2 Biomechanics of Hip Joints

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2.1 Overview

Although the musculoskeletal system is complex, it follows the basic laws of mechanics. Biomechanics may be defined as studies of mechanics that act on biological organisms, to be specific in this context, human beings. It is an interdisciplinary discipline that includes biology, engineering, sports science, and medicine. Generally, classical laws of mechanics in biological models are used to describe the characteristics and functions of organisms in biomechanics. It focuses on the forces, moments, and movements or deformations of tissues such as bone, cartilage, ligaments, synovial fluid, and tendons. Despite its role of theoretical support for clinics, it is very important for the development and design of devices commonly used in clinical joint replacement and fracture fixation.

Biomechanics of the hip joints includes solid biomechanics, kinematics, and kinetics. Solid mechanics describes the mechanical properties of living organisms, including the transmission of forces and tribology between joint surfaces. Kinematics mainly describes the movement, coordination, and control of the musculoskeletal system. Kinetics mainly describes the process of living organisms and their situation of force, in order to understand the joint stability, coordination, fracture healing, gait, and other changes.

As hip joint is an important component of the human motor system, comprehending the physiological and pathological biomechanical characteristics of the hip joint helps us with understanding the pathogenesis of hip joint diseases, guiding the effective treatment and rehabilitation of hip joint diseases, and improving the design qualities of surgical method and implants (e.g., joint prosthesis).

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2.2 Hip Solid Mechanics

2.2.1 Hip Mechanical Properties

The hip joints are ball-and-socket joints, which exhibits both stability and mobility. The congruence of the articular surfaces, depth of the acetabular cavity as well as surrounding muscles and ligaments provide a wide range of motion for the hip joint as well as enough stability. In detail, hip joints have the following characteristics: (1) Accurate ball-and-socket joints; (2) Thick and tight joint capsules; (3) Strong ligaments; and (4) Well-developed muscles around joints. The first three are statically stable structures, while the last is a dynamic stability structure [1] (Fig. 2.1).

2.2.2 Bony Stable Structure

The ball-and-socket configuration of the hip joints is the main guarantee for its inherent stability. In daily activities, hip joints are influenced by compressive stress, tensile stress, shear stress, moment, and friction. When loading, the force on the sacrum transmits through the hip joint to the femoral neck and then to the lower limb. Due to the neck-shaft angle, the direction of resultant force on femoral neck is not in line with femoral neck axis, causes, the compressive stress is always greater than the tensile stress. The maximum compressive and tensile stress locates at the medial edge of the femoral neck. The closer to the neutral axis of the femoral neck, the smaller the compressive stress and the tensile stress is. And the stresses get to zero at the neutral axis of the femoral neck. Because the resultant force is oblique to the femoral neck, a shear stress is generated. The magnitude of shear stress depends on the inclination angle between the direction of resultant force and axis of the femoral neck.

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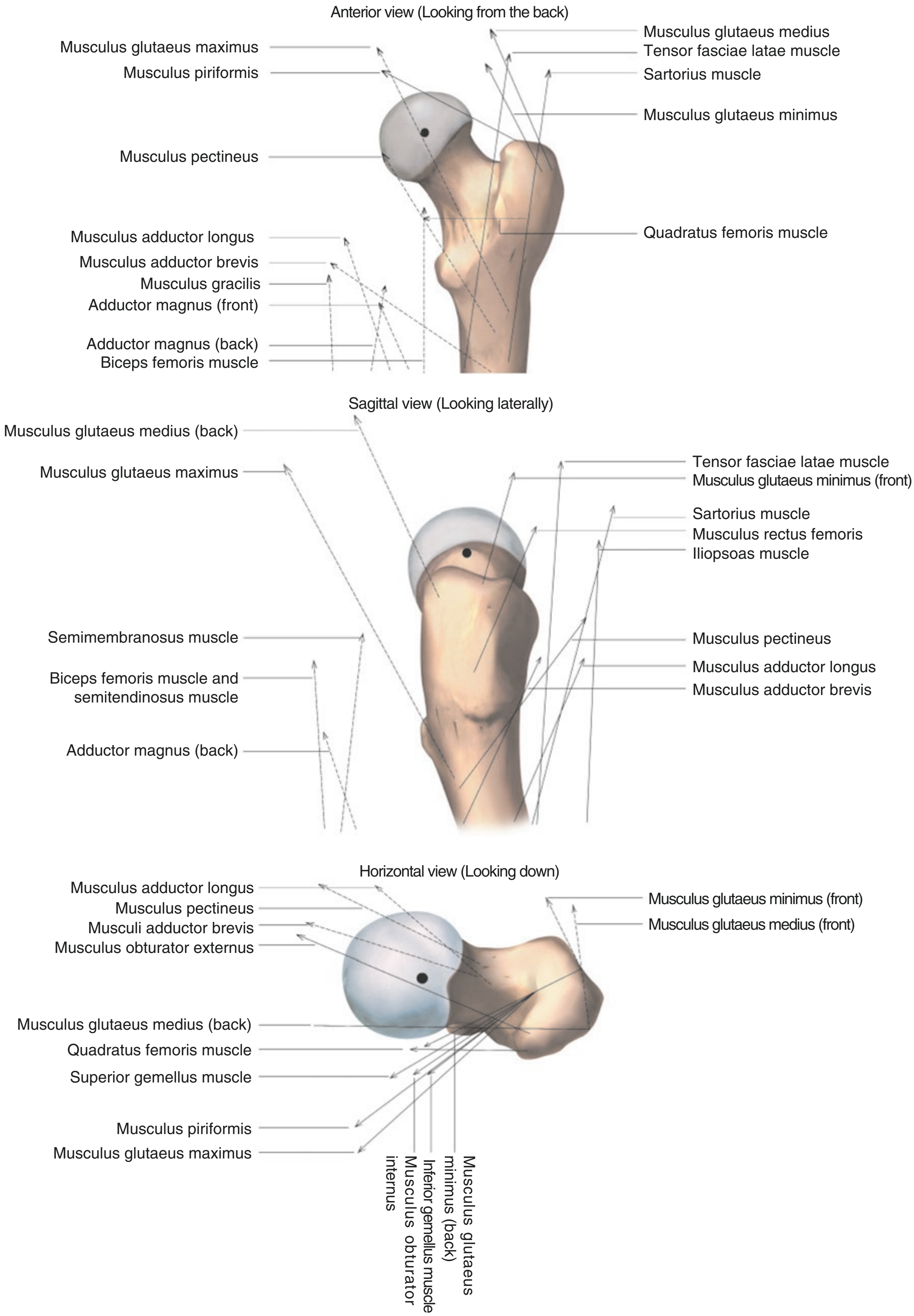

Fig. 2.1 The direction of contraction of the muscles around the hip

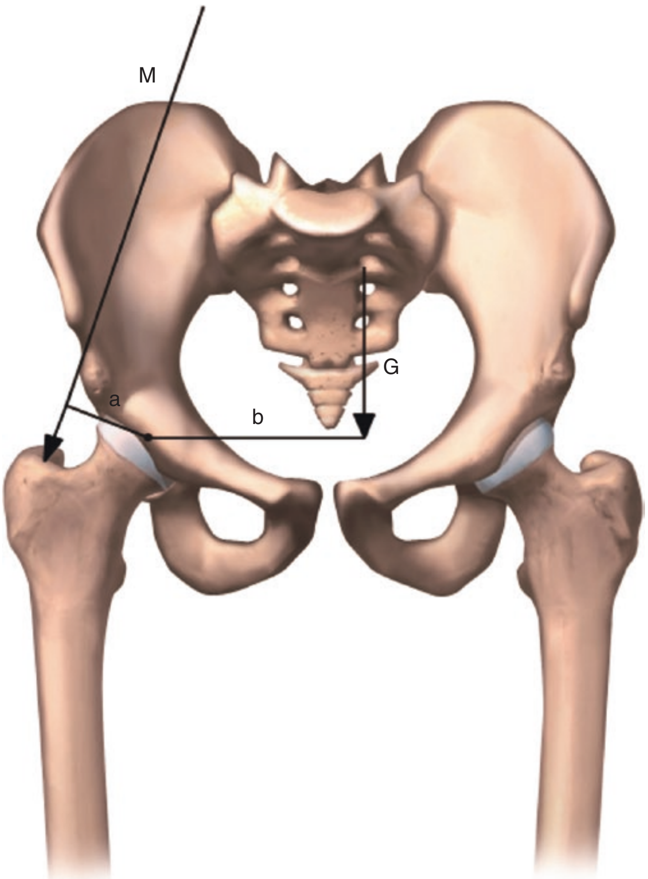

Fig. 2.2 A schematic diagram of the resultant force produced by the abductor muscles

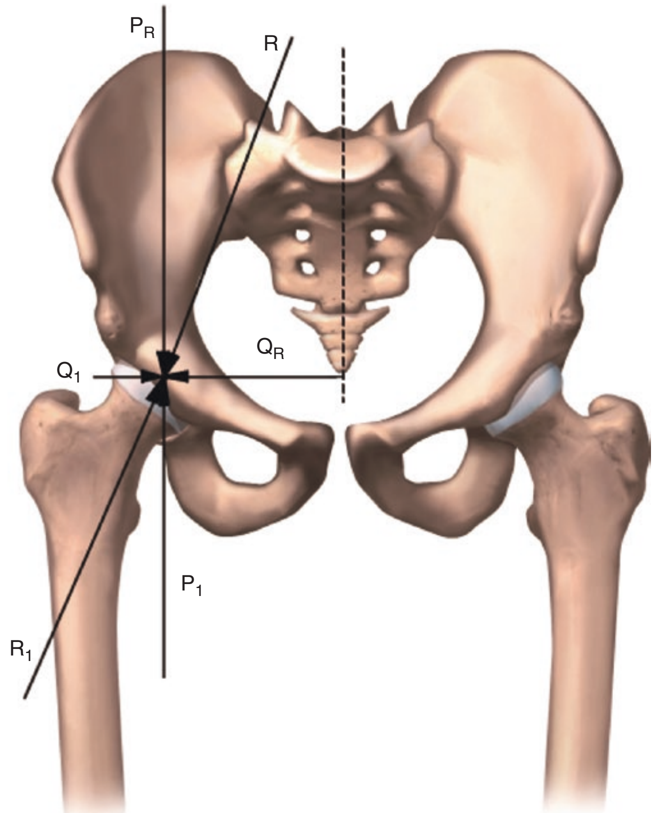

Fig. 2.3 Stress of hip joint in patients with acetabular dysplasia

Bony structural defects of the hip can lead to decreased containment between femoral head and acetabulum. For instance, acetabular dysplasia causes passive hip instability and then asks for more stresses of soft tissues surrounding acetabular (especially the anterior articular capsule labial structure). Over time, the increased stress may lead to labral injury and subsequent cartilage degeneration [2]. As shown in Fig. 2.2, under normal circumstances, the abductor's muscles produce a resultant force M, and the human body can maintain balance only when $M \times a = G \times b$ (G is gravity).

According to the formula: $M = G \times b/a$, with the load surface tilting, the femoral head also moves outwards, thus b increases and a decreases. As the arm changes, body can maintain balance only when M increase continuously. In order to maintain pelvic balance, abductor muscles, such as the gluteus medius and other muscles, have to contract more. The long-term muscle tension and contracture are also the causes of the weakness of the gluteus medius and hip pain in the clinical practice. As M increases, the resultant force R of M and G will increase. The R can be decomposed into a downward force P_R, pushing the pelvis downwards, and a outward force Q_R, pushing the femoral head outwards (Fig. 2.3). Although these two forces do not change along with the load surface tilting, the resultant force R increases when the femoral head shifts outwards, then P_R and Q_R tend to increase consequently. Figure 2.3 shows a schematic diagram of pathological hip biomechanics of hip dysplasia. Q_R tends to push the femoral head to the lateral side and cause subluxation or dislocation of the femoral head.

In this case, $R_1 = R$, that is, the resultant force R_1 on the acetabular load surface changes, and it can be decomposed into two components: the pressure P_1, perpendicular to the load surface, and shear Q_1, parallel to the load surface. These two components keep changing until $P_1 = R_1$, and then gradually decreases to its original value. During this process, the pressure on the acetabulum is greater than the normal one. According to the Poisson's effect, the cartilage is squeezed, then expands horizontally, which results in the generation of large shear stress at the tide line. Little by little, a rupture occurs at a deep layer of cartilage, that is, at the boundary between calcified cartilage and noncalcified cartilage.

On the other hand, the tensile stress and strain were generated by the lateral expansion of cartilage. If they are large enough, they will damage the collagen fibers and network structure on the joint surface. When the acetabular load surface tilts more severely, the pressure P_1 of the acetabulum load-bearing surface tends to decrease, while the shear stress Q_R of the acetabular load surface increases. Q_R acts on the load-bearing cartilage surface directly, causing more damage on cartilage surface. The greater the degree of acetabular tilt, the greater the damage would be [3].

In addition, changes in the geometry of the proximal femur will affect the hip arm, altering the hip loading situation. When the hip is in varus, the resting muscle tension of the abductor muscle increases, the joint contact force reduced accordingly. Meanwhile, as the femoral head penetrated the acetabulum, the stability of the joint increased. However, the hip arm increased, and the proximal femoral shear increased. When the hip is in valgus, the arm becomes short, the resting muscle tension of the abductor muscle and the joint contact force increased, while the femoral head was away from the acetabulum and the stability of the joint reduced. Therefore, for total hip arthroplasty, neutral or eversion can reduce the shear force, which helps to reduce PMMA wear of the prosthesis.

2.2.3 Static Stability Function of the Joint Capsule, Ligament, and Labrum

The hip joint capsule itself is thicker and can prevent the dislocation of the hip joint during extreme activity. The three different ligaments on the capsule form a complex ligament system together to maintain hip stability: (1) iliofemoral ligaments, the anterior ligament restricts hip hyperextension and internal rotation; (2) pubofemoral ligament, the anterior medial ligament, restricts the hip abduction and external rotation; (3) ischiofemoral ligament, the posterior ligament limits the internal rotation and adduction when the hip flexes. The strength of the posterior ligament is significantly lower than that of the anterior ligament, so the rate of posterior hip dislocation is significantly higher than that of the anterior dislocation.

The labrum is a horseshoe-shaped fibrocartilage tissue attached to the acetabular rim that not only deepens the acetabulum but also increases the coverage of the femoral head, making hip joint much more stable. Moreover, the labrum has important biomechanical effects [4–7], such as to synovial fluid flow regulation, joint suction, and sealing maintain and load sharing. A clinical study showed that the cases of acetabular labrum resection or pathological labrum lesion are prone to suffer from early hip arthritis or joint-related diseases [8]. A labral tear weakens the stability of the hip and causes an abnormal sliding of the hip surface, accelerating the wear of the articular cartilage [8].

In addition, there is a character of "creep" for the joint capsule and ligament tissues [9]. A fixed posture lasting for a long period after hip trauma, hip arthritis, or hip surgery, often causes contracture on one side and relaxation on the other side, resulting in joint stiffness and dysfunction. To understand the biomechanical properties of joint capsules and ligaments can help rehabilitation exercises for these diseases.

2.2.4 Hip Dynamic Stability Structure

Compared to statical stability structures, the muscles around the hip provide hip joint dynamic stability. Under the control of the nervous system, the coordination and antagonism of multiple muscles play an important role in maintaining hip stability during standing or exercising [10]. There is still little research on the dynamic stability of hip joints. It is unclear how many muscles are involved, how muscles coordinate or antagonize, and how the muscle function changes under pathological conditions.

In theory, there are two sets of muscle systems in the human body: local and global. Local muscles are considered important joint stability structures. Because they cling to the joints, they can act directly on the axis of the joints and produce major joint tightening forces (not torsional forces), such as the gluteus minimus. Simultaneously, these muscles constantly receive feedback from the nervous system to regulate joint tension. In contrast, the global muscles are relatively superficial, tend to have a larger physical cross-sectional area, such as the gluteus maximus. Due to their larger arms, they can produce a larger twisting force on the joints. The following section describes some of the deep muscles that play a major role in the dynamic stability of the hip.

Deep external rotation muscles (quadratus femoris, obturator internus, obturator externus, superior gemellus, and inferior gemellus) are important stability muscles of the hip joint. Together with gluteal muscle, they are called "Hip Joints Rotating Sleeves." Ward and his colleagues speculated that these muscles can control hip stability and fine joint movement [11]. Patients who underwent prosthetic replacement via a posterior approach with retained or repaired externally rotated muscles had a significantly lower rate of dislocation [12]. These studies show indirect confirmation of the stability function of these externally rotating muscles. However, the piriformis, the other external rotation muscle, with a horizontal force direction when contraction, shows no joint compression. Whether this muscle contribute to the dynamic stability of the hip joints needs further study.

The iliocapsularis originates from the inferior border of the anterior lower iliac spine and the anteromedial joint capsule and terminates in the lesser trochanter. When contracting, it can tense the anterior joint capsule, enhancing the stability of the joint accordingly.

The fibers of gluteus maximus are parallel to the femoral neck and attached to the upper side of the joint capsule. This anatomical feature again demonstrates that it is an important hip stability muscle.

The gluteus medius is the main hip abductor muscle and an important stability muscle of the hip and pelvis, especially when walking during single-leg standing phase, which prevents pelvic tilt and maintains straightness. Its fibers were divided into three groups: anterior, intermediate, and posterior fibers. Each fiber group has its innervation and fiber direction. During walking, the posterior fibers firmly lock the femoral head in the acetabulum, while the intermediate fibers initiate hip abduction activity and the anterior fibers initiate pelvic rotation [13]. A study about falling risk for the elderly people found that the weakened abductor function seriously affected the gait control, elderly people with whom are likely to fall [14].

The iliopsoas contains two parts, psoas and iliacus. Both have their innervation and actively contracting during hip flexion. In the late standing phase of the gait cycle, the iliacus plays an important role in stabilizing the hip joint.

2.2.5 Hip Biotribology

Hip wear is a cause of hip osteoarthritis and other related diseases. Therefore, the understanding of hip biotribology is helpful for the diagnosis and treatment of these diseases. There is a layer of compressed lubricating fluid between the articular surfaces of the hip joints, forming fluid-film lubrication with a lubricating effect. Studies have shown that hip size and shape have a certain influence on contact force [15]. Hip joint motion is a rotational sliding motion. When it does flexion, extension, abduction, adduction, and rotation, the soft tissue filled in the acetabular socket could be squeezed in or out with the pressure on the joint decreases or increases. When the contact between the femoral head and acetabulum slides and/or rotates relatively, friction will be generated. It contains two types, static friction, and dynamic friction. The dynamic friction coefficient depends on the slip velocity between the two surfaces and is usually smaller than the static friction coefficient. Therefore, to start the motion between the two surfaces, a force of high energy is often required. And once it is started, the force to maintain the motion is reduced.

The intact acetabular labrum prevents joint fluid from spilling and keeps the hip joint in a low-friction environment. Once the labrum is broken, the fluid in the joint flows out, and so-called fluid–membrane lubrication loses, then the friction between the joints increases. This may damage articular cartilage and cause osteoarthritis [16].

2.3 Hip Kinematics and Dynamics

The hip joints, the rigid ball-and-socket joints, can carry out multiaxial movement centered around the femoral head. For the sake of analysis, only three axes perpendicular to each other are selected generally. The line connecting the centers of the bilateral femoral heads is horizontal axis, the motion around whom is the flexion and extension; the line through the anterior–posterior direction of the femoral head is sagittal axis, the motion around whom is adduction and abduction. The line connecting the centers of the hip and knee joints is the mechanical axis, or rotation axis, the motion around whom is an internal and external rotation. In daily life, most activities are a combination of motions around these three axes. The maximum motion of the normal hip joint is on the sagittal axis, with 0–140 ° flexion and 0–15 ° extension. The other ranges of motion are 0–45 ° abduction and 0–30 ° adduction, 0–45 ° external rotation, and 0–50 ° internal rotation when the hip flexes. These activities are limited by joint capsules and bony structures. The normal hip joints can fully extend, but if the anteversion angle of a proximal femur is too large, the trochanter and pelvis will impinge posteriorly when the joint extends, and the external rotation will also decrease. If the anteversion angle of the proximal femur is too small, the joint impinges anteriorly, and the internal rotation is reduced.

A healthy person needs about 100 ° hip flexion and extension, 20 ° internal and external rotation, and 20 ° adduction and abduction in daily life. In different postures (decubitus, sitting, standing, and eccentric position), the characteristics of hip movements are different. Each position has a more detailed division: for instance, standing position, subdivided standing (bipedal standing, one-leg standing), walking (different speed level, upstairs, and downstairs), running, and so on. Meanwhile, the hip joint movement needs the coordinated movement of the surrounding segments (such as the waist, pelvis, etc.) to complete the functional requirements of the hip joint. Given an example, the abnormal movement of the knee joint could affect the hip joint movement characteristics [17]. Walking, the most frequent activity in the hip joint, is a kind of periodical movement, which is often taken for biomechanical studies. It is divided into the stand phase and swing phase. In the late swing phase, the lower limb moves forward with the heel, and hip flexion is the greatest. At the beginning of the stand phase, the body moves forward, the hip joint is extensive and reaches the maximum when the heel is off the ground.

The kinetics of hip joints are quite complex, and their stress conditions are not a single load but a combination of multiple loads. It changes with body movements, coupled with the irregular shape of the skeletal section. The calculation is more complicated. As measurements in vitro are affected by muscles, ligaments, and other factors, the inner mechanical parameters of the joint cannot be obtained directly. Before the emergence of implantable sensors, researchers used various mathematical models to calculate the hip joint force, of which finite element analysis is an important tool. The CT/MRI scanning images of the hip joints were modeled by modeling software and imported into the finite element analysis software. After adding appropriate boundary conditions, the mechanical properties of hip joints under different stress situations can be simulated. In a few cases, the inner stress of the hip joint can be measured by placing a strain sensor in the prosthesis. As Bergmann [18] confirmed, under normal gait, the hip stress was 2.1–4.3 times of body weight, and it reached 2.3–5.5 times of body weight when going upstairs. When the patient collapsed emergently, the stress reached 8 times of body weight.

Abnormal hip kinematics and kinetics often lead to hip joint injury and other related diseases. The most typical example is the femoral acetabular impingement (FAI). In FAI, cam deformity at the femoral head–neck junction and/or pincer deformity make the original concentric circular motion of the femoral head in the acetabulum inconsistent, resulting in damage to the labrum and cartilage, even complaint of pain and limited activity [19]. The acetabular pincer deformity can be excessive growth anterior acetabular or more general deformities such as coxa profunda or Otto's disease. When the hip flexes, the femoral neck impinges to the rim of the acetabulum, compressing the anterior labrum. With repeated hip flexion, the labrum keeps undergoing microdamage, and gradually separates from the acetabular cartilage and eventually exfoliates. As the disease progresses, the continuous pressure between the inferior posterior rim of the acetabulum and the posteromedial side of the femoral head causes acetabular cartilage damage, as so-called "flushing injury." The cam deformity on the femoral side causes the femoral head to lose its normal spherical structure, and the femoral head and neck offsets decrease as well. In the hip flexion situation, the deformed femoral head and neck rotate past the anterior upper acetabular rim, which results in shear stress and squeezing stress. The contact region between femoral head and acetabulum is between acetabular cartilage and labrum. Therefore, unlike the pincer type, the acetabular cartilage is damaged firstly in cam FAI [19].

In recent years, biomechanical scientists have been trying to evaluate FAI's complex 3D geometry and hip function accurately, and describe the exact site of impact during hip motion, as FAI has a feature of repeated dynamic impingement of the hip joints, whereas conventional X-ray, CT, and MRI can only obtain its static morphology. Puls et al. used the isometric method combined with a dynamic hip center detection for FAI, got significantly improved accuracy. It has been applied for aiding diagnosis and preoperative planning [20]. It is very important to define the hip center in hip dynamic range simulations. Studies found that concentric activity does not occur around a fixed joint center point in hip joint activity. However, there is a certain degree of displacement [21], similar to the conchoid movement [22]. So previous methods for studying kinematics and kinetics of hip joints based on fixed concentric circles will be biased inevitably, and then led to inaccurate results for FAI. Puls and his colleagues [20] compared the method rotating around the dynamic hip center with the method rotating around a fixed center, the rotation error of the latter reached 5.0–5.6 °. Therefore, accurate kinematic measurement and simulation can help to determine the degree and range of FAI clinically. However, questions still need to be answered in the future. Such as, how to measure quickly and accurately in clinical practice, like the application of dual-fluoroscopic measurement, and how to get the three-dimensional kinetics of soft tissue (such as the acetabular labrum) in FAI.

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