes forces across the implants, weakening the construct and predisposing it to failure (5).

Proper alignment of pins or wires during placement is critical to the success of ORIF. Implants must be oriented to match the inclination and anteversion angles of the femoral neck to maximize mechanical stability. Parallel pins or screws positioned to follow these angles ensure optimal force distribution across the fracture site and reduce the risk of reduction loss. Additionally, correct orientation facilitates dynamic compression of the fracture, promoting more efficient and stable healing (46).

While three-pin fixations are biomechanically stronger and more rigid compared to one- or two-pin constructs, the positioning of the implants is a more critical determinant of success than their number or diameter. This is primarily due to the significant role of local blood supply preservation in fracture healing. Disruption of vascularity, especially in young animals with open growth plates, can impair healing and compromise long-term outcomes. Pins that are well-distributed across the fracture site improve stability without excessively interfering with local vascularity, while implants that are clustered or poorly oriented may exacerbate complications (80).

Parallel pin placement provides several advantages, including uniform load distribution and minimal disruption to the physeal growth plate. Forces applied to parallel pins are transmitted equally, allowing dynamic compression across the fracture and ensuring that physiological loading of the growth plate continues uninterrupted. In contrast, divergent pins unevenly distribute loads, leading to implant fatigue and failure. Furthermore, divergent pin placement often results in excessive stress concentration on individual implants, weakening the overall construct and increasing the likelihood of mechanical complications (5).

Fluoroscopy-guided percutaneous pinning represents a less invasive alternative to open reduction and internal fixation (ORIF) for managing epiphyseal fractures in dogs and cats. This technique minimizes iatrogenic damage to local soft tissues and vascular structures, promoting faster postoperative recovery. However, the success of this method depends on achieving an adequate reduction prior to fixation, as it is best suited for fractures with minimal displacement between fragments. The use of closed reduction avoids unnecessary trauma to the surrounding tissue, but complications such as intra-articular pin migration, nonunion, and malunion remain significant risks (79).

Radiographic modalities like fluoroscopy and computed tomography (CT) may overestimate the distance between the screw tip and the articular surface, potentially increasing the likelihood of pin migration into the joint space (81). Furthermore, fluoroscopy-guided percutaneous pinning is a technically demanding procedure, requiring advanced skills in both intraoperative imaging and minimally invasive techniques—skills that are not yet widely adopted in veterinary surgical practice (14). Repeated attempts at fracture reduction, often necessitated by poor intraoperative visualization or inadequate reduction, may inadvertently exacerbate local trauma and disrupt blood flow, further complicating healing.

In skeletally mature animals, fixation with anti-rotational Kirschner wires (K-wires) or threaded cortical screws can provide stable fixation. However, these implants are contraindicated in young, skeletally immature patients, as they can cause physeal compression and premature closure of the growth plate, leading to long-term developmental complications (14). Studies have shown that interfragmentary compression screws, while effective in certain contexts, are associated with high risks of premature physeal closure, femoral neck resorption, and degenerative joint changes in the acetabulum when used in young animals (5). Due to these risks and the technical challenges associated with their application, compression screws are rarely preferred for these cases, especially given their lack of mechanical superiority over pins or wires. Regardless of the implant type, trauma incurred during the surgical procedure itself increases the likelihood of premature growth plate closure. Comparative studies have demonstrated that both a single lag screw and three parallel 2.0 mm K-wires can withstand forces equivalent to three times an animal's body weight. These methods are generally considered suitable for large-breed patients, while two parallel or divergent K-wires are more appropriate for smaller breeds (46).

Cannulated screws are characterized by a central channel through the screw body and head, allowing the passage of a guide K-wire. The guide wire is first placed across the fracture site to achieve and temporarily stabilize the reduction. The cannulated screw is then advanced over the guide wire and fixed into the bone using a specialized screwdriver. Notably, cannulated screws are equipped with self-drilling tips, reducing the need for pre-drilling and thereby minimizing bone trauma.

The smaller diameter of the guide wire, relative to the screw, ensures minimal disruption to the bone during insertion. However, improper orientation of the screw during placement may necessitate its removal and reinsertion. This repeated manipulation can create larger voids in the cancellous bone, potentially disrupting local circulation and weakening the fixation. Biomechanically, cannulated screws are slightly inferior to non-cannulated screws of the same size due to their hollow structure, but studies have shown no significant differences in clinical performance between the two types (82).

Salvage Procedure

Femoral head and neck excision (FHNE), involving resection of the femoral head and neck, serves as a vital salvage procedure for patients in which conventional repair methods are contraindicated, unsuccessful, or associated with severe complications. This procedure is particularly effective in relieving pain and restoring mobility in small patients (weighing <15 kg) with acetabular, femoral head, or neck fractures. In larger patients (weighing >15 kg) or those with contralateral hip pathology, total hip replacement (THR) is typically the preferred salvage option.

When appropriately selected and performed according to established surgical principles, excision arthroplasty yields favorable outcomes, particularly in small-breed dogs and cats. However, in larger patients, biomechanical limitations may result in suboptimal recovery, and total hip replacement may provide superior functional outcomes. Despite its advantages, THR is associated with risks, including prosthesis-related complications and technical challenges during implantation. For cases where neither excision arthroplasty nor total hip replacement can resolve the issue, **amputation** becomes the final treatment option. While amputation is rarely necessary in cats due to their smaller size and adaptability (83), it may be required in severe or refractory cases in dogs.

7. Surgical Approach

Various surgical techniques are available to address acetabular and proximal femoral fractures in dogs and cats. Commonly utilized approaches include:

• Craniodorsal approach with craniolateral incision
• Craniodorsal and caudodorsal approach with trochanter major osteotomy (Gorman method)
• Craniodorsal and caudodorsal approach with tenotomy of gluteal muscles can be used (47).

Each approach has unique advantages and limitations, and their impact on epiphyseal circulation remains a subject of ongoing debate. The craniolateral approach offers excellent access to the proximal femoral epiphysis, physis, and femoral neck. To enhance visibility, particularly in complex cases, it may be combined with greater trochanter osteotomy or gluteal muscle tenotomy. Despite its utility, the craniolateral approach is associated with potential disruption of critical vascular structures. Specifically, it can cause trauma to vessels supplying the extracapsular vascular ring, including the caudal gluteal artery and the lateral femoral circumflex artery. These same vessels are also at risk of damage during a greater trochanter osteotomy, as performed in the Gorman approach (5).

The dorsal approach with osteotomy of the greater trochanter is widely regarded as the gold standard for providing optimal surgical visualization of acetabular and proximal femoral fractures. This approach involves detaching the gluteus medius and gluteus profundus muscles from the greater trochanter and retracting them dorsally to expose the joint capsule. Once the capsule is incised and extended cranially and caudally, the femoral head and neck become visible, facilitating fracture reduction and fixation. However, ligamentum capitis femoris transection, often necessary to facilitate reduction of femoral head or neck fractures, compromises joint stability and disrupts blood flow to the femoral head in cats. This vascular compromise significantly increases the risk of avascular necrosis (46, 84).

Sciatic nerve protection is paramount during this approach, as the nerve lies just caudal to the greater trochanter. Care must be taken to avoid iatrogenic damage during osteotomy and throughout the procedure (38). This method allows comprehensive exposure of the dorsal acetabulum, the caudal ilium, and the cranial ischium, providing excellent access for manipulation of the femoral head and neck as well as plate placement.

For juvenile and young animals, where iatrogenic injury to the physis of the greater trochanter is a concern, tenotomy of the gluteus medius and gluteus profundus muscles serves as a viable alternative to greater trochanter osteotomy. This approach avoids potential physeal damage while providing equivalent surgical visibility of the acetabulum and sciatic nerve (46, 85). Comparative studies have shown no significant difference between the two techniques regarding surgical exposure or outcomes (60, 86).

The intergluteal approach provides access to the acetabulum by retracting the gluteal muscles without detachment or osteotomy. While this method can be effective in cats and small dogs, its utility in larger dogs is limited due to inadequate surgical exposure. In large dogs, visualization and manipulation of fracture fragments, as well as plate placement, are significantly more challenging (87).

The dorsal acetabular rim has a triangular cross-sectional shape that tapers laterally, necessitating careful plate placement. Plates should be positioned as medially as possible, closer to the cavum pelvis, to maximize the depth and bone volume available for screw fixation. This positioning reduces the likelihood of screw penetration into the acetabulum and enhances fixation stability. Proper placement ensures sufficient cortical bone engagement while minimizing the risk of intra-articular complications.

Conflict of Interest

The authors declared that there is no conflict of interest.

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Authors' Contributions

Motivation / Conceps: Barış KÜRÜM
Design: Barış KÜRÜM, Merve BAKICI
Control / Supervision: Barış KÜRÜM
Data Collection: Merve BAKICI
Analysis and / or Interpretation: Barış KÜRÜM, Merve BAKICI
Literature Review: Merve BAKICI
Writing Manuscript: Merve BAKICI
Critical Review: Barış KÜRÜM, Merve BAKICI

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