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# From Koch's Bone Biomechanical Analysis to Contemporary Proximal Femur Fracture Management

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## Abstract

This article presents a current and comprehensive review of the biomechanical forces on the proximal femur, as preliminarily presented by Koch's cornerstone work on the bone architecture of the proximal femur. His work reflected on the complexity of proximal femur fractures and subtrochanteric fracture management in parallel with implant evolution and classification. Multiple ways of classifying subtrochanteric fractures exist, however, there is not one classification system that is used to guide operative management. The management of subtrochanteric fractures is surgical fixation which involves intramedullary nailing and plating (e.g., fixed angle and locking). The gold standard management is intramedullary nailing with antegrade and retrograde nail options. Though antegrade nailing presents an advantage due to the deforming forces, retrograde nailing of proximal femur fractures offers less operative time and blood loss. Similar outcomes have been reported between the two methods. Decision making when contemplating antegrade versus retrograde nailing for femur fractures is mostly driven by body habitus and associated injuries, and not by fracture distance of the proximal femur to the trochanteric region.

**Keywords:** Proximal femur fractures; Subtrochanteric fractures; Subtrochanteric classifications; Cortical diameter; Koch

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## Introduction

The biomechanical and anatomical morphology of subtrochanteric femur fractures is complex. Their management has advanced to reduce complications, improve patient functionality, and prompt ambulatory recovery [1-6]. Briefly, the bone's structural subtrochanteric region comprises primarily cortical bone [2,7]. During gait, it sustains significant compression forces on the medial side as compared to the tension forces on the lateral side and is subject to multiple deforming muscular forces which give the classic radiographic presentation and ultimately lead to a more challenging reduction [2,8-11]. The incidence of these injuries is varied, accounting for approximately 10 - 34% of proximal femur fractures with a bimodal age and mechanistic distribution [9,12].

Intramedullary nailing (IMN) remains the gold standard for femoral shaft and subtrochanteric fractures. It allows early recovery and return to activities [13]. Antegrade IMN is one of the most stable and reliable fixation techniques for controlling the proximal fragment given the deforming forces present and the lower risk of malalignment [7,12,14,15]. Current principles state that fractures within 5 cm from the lesser trochanter (LT) have been considered a relative contraindication to retrograde IMN due to the muscular deforming forces and prior reported complications (i.e., delayed union, malunion, need for second surgeries) [16-18]. Although this region has been traditionally defined as subtrochanteric, its low reproducibility and omission of ethnic variations arguably make it an outdated, arbitrary definition. The scope of this review article aims to expose Koch's initial understanding of the proximal femur biomechanical composition and behavior, and evolution in the management of subtrochanteric femur fractures [8].

## Koch's Proximal Femur Structure and Biomechanics

A fracture in the proximal femur is subject to multiple deforming muscular forces that present with a classic radiographic presentation of procurvatum and varus, and can complicate reduction [9,10]. Koch's 1917 biomechanical work of the femur provides no definition of the subtrochanteric region or the calcar but describes in detail the cortical and trabecular bone system around the LT with its implicated withstanding forces (Figure 1) [7,8]. Koch stated that bone cross-sectional analysis is the most accurate way to compute bone strength in the proximal third of the femur [8]. He describes the, later called, calcar as the cortical thickening that starts proximally posteroinferior to the femoral neck and extends posteromedial and distal to LT, while thinning out around the LT (Figure 1) [7,8,12]. Based on his work, the medial portion of the proximal third femur from approximately 2.5 - 7.5 cm from the LT is subject to high compression forces [7,8]. For instance, the medial compression forces in a 200 lb individual can generate on average about 1200 lb/in$^2$ [8]. Koch advocated that his own findings in a 35-year-old, 6 ft tall African American male could reflect structurally the femur in a healthy normal individual, being subject to variability based on age, sex, ethnicity, occupation, body weight, etc. [8]. In addition to the aforementioned structure, the vasculature is precarious making fracture consolidation difficult in the absence

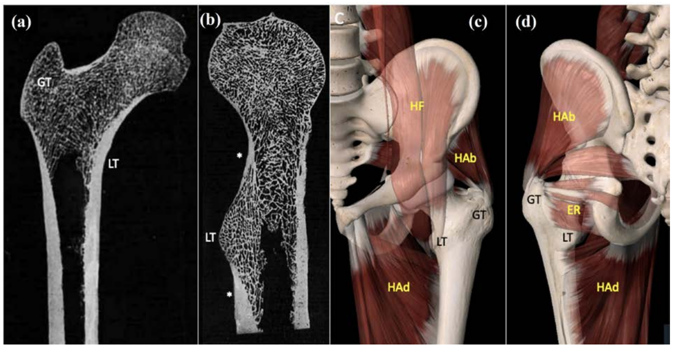


**Figure 1: (a)** Coronal and **(b)** sagittal sections of Koch's biomechanical study in 1917, showing the trabecular pattern and the cortical bone around the lesser trochanter (*: cortical bone structure projecting posteroinferior to the femoral neck, towards the posteromedial aspect distal to the lesser trochanter, with thinning around the lesser trochanter). **(c)** Anterior and **(d)** posterior schemes of deforming muscular forces around the hip, involved in displacing the proximal and distal fragment. These result in proximal fragment abduction, flexion, and external rotation by the abductors (gluteus medius and minimus), hip flexors (iliopsoas), short external rotators (piriformis, obturator internus, quadratus femoris, superior/inferior gemelli); and distal fragment adduction and shortening by adductors, and gracilis.

**Note:** GT, greater trochanter; LT, lesser trochanter; HF, hip flexors; HAb, hip abductors; HAd, hip adductors; and ER, external rotators.

of adequate medial support which can lead to nonunion, hardware failure, and reoperations [12]. Although Koch's work contributes to understanding the biomechanical stress of the femur, further research by Rybicki et al. adds to his theory and related biomechanical intricacies that are not the focus of this study [11].

## Ward's Triangle

Frederick O. Ward described in 1838 the now-called Ward's triangle as the area in the femoral neck and head with the lowest bone mineral density where compressive and tensile forces balance each other [19]. Its borders are made up of the three main compressive and tensile trabeculae; the primary compressive trabeculae which are vertically oriented from the medial femoral head, the principal tensile trabeculae from the inferior aspect of the fovea to the greater trochanter, and lastly the secondary compressive trabeculae from greater to LT [20]. Studies on the proximal femur have found that the thickest cortex is found at the upper wall of the femoral neck, as well as the medial and lateral walls of the trochanteric area, with Ward's triangle being in the center [21]. These three areas form the triangle, and Xu et al. hypothesized that this area, when under physiologic load, reduces shear forces and the bending moment of the femur and balances the distribution throughout [21]. The triangular theory is in line with Koch's theory, with his descriptive analysis of the thick inferior-medial femoral neck cortex, and its critical role in withstanding the balance of the forces placed on the proximal femur. Fractures in this area lead to mechanical instability, and theoretical restoration of the three parts of the triangle leads to a significant advantage in terms of stability [22].

## No Ideal Subtrochanteric Classification System

Subtrochanteric fractures have multiple classifications [23]. The shortcomings of current classification schemes include substantial overlap with other fracture types (e.g., Seinsheimer or Russell and Taylor trochanteric classifications), interobserver variability or lack of agreement, and limited value in guiding clinical treatment options [23]. Loizou et al., reviewed and compared 15 identified different classifications from 1949 to 1992, with only 8 of these specifying the upper and lower limits of the subtrochanteric region. The most commonly agreed distal limit extension is 5 cm from the LT. The Seinshemer and AO were the most frequently used in the encountered literature [23]. For instance, Fielding's anatomic classification for subtrochanteric fractures might stem anatomically from Koch's biomechanical understanding of the femoral proximal third structural bone conformation. It is divided into three prognostic types depending upon the distance from LT: I, at LT; II, 0 - 2.5 cm below LT; III 2.5 - 5 cm below LT [2,12,24]. Although classifications were found to be historical (low reproducibility and omits individual or ethnic variations), in the clinical setting, traditionally subtrochanteric fractures are those occurring within 5 cm of the LT [8,23,24]. Moreover, no classification seems to guide surgical treatment choices apart from comminuted fractures or those that extend into the trochanteric region. These fractures lead to a higher fixation failure rate, and thus screw-plate or IMN fixation can be used for stable fractures, and IMN for unstable fractures [23,25,26]. Over time, with the improvement of IMN implants and reduction techniques, the clinical utility of classifications has decreased [26]. Loizou et al. propose a classification system with significant inter- and intra-observer reliability, that may guide treatment options, but testing outcomes are not established yet [23].

Koch's descriptive biomechanical work of the cross-sectional area appears to be a more accurate method to evaluate the bone strength at the proximal third of the femur. It approximates the patient's physiognomy given the variability in the subtrochanteric region due to age, activity, and body habits. Therefore, hypothetically, radiographic measured fracture distance from the LT in cortical diameters, instead of millimeters, would create a standardized relative definition of proximal femoral shaft fractures that are tailored to patient physiognomy and is not subject to radiographic magnification [27].

## Evolution in Subtrochanteric Fracture Management

The most common management of subtrochanteric fractures is surgical fixation which currently involves IMN and plating (e.g., fixed angle and locking). IMN has evolved enough to become the gold standard due to decreased operative times and blood loss, shorter time to union, lower nonunion rate, lower reoperation rate, and for allowing immediate mobilization [4-6,9,13,28,29]. A biomechanical study has shown IMN to have a higher withstanding load and less varus collapse versus blade plates in comminuted subtrochanteric femur fractures [30]. These treatments have undergone evolution throughout the years.

Interestingly, ancient Egyptian mummies were found with intramedullary implants in the lower extremities. But IMN stabilization through surgery was first reported by anthropologists in 1524 on Hernán Cortes' explorations [3]. They witnessed surgeries in which the medullary cavity was accessed with obsidian knives and a wooden stick with resin was inserted to stabilize the fracture [31]. In the mid to late-1800s, physicians in Germany published research on IMN osteosynthesis with the use of ivory pegs on diaphyseal fractures of the femur and tibia [32]. Later that century, physicians in Germany began using ivory based IMN fixation devices for the treatment of pseudarthrosis in the femur. These were further stabilized with experimental interlocking nails and pins also made from ivory to improve rotational stability [33,34]. Julius Nicolaysen is regarded as the father of IMN as he highlighted the biomechanical advantage of nail length and the use of static interlocking screws at the proximal and distal end of the bone [34]. While the ivory material initially worked, researchers found that it was resorbable and did not last long enough for stabilization to be maintained. Fixation transitioned to the use of metallic materials in the 1900s, which presented its own challenges as metallic nails would loosen due to tissue reactions in the body [35]. At the turn of the century, the biomechanical advantage of a longer, solid nail for the stabilization of inter and subtrochanteric fractures of the femur was realized. With the advances in aseptic technique, anesthesia, and technical advances in materials, the management of fractures began to improve. In the first half of the 19th century, the introduction and progress of X-rays (i.e., 1910s) improved visualization, less invasive techniques to preserve biology, as well as IMN reaming (i.e., 1940s) prior to nail insertion to increase the surface area in contact with the nail improving stability [3,32,34]. IMN fell out of favor in the 1960s as nail designs of the time made it difficult to reduce and stabilize oblique and comminuted fractures, but this was improved with the renascence of interlocking screws idea with Künstcher and the cloverleaf-shaped nail [3]. Later, the concept of dynamization was introduced into newer designs to enhance bone healing in stable fracture patterns and those non-union cases [3]. Antegrade and retrograde IMN insertion are both used, with situations of both being discussed later in this review.

Extramedullary fixation is the other stabilization option for subtrochanteric fractures [36]. The first plate osteosynthesis method was documented in the late 1800s. The plates were used to treat fractures and non-unions of the femur, radius, humerus, and ulna. The first angled blade plate for osteosynthesis of femoral neck fractures was designed in 1914 [32,37]. Further research has demonstrated the effectiveness of the fixed angle blade since its introduction in the 1960s in the treatment of subtrochanteric fractures [24,38,39]. However, the use of blade plates for acute injuries can lead to higher failure and revision rates, and their use should be limited when there is comminution, medial calcar involvement, subtrochanteric extension, and poor bone quality [9,38,40]. It has been investigated that the dissection required for fixed blade plating de-vascularizes the bone and surrounding tissues, which may lead to a delay in healing [38]. As mentioned, the subtrochanteric region vasculature is precarious and could lead to delayed fracture consolidation, or non-union even in the latest reports on using IMN (7 - 20%) [41]. However, for such complications, fixed-angle blade plates offer a reliable option for revision surgery with a high union rate [42]. It allows the removal of soft tissue interposition at the fracture interval, correction of malalignment, and addition of graft augmentation and compression. A recent intertrochanteric and subtrochanteric non-union management literature review of 289 cases found that 65.7% of them were treated with a blade plate (61.6% were 95-degree angle), and the union rate ranged from 91 - 100% [42].

## Intramedullary Nailing, Antegrade or Retrograde, Where Are We At?

In terms of nail entry, there are two antegrade approaches, the piriformis and trochanteric entry points. In the piriformis approach, the entry of the guide wire is centered over the piriformis fossa and in line with the femur axis. In the trochanteric entry, the guide wire is slightly medial over the tip of the greater trochanter and is lateral to the long axis [9]. The entry point does not affect the union rate, but the trochanteric nail often shows less operative time and intraoperative radiation and is less traumatic to the abductors [43]. On the other hand, piriformis entry nail reduces the incidence of varus malreduction and medial cortex injury [44]. Regarding retrograde IMN, it was first introduced as a concept in the 1970s, which later evolved into an intercondylar notch entry point [45,46]. Initially introduced to cope with post-surgical hip pain and abnormal gait/balance after antegrade IMN, it eventually became advocated for treatment of supracondylar or intracondylar distal femur fractures and ipsilateral shaft or neck fractures [45,47]. Its indications have expanded to overcome antegrade IMN limitations and now include polytrauma patients, multisystem injury, hip soft tissue injury, obesity, pregnancy, ipsilateral pelvic ring/hip/acetabular/tibia fractures, bilateral femur shaft fractures, and ipsilateral hip/knee arthroplasties [16,18,46,48]. Early reports of retrograde IMN demonstrated slower union and higher nonunion rates, however, nonunion rates have improved with reaming and use of larger diameter nails, thereafter, matching the low nonunion rate of antegrade IMN (<5%) [16,48-51]. Brewster et al., comparing retrograde vs antegrade IMN, recently found no difference in long-term functional outcomes but did note an increased rate of hip pain with antegrade IMN [13,49,52,53]. Hence, retrograde IMN has become a feasible, convenient technique given its aforementioned broader indications, faster setup/positioning, shorter operating time, decreased blood loss, and less radiation time [16,46,53,54].

Given its convenience in some settings for femoral shaft fractures, and the concern of a short segment fixation for proximal third femur fractures, several studies show conflicting results when considering retrograde IMN as an equivalent option for subtrochanteric fractures. DiCicco et al., in their 16-patient retrospective study of subtrochanteric fractures treated with retrograde IMN, found a union rate of 64.7% [18]. This improved to 100% after 5 patients underwent 6 reoperations for implant revision, at approximately 22 weeks, with a varus deformity averaging 5.06 degrees (35 % malreduction rate) [18]. Kuhn et al. reported that fractures within 10 cm from the LT can be treated with either antegrade or retrograde IMN with no difference in outcomes [55]. Yet, some argue that if the fracture is closer than 4 cm from the LT, retrograde IMN should be avoided due to higher complication rates [10,17]. Moreover, Kuhn et al. explored "stressing" the concept of the fracture distance from the LT in relation to the proximal end of the nail formulating a ratio and found no direct relationship between adverse outcomes and the proximity of the fracture to the LT. They also found that the working length of the nail and nail advancement as far proximal as possible are important in preventing malunions [10]. In relation to the retrograde nail proximity to the trochanteric region, a biomechanical study evaluating the proximal femur strain showed that the proximal end of the nail ending at 4 cm distal from the LT revealed an increasing trend in torsion and axial stress [56]. In addition, another biomechanical study by Tejwani et al., recommended ending the tip of the retrograde nail at or above the LT to avoid stress risers [57].

A recent study by Parry et al looked at cortical diameters as a more individualized measure to define proximal third femur fractures comparing antegrade and retrograde IMN outcomes [27]. In a cohort of 54 patients with proximal femur fractures within 3 cortical diameters, there was no difference in outcomes (i.e., union rate, time to union, complications) among antegrade versus retrograde IMN-treated groups, and there was no varus malalignment [27]. As found in the literature, the retrograde group had less blood loss and operative time [27]. Interestingly, the median number of cortical diameters at 5 cm from the LT was 1.6 (range 1.2-2.0) [27]. Seems, retrograde IMN for a proximal femur fracture within 3 cortical diameters (sparing intraoperative advantages) provides similar outcomes to antegrade IMN. Cortical diameter theoretically controls the patient's size, physiognomy, and radiographic magnification. Although a biomechanical interpretation of this clinical study would be interesting to pursue, this approximates Kock's preliminary understanding of the cross-sectional area as a bone strength parameter that could potentially guide choosing treatment options [8].

## Conclusion

In conclusion, Koch found that there are high compression forces near the LT on the proximal medial third of the femur and hypothesized that cross-sectional area was a more accurate measure of bone strength [8]. Intramedullary nailing as well as extramedullary fixation through fixed angle and locking devices are the current treatments for subtrochanteric fractures. The IMN requires decreased operative time, causes less blood loss, and increased mobility, and thus is the gold standard treatment [4,5,29]. Antegrade and retrograde IMN approaches have no difference in long-term functional outcomes [13]. Cross-sectional measurements at the fracture and the distance from LT could potentially guide IMN treatment options, but there remains further research.

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## Conflict of Interest

The authors declare that they have no conflicts of interest.

### Ethics Statement

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