Kenneth A. Egol
Philipp Leucht *Editors*

Proximal Femur Fractures

An Evidence-Based Approach to Evaluation and Management

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This book is dedicated to my family, Lori, Alex, Jonathan, and Gabby, for their unending support and to all those who dedicate themselves to be better physicians and surgeons

Kenneth A. Egol, MD

To my wife Alesha and our son Finn for their never-ending support and love and for bringing joy and balance to my life

Philipp Leucht, MD

Foreword

I began studying hip fractures in the late 1950s leading to my doctoral thesis focused on the forces required to cause fractures about the proximal femur. I am excited to know that fractures of the hip remain a critically important topic in orthopedic surgery and education. The significant and increasing number of hip fractures that occur each year makes them a common problem treated by the majority of practicing orthopedic surgeons and an ever-increasing public health concern. In this important context, the timing of this publication is spot on. The editors, Drs. Egol and Leucht, have assembled an international panel of experts in hip fracture care to write the chapters of this text. The book is organized into thirteen well-written chapters encompassing all fracture types, anatomical and biomechanical considerations as well as complications and expected outcomes.

Dr. Egol and Dr. Leucht are busy academic orthopedic trauma surgeons, who have dedicated themselves to patient care, education, and musculoskeletal research. Working at one of the largest academic centers for orthopedic care, they provide much needed fracture care services for New York City's underserved populations and train residents and fellows in the nation's largest orthopedic surgery training program. The contributors to this book have devoted many years to practice and the study of fractures of the proximal femur, thereby sharing their expertise to all who read the text and the patients they treat. The editors and authors are to be congratulated for compiling a comprehensive text presenting practical treatment principles in a clear and concise manner. This text will benefit anyone who treats patients with fractures of the proximal femur.

Seattle WA, USA — Victor Frankel, MD, PhD, KNO

Preface

The incidence of proximal femur fractures is ever increasing, in part due to the aging population being more prone to this particular injury type and increased number of younger trauma patients surviving high-energy injuries. While there are many textbooks written about the fundamentals of proximal femur fracture management, none of these books outline the current evidence-based approaches that have begun to significantly improve diagnosis and management of these complicated fractures.

In this book, we have assembled a group of renowned authors from around the world with the goal to establish a text that can be used as a one-stop shop for academic and community-based orthopedic surgeons seeking evidence-based information on these difficult fractures. The book is divided into three succinct sections: basic principles including anatomy, biomechanics, and surgical approaches to the proximal femur; detailed chapters focusing on individual fracture locations and types; and, finally, chapters summarizing optimal perioperative medical management and quality and safety concerns.

Authors of the individual chapters are internationally recognized experts and were asked to provide readers with a comprehensive summary of the specifics of each fracture type, with special emphasis on up-to-date, evidence-based literature. Surgeons will be able to utilize this text to prepare for any particular proximal femur fracture procedure and subsequently will enter the operating room with an in-depth knowledge of the anatomy, preoperative evaluation, perioperative medical management, surgical approach, and fracture-specific reduction and fixation techniques. The format is beneficial for a quick review of the newest evidence but also allows an in-depth review of the details associated with specific fracture types around the hip.

We thank the authors for dedicating their time and expertise in generating this outstanding book. We would also like to thank the editorial staff at Springer for their hard work and editorial expertise. We hope that this book will serve you as a valuable tool and that you will often return to these chapters in preparation for surgical procedures involving proximal femur fractures.

New York, NY, USA — Kenneth A. Egol, MD
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Anatomy of the Proximal Femur

1

Sanjit R. Konda

Introduction

The proximal femoral anatomy starts its developmental path as early as 4 weeks in utero and continues development through puberty. The complex signaling pathways that lead to differentiation, growth, and maturation of the bone, cartilage, muscle, tendon, and synovial joints of the hip result in a complex structure responsible for supporting the entire body weight and allowing for ambulation. Understanding the proximal femoral geometry, blood supply, and anatomical structures allows for a methodical approach to treatment of fractures of the proximal femur.

Intrauterine and Childhood Development

A complex host of physiologic and biomechanical factors play a role in the intrauterine development of the proximal femur. Limb formation in the embryo starts at 4 weeks with development of limb buds which are outpouches from the ectodermal layer of the ventrolateral wall [1]. The underlying mesodermal layer is responsible for development of the bone, cartilage, muscle, tendon, and synovial joints. By 7 weeks, the cartilaginous femur and acetabulum have developed, and a controlled apoptosis between the two structures occurs creating a cleft which is the future hip joint [2]. At 8 weeks' gestation, the start of the fetal stage of development, there is a shift from primarily cell differentiation to primarily cell growth and maturation. The ossification center of the femur appears in the central aspect of the femoral shaft and ossification proceeds proximally and distally. Concurrently, the proximal femur arterial supply appears at the proximal femoral shaft at the site of the nutrient artery with capillary invasion into the cartilaginous model of the proximal femur. At 11 weeks the hip is fully formed in appearance [3]. At 12–14 weeks, vascularization of the proximal femur takes the form of a ring of vessels around the base of the femoral neck. These vessels will gradually differentiate into the medial and lateral circumflex vessels [2]. By 16 weeks the femur is ossified proximally to the level of the lesser trochanter, and the femoral head and acetabular articular surfaces are covered in mature hyaline cartilage (Table 1.1).

Femoral anteversion is first defined at 11 weeks' gestation at which time it measures 5–10°. As the fetus develops, femoral anteversion increases to maximum of 45° at the time of

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Table 1.1 Timeline of proximal femur development during gestation

Timepoint	Milestone
4 weeks	Limb buds form from ectodermal layer of ventrolateral wall
7 weeks	Cartilaginous models of femur and acetabulum have developed from mesodermal layer. Apoptosis creates cleft between acetabulum and femur which is the site of future hip joint
8 weeks	Shift from cell differentiation to cell growth and maturation. Appearance of femoral ossification center. Appearance of blood supply at nutrient artery site with capillary invasion into cartilage model of the femur
11 weeks	Hip fully formed in appearance
12 weeks	Vascular ring of vessels formed at the base of femoral neck
16 weeks	Femur ossified to the level of lesser trochanter. Femoral head and acetabulum covered in mature hyaline cartilage

birth. Subsequently, in the normally developing femur, femoral anteversion gradually decreases to 15° by 16 years of age [4, 5].

The relationship between the neck-shaft angles of the proximal femur also varies through development starting in the fetal stage. At 15 weeks' gestation the neck-shaft angle is 145° and gradually decreases to 130° by 36 weeks' gestation [3]. A range of normal neck-shaft angles throughout childhood development has been established in a cohort of 400 children (800 hips), and the authors found that by age 18 the mean neck-shaft angle was 127.3° [6].

Blood Supply to the Femoral Head

As the blood supply to the proximal femur matures through gestation, it develops into three distinct arterial systems, the capsular (retinacular), foveal, and intraosseous [7–12]. The foveal blood supply through the ligamentum teres has consistently been shown to provide minimal blood supply to the femoral head. In fact, resection of the ligamentum teres during open hip reduction procedures in patients with dysplastic hips has shown no increased incidence of osteonecrosis of the femoral head further supporting the notion of minimal contribution to femoral head vascularity [2].

The capsular blood system originates with the medial and lateral femoral circumflex arteries which branch off the profunda femoris in 79% of cases. In 20% of cases 1 of these arteries branches off the femoral artery, and in 1% of cases both arteries arise directly from the femoral artery [13]. The medial and lateral femoral circumflex arteries form an anastomotic extracapsular ring around the base of the femoral neck. The medial circumflex artery is the main contributor of blood supply to the femoral neck, and the deep branch of the medial circumflex artery is the conduit for a majority of the blood flow and comprises the majority of this anastomotic ring. Branching off the extracapsular ring are the ascending cervical (retinacular) arteries which penetrate the joint capsule at the base of the femoral neck along the intertrochanteric line. From here, there are four main groups of ascending cervical arteries of which the lateral (superior) cervical artery is the most important to provide perfusion to the femoral head [7–12]. There is new literature to suggest that the inferior retinacular artery may also provide a significant amount of perfusion to the femoral head [14]. The ascending cervical arteries form a secondary vascular ring at the subcapital region of the femoral neck termed the subsynovial vascular ring of which the terminal branches of the deep branch of the medial circumflex vessels penetrate the posterosuperior aspect of the femoral head 2–4 mm proximal to the start of the articular surface (Fig. 1.1).

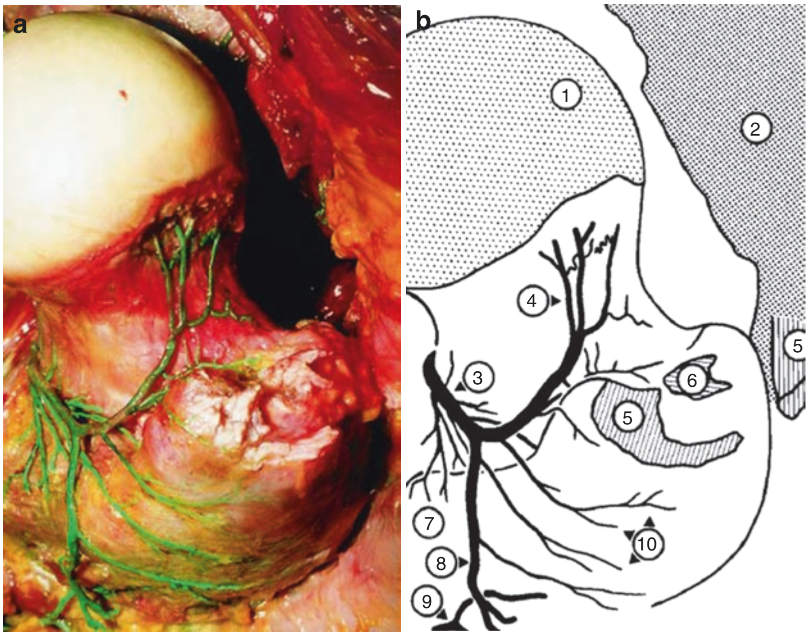

Fig. 1.1 (**a**) Photograph showing the perforation of the terminal branches into the bone (right hip, posterosuperior view). The terminal subsynovial branches are located on the posterosuperior aspect of the neck of the femur and penetrate the bone 2–4 mm lateral to the bone-cartilage junction. (**b**) Diagram showing: (*1*) the head of the femur, (*2*) the gluteus medius, (*3*) the deep branch of the MFCA, (*4*) the terminal subsynovial branches of the MFCA, (*5*) the insertion and tendon of gluteus medius, (*6*) the insertion and tendon of piriformis, (*7*) the lesser trochanter with nutrient vessels, (*8*) the trochanteric branch, (*9*) the branch of the first perforating artery, and (*10*) the trochanteric branches (Figure and Caption copyright Gautier et al. [12].)

Anatomy of the Proximal Femur

Proximal Femoral Geometry

Normal constant relationships between the femoral head, femoral neck, greater trochanter, and femoral shaft exist in the grown adult. These relationships are important to define as they are the normal relationships that should be established in the course of operative treatment of a fracture about the proximal femur. As described by Dror Paley, the normal tip of the trochanter to the center of femoral head line orientation to the mechanical or anatomical axis is 90° ± 5° (lateral proximal femoral angle [LPFA]) and 84° ± 5° (medial proximal femoral angle [MPFA]). Another reference line is the neck anatomic axis or medial neck-shaft angle (MNSA) which is 130° ± 10° ([15]; Fig. 1.2).

Internal Geometry of the Femoral Neck

The internal geometry of the femoral neck was defined in 1838 by Ward [16]. He described a trabecular network of which there were compression trabeculae medially along the femoral neck and tensile trabeculae laterally along the femoral neck. Secondary trabeculae are oriented throughout the rest of the proximal femur in accordance with Wolff's law which states that living bone will react to mechanical loading and unloading of

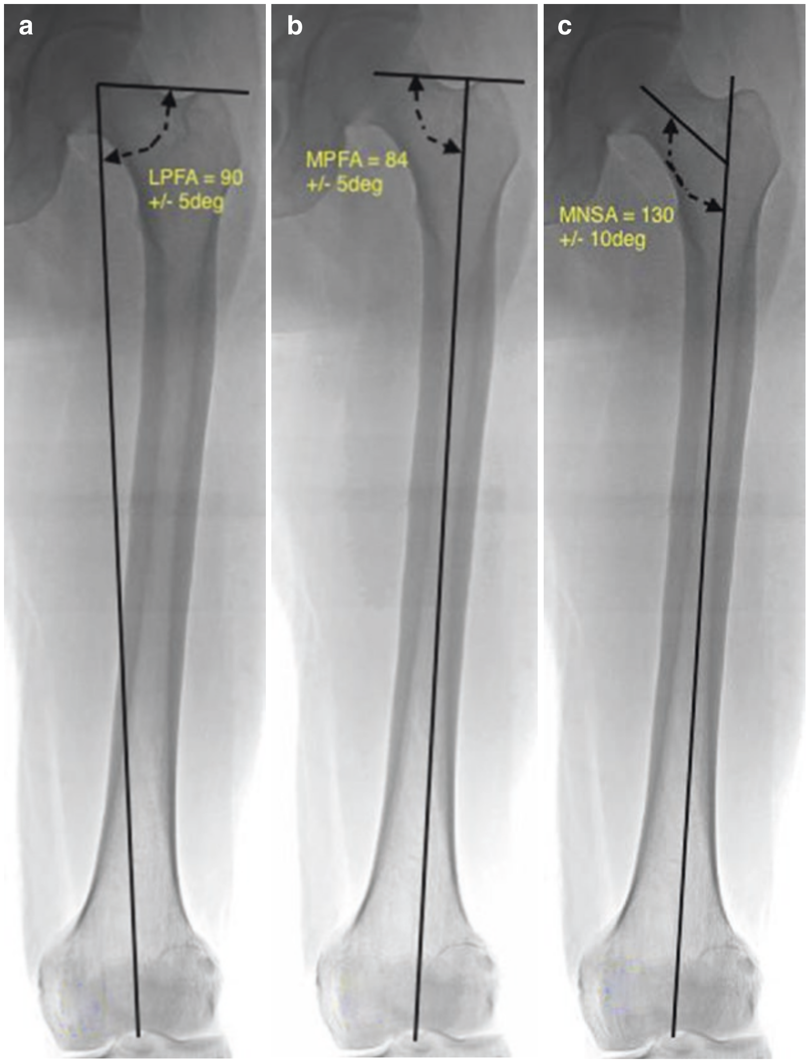

Fig. 1.2 (**a**–**c**) Angle measurements of the proximal femur. The normal tip of the trochanter to the center of femoral head line orientation to the mechanical or anatomical axis is 90° ± 5° (lateral proximal femoral angle [LPFA]) and 84° ± 5° (medial proximal femoral angle [MPFA]). Another reference line is the neck anatomic axis or medial neck-shaft angle (MNSA) which is 130° ± 10°

bone segment. In the case of repetitive loading, the bone will remodel overtime to become stronger (i.e., increased trabeculae in the femoral neck) to accommodate the increased load. The area of the femoral neck deficient in trabeculae is termed Ward's triangle ([16, 17]; Fig. 1.3).

Anatomic Regions of the Proximal Femur

The proximal femur can be divided into four main regions: femoral head, femoral neck, intertrochanteric, and subtrochanteric. Figure 1.4 depicts these radiographically. The femoral head-neck junction is defined as the subcapital region of the femoral neck and it is located intracapsularly. The femoral neck-intertrochanteric junction is defined as the basicervical region and this is located extracapsularly. The intertrochanteric region is defined by the area encompassed by the greater and lesser trochanter of the femur. The region extending 5 cm distal to the lesser trochanter is defined as the subtrochanteric region (Fig. 1.5).

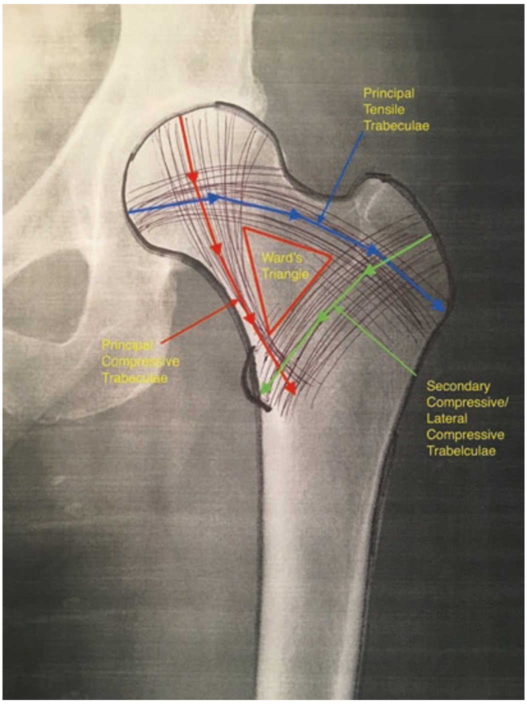

Fig. 1.3 Plain AP radiograph of the left hip demonstrating the principal compression and tension trabeculae of the proximal femur as well as the secondary compressive trabeculae. Note the central aspect of the femoral neck which is devoid of trabeculae called Ward's triangle and which is bounded by the principal tensile and compressive trabeculae and the secondary compression force

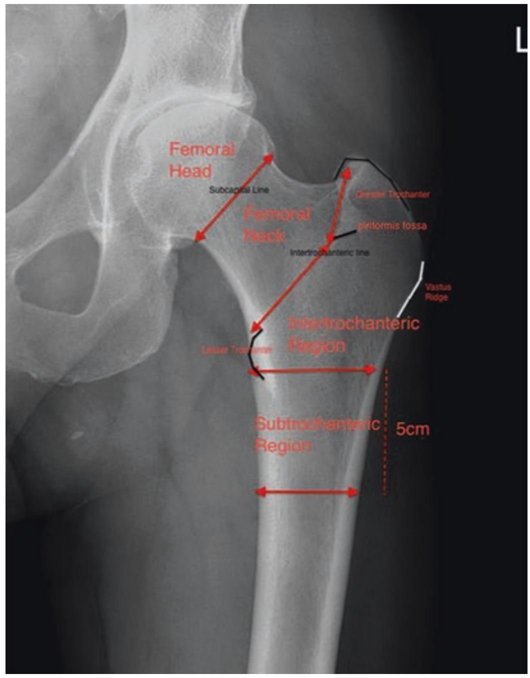

Fig. 1.4 Plain AP radiograph of the left hip demonstrating various anatomic regions and landmarks

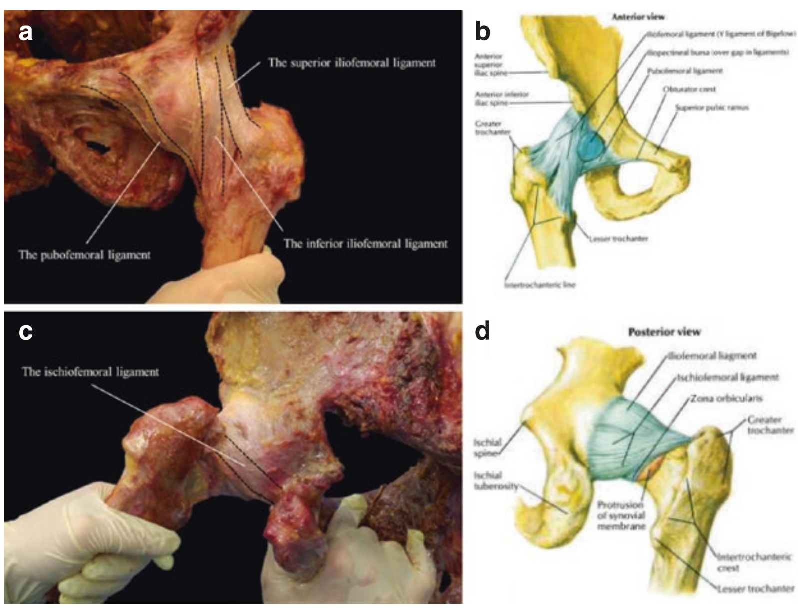

Fig. 1.5 (**a** and **b**) Cadaveric left hip specimen and associated diagram with removal of overlying musculature revealing the superior and inferior iliofemoral ligament and pubofemoral ligament. Figures (**c** and **d**) with diagrammatic labeling of the ischiofemoral ligament (Adapted from Hidaka et al. [18] and Thompson JC. Netter's Concise Orthopaedic Anatomy, 2nd ed. Philadelphia: Saunders Elsevier; 2002.)

Hip Capsule, Ligaments, Muscular Origins and Insertions, and Innervation Around the Proximal Femur

The hip capsule originates on the acetabulum of the pelvis. Anteriorly, it extends to the base of the femoral neck at the intertrochanteric line. Posteriorly, the lateral half of the femoral neck is extracapsular. The intracapsular portion of the femoral neck has no periosteum; therefore, intracapsular fractures must heal via endosteal healing.

There are three main ligamentous structures about the hip joint which are confluent with the hip joint capsule: ischiofemoral, iliofemoral, and pubofemoral ligament. The ischiofemoral ligament controls hip internal rotation in flexion and extension. The lateral aspect of the iliofemoral ligament has control of hip internal rotation in extension only and control of hip external rotation in both flexion and extension. The pubofemoral ligament controls external rotation in extension ([19]; Fig. 1.6).

On the anterior aspect of the proximal femur, the indirect head of the rectus femoris, innervated

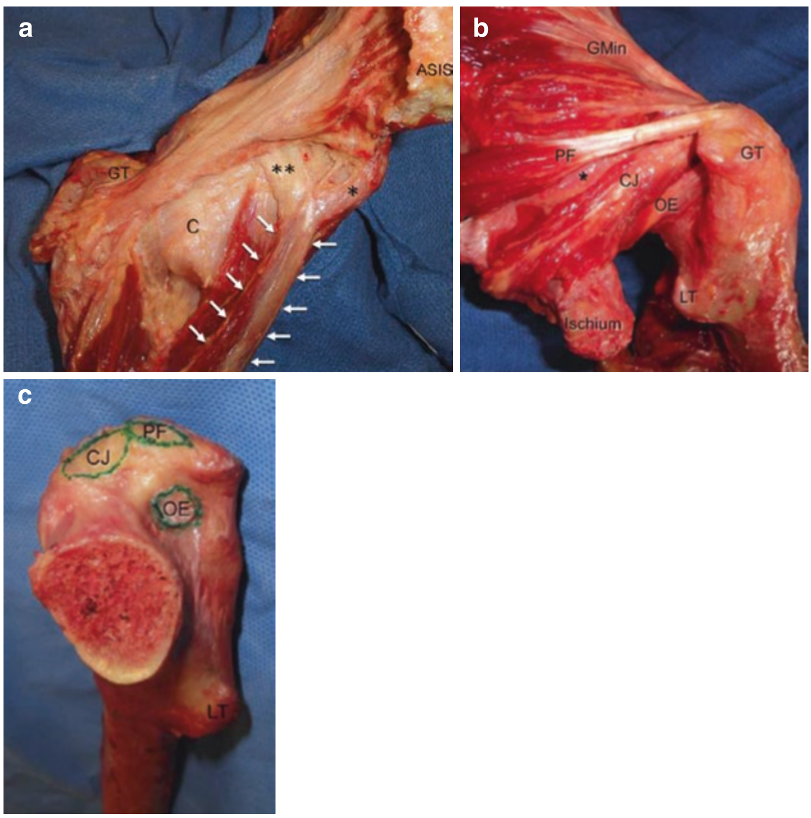

Fig. 1.6 (**a**) Anterior view of the hip capsule [C] and surrounding pericapsular structures. The rectus femoris (*arrows*) is illustrated overlying the iliocapsularis muscles, along with its direct (*) and indirect (**) heads. The indirect head originates in part of the anterosuperior capsule at the acetabular rim. The tip of the greater trochanter (GT) and anterior superior iliac spine (ASIS) are labeled for orientation. (**b**) Posterosuperior view of the hip capsule (*asterisk*) with the overlying pericapsular muscles and tendons. Gluteus medius (Gmin), piriformis (PF), conjoint tendon of the obturator internus and gemelli (CJ), and obturator externus (OE) each have consistent capsular attachments. The ischium, greater trochanter (GT), lesser trochanter (LT), and capsule (*asterisk*) are labeled for orientation. (**c**) Medial view of the tendinous insertions onto the medial greater trochanter. The photograph was taken after the tendons were sharply removed from their respective insertion points (Figure and Caption Copyright Cooper et al. [20])

by the femoral nerve, originates from the anterior hip capsule. The vastus medialis and vastus intermedius, both innervated by the femoral nerve, originate at the superior aspect of the subtrochanteric region on the anterior aspect of the femur (Fig. 1.6).

On the lateral aspect of the femur, the gluteus medius and minimus, both innervated by the superior gluteal nerve, have a broad insertion over the superolateral aspect of the greater trochanter. The vastus lateralis, innervated by the femoral nerve, originates laterally on the vastus ridge, just inferior to the greater trochanter.

Posteriorly, the short external rotator muscles of the hip insert along the intertrochanteric line in a predictable order from superior to inferior. At the posterosuperior aspect of the greater trochanter, the piriformis (piriformis nerve) inserts followed by the obturator externus (obturator nerve), the superior gemellus, obturator internus, and inferior gemellus (all innervated by the nerve to obturator internus). The quadratus femoris (nerve to quadratus femoris) inserts along the inferior aspect of the intertrochanteric ridge posteriorly. The lesser trochanter is a posterior structure, and inserting onto it is the iliopsoas muscle (femoral nerve) (Fig. 1.6).

Along the posterior aspect of the proximal femoral shaft distal to the intertrochanteric ridge are the insertions for the gluteus maximus (inferior gluteal nerve), adductor magnus and adductor brevis (obturator nerve), and pectineus (obturator nerve).

Conclusion

In-depth understanding of proximal femoral anatomy including development, geometry, and muscular and ligamentous insertions is necessary to develop cogent treatment plans for fractures of the proximal femur.

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Biomechanics of the Hip

2

Lorenz Büchler, Moritz Tannast,
Klaus A. Siebenrock, and Joseph M. Schwab

Introduction

The hip joint plays a crucial role in the generation and transmission of forces during routine activity. To meet the requirements of ambulation, the hip differs in design from the more common hinge joints and is characterized by a large amount of inherent bony stability and extensive ligamentous and muscular support. Regardless of this stability, the hip joint maintains a wide functional range of movement. The great physical demands placed on the hip joint during athletic activities predisposes it to injury or chronic pathologic processes. Biomechanical considerations of the hip play a crucial role in understanding structural hip abnormalities and mechanisms of injury, and have important implications in the treatment of trauma-related injuries and reconstructive surgeries.

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Evolution of the Human Hip

A common feature of the hip joints of *hominids* (great apes) is a spherical femoral head (*coxa rotunda*) with a long, narrow femoral neck [1]. This enables a wide range of motion of the hip joint, allowing the individual to sit, stand, and climb trees, and is ideally adapted for a jungle habitat. The obvious advantage is that the upper extremity is not exclusively used for locomotion, with hands that are free to grasp an object. The specific anatomy and biomechanics of the human hip joint is a consequence of the evolution from a sporadic to a permanent bipedal gait. It remains a matter of controversy as to why permanent bipedalism first emerged. A changing habitat—from jungle to open savanna—might have favored a predominantly bipedal running locomotion, allowing the eyes to look over tall grasses in the open savanna for possible food sources or predators. The earliest evidence includes fossil footprints similar to those of modern humans found at a site in Tanzania (Laetoli footprints). They are believed to have originated from *Australopithecus*, human ancestors that evolved in eastern Africa some 3.2 million years ago [2].

The most complete fossil of this species, "Lucy," shows pelvis and leg bones that are almost identical to those of modern humans. The brain and body size, however, are like those of a chimpanzee, indicating that bipedal gait evolved

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before the use of tools. Permanent bipedal gait required several mechanical and neurological adaptations [3]. The gluteus maximus muscle, a relatively minor muscle in the chimpanzee, was transformed into the largest muscle in the body as a hip extensor to stabilize an upright torso and major propulsive muscle in upright walking. The increase of forces exerted on the femoral neck favored a sturdier hip with a femoral neck less prone to fracture—which might explain the genetic basis for the relatively high prevalence of a *coxa recta* (cam morphotype) in the European male population [4].

History of Research on Biomechanics of the Hip Joint

The earliest research on biomechanics of the hip dates back to the nineteenth century. Braune and Fischer published extensive research on human gait and biomechanics of the hips between 1895 and 1904 [5]. In contrast to earlier research on the subject, their approach was very analytical, involving the use of a camera apparatus to analyze human motion and determine the activity of muscles during ambulation. Using a three-dimensional coordinate system, the center of gravity in various phases of the gait cycle was defined. These findings were the foundation of the later fundamental work on the forces acting on the proximal femur and acetabulum by Frederick Pauwels [6]. Much experimental and clinical research using sophisticated methodology (e.g., ENMG, strain gauge prosthesis, finite element models) has since been conducted on this subject, generally confirming Pauwels's work.

Anatomical Considerations

The demands on both stability and range of motion of the human hip joint are extraordinary. The anatomical properties of the acetabulum and proximal femur of a normal hip ensure a stable hip joint with an impingement-free range of motion during movements that are necessary in daily life.

Acetabular Anatomy

The spatial orientation and size of the acetabulum can be described from radiographs by lateral center edge angle (LCE), the inclination of the weight-bearing surface (acetabular inclination or index AI), and the relation of the anterior and posterior wall on antero-posterior radiographs (retroversion index). Normal values are a craniocaudal acetabular coverage of 78 ± 7%, LCE 26° ± 5°, AI 9° ± 4°, and an entirely anteverted acetabulum [7]. Lining the acetabular rim is the fibrocartilaginous labrum, which increases the functional size of the acetabulum and acts as a seal for joint fluid; it also significantly increases the functional stability of the joint [8]. Changes in the normal anatomy of the acetabulum have a great influence in the biomechanical properties of the hip joint. Acetabular undercoverage (dysplasia), overcoverage (pincer-type impingement), or malrotation (acetabular retroversion) can result in static overload and/or dynamic impingement of the hip, and is believed to be a cause of degenerative hip disease.

Femoral Anatomy

The relative size of the femoral neck to the femoral head is a compromise between resistance to fractures and range of motion of the hip joint. The offset can best be described using the alpha angle. Normal values are 40–45°, allowing an impingement-free range of motion [9]. A reduced offset can lead to cam-type femoroacetabular impingement (FAI) that causes significant damage to the labrum and cartilage. Femoral antetorsion ranges from 30 to 40° at birth, and decreases progressively throughout growth. Normal values in adults show a wide range, with an average of 8° in males and 14° in females. While a higher antetorsion increases the lever arm of the gluteus maximus muscle, it decreases the lever arm of the abductors and can lead to posterior FAI [10]. The inclination between the femoral neck and shaft (CCD angle) also decreases during one's lifetime, with an average angle of 150° in newborns and 125 ± 5° in adults. A decrease in the CCD angle (varus hip) increases the lever arm of the abductors and thus decreases joint forces. On the other hand, the stresses on the femoral neck are increased. This partially explains why valgus-impacted femoral neck fractures have a better chance of healing.

Muscle and Tendons/Ligaments

The hip is enclosed by a fibrous capsule. Intracapsular reinforcements (ilio-femoral, ischio-femoral, and pubo-femoral ligaments) stabilize the hip joint in the terminal range of motion. Numerous muscles are responsible for the motion of the hip joint. The iliopsoas, rectus femoris, sartorius, and tensor fasciae latae muscles contribute to hip flexion. The gluteus maximus and hamstrings extend the hip. Gluteus medius, gluteus minimus and tensor fasciae latae are hip abductors and internal rotators. Adductor magnus, -longus and -brevis muscles adduct the hip. External rotators are piriformis, gemellus superior and inferior, obturator internus and externus, and quadratus femoris muscles.

Function of the Hip/Gait Patterns

Range of Motion

The normal range of motion of a healthy adult hip measured with goniometric techniques shows significant variation: Mean hip flexion 120° (90–150, SD 8.3), extension 9.5° (range; 0–35, SD 5.3), abduction 38.5°(15–55, SD 7.0), adduction 30.5 (15–45, SD 7.3), internal rotation 32.5 (20–50, SD 8.2), and external rotation 33.6 (10–55, SD 6.8) [11]. Hip rotation appears to decrease by about 15–20° per decade during the first two decades of life, and about 5° per decade thereafter [12]. Measurements using dynamic ultrasound found lower values of passive ROM in the asymptomatic hip because it allows anatomic confirmation of terminal hip motion [13]. Joint motion varies with age, and is generally more restricted in the older age group [11, 12, 14]. In a normal hip, the joint capsule, ligaments, and musculotendinous units limit the terminal range of motion. In FAI, or generally hyperlax patients, this limitation is insufficient, leading to a bony abutment between the femoral neck and acetabular rim.

Walking

In humans, the sequence of ambulation is composed of several successive processes: (1) double limb stance. The body weight is equally distributed across both hips; (2) anterior tilt of the pelvis in the sagittal plane (5° in walking, 15–20° in running), shifting of the center of gravity over the stance leg and hip extension 5–10°; (3) anterior rotation of the pelvis and weight release of the swing leg; and (4) rise of the pelvis 5–6° in the frontal plane and hip flexion 40–50° to elevate the swing leg. Propulsion with extension of the stance leg and plantar flexion of the ankle. A most energy-efficient gait is achieved at a mean velocity of 1.2–1.5 m/s (4-5-5 km/h), a step length of 0.65–0.75 m, and a cadence of 105–130 steps/min [15].

Biomechanics of the Hip

The hip is a highly constrained ball and socket joint that attaches the lower limb to the rest of the body. The center of gravity is above the hip joints, and a continual muscular force must be applied to balance the body's mass on the hip. In contrast to many animals, standing is not a resting position for humans. To reduce energy consumption while standing, humans tend to shift weight from one leg to the other and position them in hyperextension to lock the hips onto the ilio-femoral ligaments.

Depending on the activity, the hip joint can see a peak force of up to eight times body weight (Table 2.1). This is primarily a result of muscular contraction across the hip joint that counteracts the weight of the body when attempting to stabilize the pelvis in single leg stance. A free body diagram of the hip joint shows how the moment arms acting on the hip joint can be used