18 Biomechanics of Hip Function

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18.1 Anatomy

18.1.1 Bony Anatomy

The acetabulum is composed of the triradiate cartilage and the acetabular cartilage complex formed by the fusion of the ilium, ischium, and pubis [1]. The triradiate cartilage will form the non-articular medial wall, and the acetabular cartilage complex, composed mainly of hyaline cartilage, will form the articular portion of the acetabulum [1]. Physeal growth occurs through the triradiate cartilage with appropriate height and depth of the socket developing in response to the presence of the femoral head [2]. Acetabular maturation continues until the fusion of the triradiate cartilage, usually from 16 to 18 years of age [2]. The normal acetabulum is anteverted 15–20° with a mean depth and diameter of 29.49 ± 4.2 millimeters (mm) and 54.29 ± 3.8 mm, respectively [3]. A deep acetabulum (profunda or protrusio) may result in pincer type impingement, while failure of the secondary ossification centers to develop will result in a shallow socket known as hip dysplasia [2, 4, 5].

The femoral head develops simultaneously with the acetabulum with growth occurring through the longitudinal (between the femoral head and the neck), trochanteric (between the femoral neck and the greater trochanter), and femoral neck isthmus physes [1, 2]. The neck shaft angle is the angle measured between the axis of the femoral neck and the femoral shaft. The angle is highest at birth, but decreases to an average adult value of 125 ± 5° [1, 6]. Femoral neck version is the angle between the femoral neck and the axis that crosses the distal femur epicondyles with the normal amount of adult anteversion ranging from 12 to 14° for a mean of 15.4° [1, 3, 7, 8]. The mechanical advantage of the gluteus maximus muscle increases while the hip abductor mechanical advantage decreases with increasing proximal femur anteversion [9].

The femoral head-neck junction is normally shaped with the femoral neck narrower than its head. The head-neck junction morphology can be quantified by the anterior offset or the alpha angle [10–13]. The offset is measured as the ratio between the femoral head and neck radii, or as an absolute distance, which is normally about 10 mm [11, 14]. The alpha angle is a method to quantify the concavity at femoral head-neck junction with normal alpha angle values less than 50 or 55°. The two bony prominences on the superior-lateral and posterior-medial aspects of the proximal femur are named the greater and lesser trochanters, respectively, and serve as the insertion sites for a variety of muscles that contribute to hip motion.

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18.1.2 The Hip Joint Capsule

The hip joint is surrounded by a thick fibrous capsule that extends from the acetabular rim to the proximal femur attaching anteriorly to the intertrochanteric line, superiorly to the base of the femoral neck, superomedially to the intertrochanteric crest, and inferiorly to the femoral neck near the lesser trochanter [15, 16]. Three reinforcing ligaments are confluent with the hip capsule that help to provide hip stability. These include the iliofemoral ligament (Y ligament of Bigelow), pubofemoral ligament, and ischiofemoral ligament (Fig. 18.1). The ligaments serve as the primary hip rotational restraints depending on the position and rotation of the hip during specific motions [17, 18]. The iliofemoral ligament originates from the anterior inferior iliac spine (AIIS) and splits distally into two distinct arms with the lateral arm inserting on the anterior prominence of the greater trochanteric crest and the medial arm inserting on a subtle angulated prominence of the anterior-inferior femur at the level of the lesser trochanter. This acts to restrict external rotation in all hip positions and both internal and external rotation with the hip in extension. The medial arm was most dominant in hip neutral flexion or extension while the lateral arm dominated in all other hip positions [17, 19, 20]. The pubofemoral ligament attaches to the superior pubic ramus proximally and then blends with the ischiofemoral and iliofemoral ligaments distally as it lacks a true bony femoral attachment [15]. It was previously believed to control external rotation in extension; however, a recent study by Martin et al. demonstrated the key function of the pubofemoral ligament as limiting internal rotation with increasing hip flexion [20, 21]. The ischiofemoral ligament extends from the ischium to the femoral neck-trochanteric junction acting as a primary restrictor of internal rotation in both high and low hip flexion [17, 20]. The iliofemoral ligament is the strongest of these ligaments while the posterior ischiofemoral ligament is the thinnest and weakest [22]. Several studies have demonstrated the important role of the hip capsule in providing stability to the joint synergistically with other static soft tissue stabilizers such as the acetabular labrum and transverse acetabular ligament throughout physiologic and supraphysiologic range of motion [23–26].

18.1.3 Intra-Articular Structures

The acetabular labrum is a horseshoe shaped structure attached to the acetabular rim that lies just deep to the hip capsule. The capsular side of the labrum is composed of mainly type I and III collagen, while the articular side is composed of fibrocartilage [27]. The labrum functions to deepen the acetabulum with labral size inversely proportional to the depth of the bony acetabular socket. It also acts to increase hip stability by increasing the acetabular surface area and volume while creating a suction seal that opposes the flow of synovial fluid in and out of the central compartment [28, 29]. Weight bearing activities with a functioning labral seal leads to an increase in intra-articular pressure that reduces intra-articular friction by improving joint lubrication [30, 31]. Additionally, Safran et al. demonstrated that the labrum has strain at rest, which can increase and decrease in different locations of the labrum depending on hip position [32].

The ligamentum teres is composed of well-organized collagen bundles that attaches the femoral head to the acetabulum. The biomechanical role of the ligamentum teres has been a widely debated topic with proposed functions including hip stabilizer, fluid and force distributor of the acetabulum, and embryonic remnant without a specific function in adults [33–36]. However, recent studies have shown the ligamentum teres to be taut in flexion, adduction, and external rotation, leading some authors to believe that it does provide some degree of hip stability, resisting dislocation, and micro-instability [33, 37–39].

Hip articular cartilage has been shown to be highly inhomogeneous in thickness distribution on both the acetabular and femoral sides. A study by Von Eisenhart et al. demonstrated that maximum cartilage thickness was found ventrosuperiorly in the acetabulum and in the femoral head with a maximal thickness that ranged from 2.6 to 4.3 mm in the acetabulum and from 2.4 to

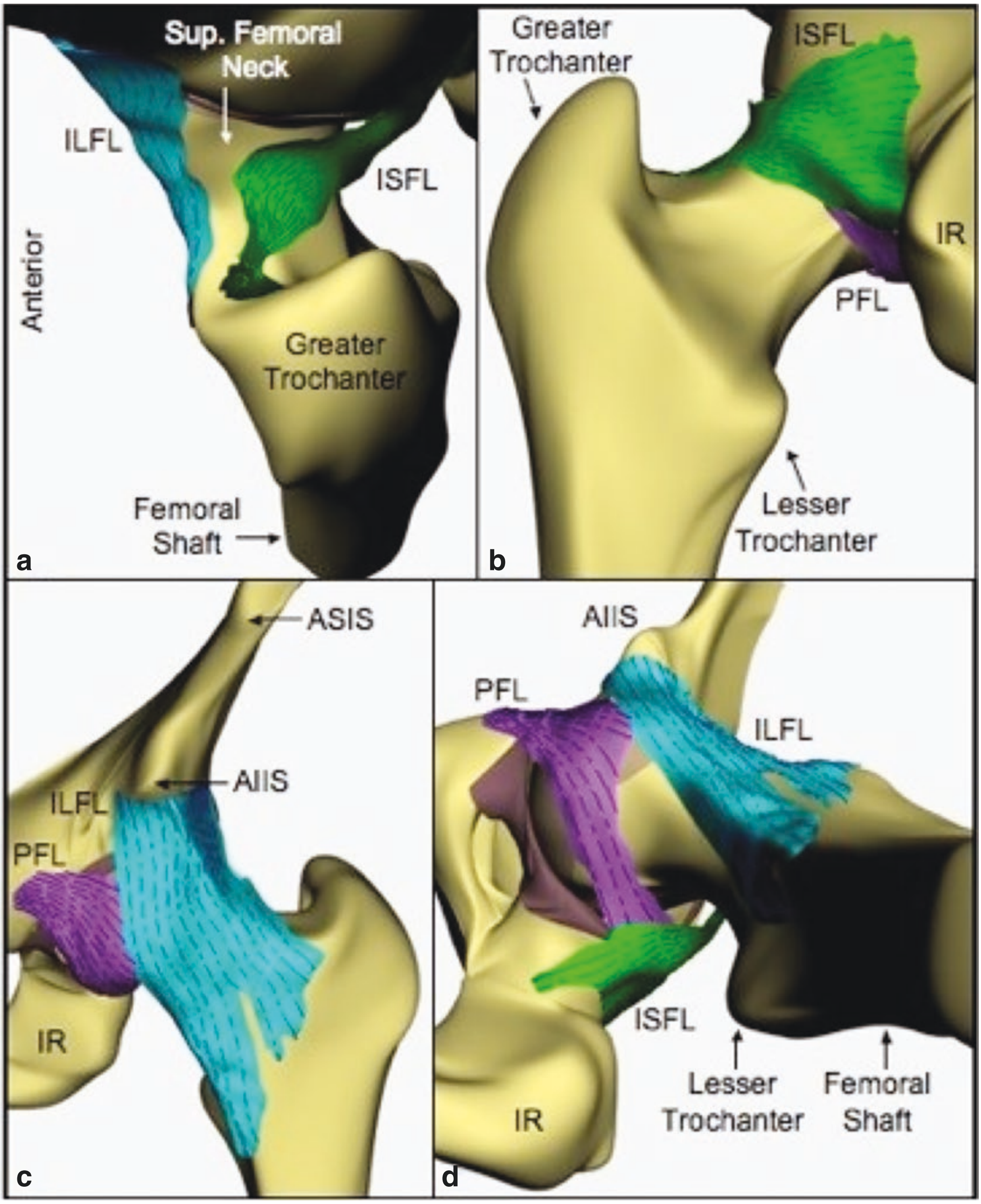

Fig. 18.1 Ligamentous relationships of the hip capsule. Computer model (**a**) demonstrating the relationship of the distal lateral iliofemoral ligament (ILFL) and the distal ischiofemoral ligament (ISFL), viewed from a superior position looking down the femoral shaft. Computer model showing (**b**) the posterior blend of the pubofemoral ligament (PFL) and ISFL, and (**c**) the anterior blend of the PFL and ILFL. Fig. (**d**) demonstrates the relationships of all three ligaments as viewed from an inferior position looking upwards at the inferior aspect of the femoral head. Figure used with permission from the senior author. (ASIS, anterior superior ischial spine; AIIS, anterior inferior ischial spine; IR, ischial ramus). Reprinted from DeLee Drez and Miller's Orthopaedic Sports Medicine, Fifth Edition, Mark D. Miller, MD and Stephen R. Thompson, MD, MEd, FRCSC, Hip Anatomy and Biomechanics, 907–924, 2020, with permission from Elsevier

5.3 mm in the femoral head [40]. This location of maximum thickness corresponded with location of maximum pressure recorded during the walking cycle.

18.1.4 Muscles around the Hip Joint

There are more than 20 muscles that cross the hip joint and contribute to hip motion (Table 18.1). These muscles can be grouped according to their main function and innervation. The hip abductors and internal rotators (gluteus medius, gluteus minimus, and tensor fascia lata) are innervated by the superior gluteal nerve [6]. The iliopsoas, rectus femoris, sartorius, and pectineus are responsible for hip flexion and are innervated by the femoral nerve [6]. Adduction of the hip occurs through action of the adductor magnus, adductor longus, adductor brevis, and gracilis through innervation by the obturator nerve. The gluteus maximus and hamstrings (biceps femoris, semi-

Table 18.1 Muscles around the hip joint sorted by function

Hip abductors and internal rotators						
Muscle	Origin	Insertion	Innervation	Spinal Level	Additional Function	Notes
Gluteus Medius	Ilium (between posterior-anterior gluteal lines)	Greater trochanter	Superior gluteal	L4-S1		
Gluteus Minimus	Ilium (between Anterior/Inferior Gluteal Lines)	Greater trochanter	Superior gluteal	L4-S1		
Tensor fasciae Latae	Anterior iliac crest	Iliotibial band (Gerdy's tubercle)	Superior gluteal	L4-S1		
Hip flexors						
Muscle	Origin	Insertion	Innervation	Spinal level	Additional function	Notes
Iliopsoas	Iliac Fossa (iliacus) Transverse process L1-L5 (psoas)	Lesser trochanter	Femoral	L2–4	External rotation	Strongest hip flexor
Pectineus	Pectineal line of pubis bone	Pectineal line of femur	Femoral	L2–4	Adduction	
Rectus Femoris	AIIS (straight head) Anterior acetabular rim (reflected head)	Patella	Femoral	L2–4		Biarthrodial muscle
Sartorius	ASIS	Proximal medial tibia	Femoral	L2–4	External rotation	Biarthrodial muscle
Hip external rotators						
Muscle	Origin	Insertion	Innervation	Spinal level	Additional function	Notes
Gluteus Maximus	Ilium along crest posterior to posterior gluteal line	Iliotibial band/ posterior femur	Inferior gluteal	L5-S2	Extension	
Piriformis	Anterior sacrum, through sciatic notch	Proximal greater trochanter (piriformis Fossa)	Piriformis	S1-S2		

Table 18.1 (continued)

Obturator externus	Ischiopubic rami and external surface of the obturator membrane	Medial greater trochanter	Obturator (posterior branch)	L2–4	Adduction	
Obturator internus	Ischiopubic rami/ obturator membrane	Medial greater trochanter	Obturator internus	L5-S2		
Superior Gemellus	Ischial spine	Medial greater trochanter	Obturator internus	L5-S2		
Inferior Gemellus	Ischial tuberosity	Medial greater trochanter	Quadratus Femoris	L4-S1		
Quadratus Femoris	Ischial tuberosity	Quadrate line of femur	Quadratus Femoris	L4-S1		
Hip extensors						
Muscle	Origin	Insertion	Innervation	Spinal level	Additional function	Notes
Gluteus Maximus	Ilium along crest posterior to posterior gluteal line	IT band/posterior femur	Inferior gluteal	L5-S2	External rotation	
Long head of biceps Femoris	Medial ischial tuberosity	Fibular head/lateral tibia	Tibial	L5-S2		Biarthrodial muscle, also flex the knee
Semitendinosus	Distal medial ischial tuberosity	Anterior Tibial Crest	Tibial	L5-S2		Biarthrodial muscle, also flex the knee
Semimembranosus	Proximal lateral ischial tuberosity	Posterior/medial tibia, posterior capsule, medial meniscus, popliteus, popliteal ligament	Tibial	L5-S2		Biarthrodial muscle, also flex the knee
Hip adductors						
Muscle	Origin	Insertion	Nerve supply	Spinal level	Additional function	Notes
Adductor Magnus	Inferior pubic ramus/ischial tuberosity	Linea Aspera/ adductor tubercle	Obturator (posterior branch) sciatic (Tibial)	L2–4	Flexion External rotation Extension	
Adductor brevis	Inferior pubic ramus	Linea Aspera/ pectineal line	Obturator (posterior branch)	L2–4	Flexion External rotation	
Adductor longus	Anterior pubic ramus	Linea Aspera	Obturator (anterior branch)	L2–4	Flexion Internal rotation	
Gracilis	Inferior symphysis/pubic arch	Proximal medial tibia	Obturator (anterior branch)	L2–4	Flexion Internal rotation	Biarthrodial muscle, also flex the knee

membranosus, and semitendinosus) function as the hip extensors with innervation by the inferior gluteal nerve and tibial branch of the sciatic nerve, respectively [6].

18.2 Hip Motion

Although the femoral head moves relative to the acetabulum, the hip functions as a ball-in-socket joint [41, 42]. The acetabulum acts as the socket with the femoral head serving as the ball. As such, it has six degrees of freedom with three planes of motion (flexion-extension, abduction-adduction, and internal-external rotation) and three of translation (anterior-posterior, medial-lateral, and proximal-distal).

Hip range of motion is generally greatest in the sagittal plane. However, this may be affected by the bony morphology and/or laxity of ligaments and muscles around the hip. Knee position can also have a significant impact on hip motion as several muscles are biarthrodial, crossing both the hip and knee joints. As such, hip flexion ranges from 120° to 140° with the knee flexed and 90° with the knee fully extended due to increased tension across the hamstring muscles [9, 43]. Normal hip extension ranges from 10° to 30°, but is limited by the iliofemoral ligament, anterior capsule, and hip flexors [9, 43]. Normal hip abduction and adduction is at least 50° and 30°, respectively. Internal and external rotation of the hip is dependent upon the degree of hip motion in the sagittal plane (flexion or extension) with considerably less internal and external rotation possible with the hip extended due to increased soft tissue tension. Internal rotation is limited by the short external rotator muscles (obturator internus and externus, superior and inferior gemelli, quadratus femoris, and piriformis) and the ischiofemoral ligament [44]. External rotation is limited by the lateral band of the iliofemoral ligament, the pubofemoral ligament, the internal rotator muscles, and the degree of femoral neck anteversion [45]. During hip flexion, hip internal rotation ranges from 0° to 70° and external rotation can range from 0° to 90° [46].

Abnormalities of the proximal femur or acetabular morphology in conditions such as femoroacetabular impingement can also lead to reductions in hip range of motion. It is often limited because of abnormal bony contact between the proximal femur and acetabulum at the extremes [47]. However, surgical correction of these bony abnormalities has been shown to reduce this impingement and lead to improved hip range of motion similar to normal values [48, 49].

It is important to note that hip motions are the result of combined hip joint, pelvic, and lumbar spine motion with increased contribution from the pelvis and lumbar spine when there is bony impingement at the hip [50]. A previous study by Dewberry et al. determined that 26–39% of hip flexion comes from lumbopelvic rotation depending on whether the knees were flexed or extended, respectively [43]. Pelvic rotation has also been found to contribute 18% of hip flexion during weight-bearing [51]. Additionally, lumbar spine motion significantly contributes to hip flexion with the majority of the contribution occurring early in the forward bending process [52]. This intimate connection between the hip, pelvis, and spine may lead to "hip-spine syndrome" as stress can be transferred from the hip to the spine and vice versa when there is abnormal sagittal balance, bony morphology, or irregular gait [53].

18.3 Gait Cycle

The human bipedal gait cycle consists of the stance and swing phases as measured from heel strike to heel strike. The stance phase is defined by the period of time that the foot is on the ground. During walking, the stance phase accounts for about 60% of the gait cycle with both feet on the ground (double-support) occurring for approximately 20% of the time [54]. This double-support phase defines walking. It is eliminated with running and replaced by the addition of the float phase, in which both legs are in the air at the same time [54–56]. As the velocity of running increases, the stance phase shortens to less than 22% of the cycle at maximum velocity [54].

Hip motion during gait is dependent upon the different phases of the gait cycle with the main motion of the hip occurring in the sagittal plane (flexion and extension). The extent to which the hip flexes and extends is dependent upon the rate of ambulation as it increases from walking to jogging to running. The hip is extended, adducted, and internally rotated in the stance phase while it is flexed, abducted, and externally rotated in the swing phase of the gait cycle [44, 45, 56]. During normal walking, the hip flexes to about 30° and extends to around 10° [44, 45]. Hip flexion increases with running and sprinting to approximately 50° and 65°, respectively [54]. Extension of the hip has also been found to increase with running but paradoxically decreases with sprinting [54, 57].

The amount of hip abduction and adduction also differs between walking, jogging, and running with maximum values of both occurring with running. Hip adduction is 5–10° while walking and increases to 15–20° during running just before heel strike [44, 45]. Maximum abduction, on the other hand, occurs after toe-off during the swing phase of running.

The muscles around the hip joint work in conjunction with each other during the gait cycle. Hip flexors are most active during the swing phase, while extensors increase activity during the stance phase. In terminal swing, however, the gluteus maximus and the hamstrings also function to decelerate the swinging thigh [54, 58]. Hip adductor muscles are active throughout all phases while running, but only activate from the swing phase to mid-stance when walking [56]. The gluteus medius and tensor fascia lata also help to stabilize the pelvis in normal gait. During running, they are active in the swing and early stance phases. However, while walking, they are mainly active during the stance phase only [58].

18.4 Forces around the hip

The human hip is biomechanically complicated with several forces contributing to the joint reaction forces across the hip. Direct measurement can be difficult. As such, free body diagrams have been developed to estimate these forces based on several assumptions regarding the soft tissue structures around the hip and their individual contributions (Fig. 18.2) [44]. The most commonly used free body diagram makes estimates using single limb stance [46, 59, 60]. Under static conditions, the gravitational force, force from the abductor muscles (A), and force exerted by the femoral head on the acetabulum (F, joint reaction force) act on the hip to keep the hip level [60]. The gravitational force is the weight of the body (W) minus the weight of the contralateral lower limb (1/6 W) or 5/6 W. It is possible to determine the joint reaction force (F) after the force from the abductor muscles (A) is calculated. This can be calculated with knowledge of a person's weight, moment arm of the gravitational force (*d*), and moment arm of the abductor muscles (*l*) using the following equation [46]:

$$A = \frac{5/6W \times d}{l}$$

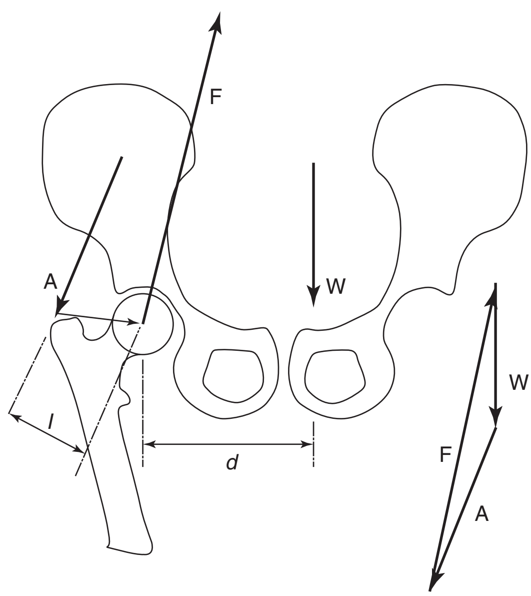

Fig. 18.2 Forces acting on the hip joint during single leg stance under conditions of equilibrium. Gravitational force W, abductor muscle force A, hip joint reaction force F, abductor muscle moment arm *l*, and force of gravity moment arm *d*. Reprinted from DeLee Drez and Miller's Orthopaedic Sports Medicine, Fifth Edition, Mark D. Miller, MD and Stephen R. Thompson, MD, MEd, FRCSC, Hip Anatomy and Biomechanics, 907–924, 2020, with permission from Elsevier

At equilibrium, according to Newton's first law of motion, the joint reaction force (F) is equal to the sum of the gravitational force and force from the abductors. As such, F is calculated to be 2.7 times the body weight during the single leg stance phase of walking with the pelvis parallel to the floor [46].

These principles can also be applied to estimate the forces exhibited on a hip joint in motion, which may be more applicable and of greater interest in the treatment of athletes. Previous studies using kinetic and kinematic data have estimated that the hip is loaded up to 4 times body weight while slow walking [61]. The forces seen by the hip increase as the speed of gait increases with forces 7–8 times body weight transmitted to the hip during running [61]. Unfortunately, these estimates are based on straight line motion. As such, sports with cutting, pivoting, and twisting motions would be expected to have even higher forces across the hip. This has been demonstrated in mogul skiers with as much as 12.4 times body weight seen by the hip joint [62].

Direct measurements of these activities can be difficult in athletes due to the requirement for surgical implantation of a force transducer. In order to account for this, Bergmann et al. was able to determine the forces acting on the hip during several activities after total hip arthroplasty by implanting pressure transducers at the time of surgery [63]. The results of the study confirmed previous estimates with increasing hip joint forces as gait speed increases. The forces transmitted to the hip were 300% body weight during slow walking, 350% to 400% with quick walking, and up to 500% during jogging [63]. This in vivo measurement has the advantage of including all the forces acting on the hip during activities, but is likely dependent upon hip implant position to a certain degree [64].

18.5 Hip Joint Surface Pressure

Focal increases in hip articular cartilage pressure has been thought to contribute to the development of hip osteoarthritis. As such, understanding of this mechanism and the pathology that contributes is paramount for the sports medicine surgeon and hip preservation specialist. Joint pressure (P) can be estimated based on the joint reaction force (F) and surface area (A) over which this force is distributed using the following equation [60]:

$$P = F / A.$$

Based on the above calculations, the average pressure seen by the hip joint is 75 N/cm^2 assuming a body mass of 60 kilograms, femoral head diameter of 5 centimeters (cm), and joint reaction force of 1500 Newtons (N) [60, 65].

However, the pressure distribution across the hip articular cartilage is not uniform due to the bearing surface lacking perfect sphericity. In a native hip, the femoral head is slightly out-of-round and the acetabulum is a horseshoe shaped, nonuniform hemisphere. This leads to low pressures at the most constrained aspects of the hip and increasing pressures on the articular cartilage near the uncovered rim of the acetabulum [60]. This principle has been further reinforced by Greenwald and Brinckmann. Decreased acetabular coverage, as in hip dysplasia, leads to significantly greater and more laterally (along the acetabular rim) based pressure on the articular cartilage compared to normal hips [60, 66].

In addition to the acetabular bony morphology, cartilage and soft tissue structural integrity have been shown to contribute to hip joint pressure. Day et al. have shown up to 5 times normal pressure in areas with thin fibrocartilage, located mainly at the top of the acetabulum [67]. Another study by Song et al. measured the resistance to rotation, which reflects articular cartilage friction, in an intact hip and after focal and complete labrectomy. Resistance to rotation, and likely resultant joint pressure, was significantly increased by up to 20% following focal and complete labrectomy indicating the importance of the labrum in maintaining joint homeostasis and normal hip joint biomechanics [30].

Hip position can also affect hip pressure distribution by decreasing the surface area between the femoral head and acetabulum [68]. Deep hip flexion, as seen in sitting with subsequent rising from a chair as well as stair climbing produces the highest joint pressure predominantly in the posterior acetabulum [68, 69]. This is in contrast to normal walking where the hip joint pressure is the lowest of all full weight bearing activities and is maximally focused on the superior aspect of the acetabulum [69].

18.6 Summary

Several studies of basic hip joint anatomy and biomechanics have been published over the years. These mostly involve straight line motion, and therefore likely underestimate the complex movements and resultant interactions between the bony anatomy, capsule, labrum, ligaments, and muscles of this joint in high level athletes. As such, future research and biomechanical studies should focus on abnormalities of these structures and how injury may affect changes to the biomechanics of the athletic hip.

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