

Anatomy & Biomechanics of the Hip

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Abstract: The hip joint is unique anatomically, physiologically, and developmentally; therefore understanding the basic structure and biomechanics of the hip is essential for clinicians, physiotherapists and engineers alike. In this review we outline the function of the key anatomical components of the hip and discuss the relevant related biomechanical issues. Understanding the forces that cross the hip and the details of the anatomy leads to a better understanding of some of the failures of the past and gives credence to current and future solutions.

Keywords: Hip, anatomy, biomechanics.

INTRODUCTION

The hip is a true ball-and-socket joint surrounded by powerful and well-balanced muscles, enabling a wide range of motion in several physical planes while also exhibiting remarkable stability. As the structural link between the lower extremities and the axial skeleton, the hips not only transmit forces from the ground up but also carry forces from the trunk, head and neck, and upper extremities [1]. Consequently this joint is crucial to athletic activities in which it is often exposed to many greater than normal axial and torsional forces.

The hip joint is unique anatomically, physiologically, and developmentally; and therefore the diagnosis of pathologic conditions is more difficult than for most joints [2]. Because of these diagnostic challenges, the hip has received considerably less attention than other joints in the past, particularly in reference to sports medicine and surgery literature. The clinical setting of a plain x-ray of the pelvis exhibiting non-arthritis was a difficult situation – patients were potentially diagnosed erroneously with a ‘groin strain’ or otherwise. With the advent of improved magnetic resonance imaging (MRI) enhanced by arthrography, we now have a better comprehension of pathological processes within the hip joint. Accompanying this increased understanding is the evolving potential to treat these problems.

For one, hip arthroscopy is undergoing continued development and excellent results have been reported treating a variety of intra-articular conditions [3, 4]. While we can now assess and treat patients with newer diagnoses, we must also ensure that our knowledge of hip anatomy and biomechanics also evolves. Only with this fundamental understanding can the clinician or engineer provide adequate treatment for the patient suffering from hip disease or malfunction.

In this review we outline the function of the key anatomical components of the hip and discuss the relevant related biomechanical issues.

ANATOMY OF THE HIP

The hip is a classical ball-and-socket joint. It meets the four characteristics of a synovial or diarthrodial joint: it has a joint cavity; joint surfaces are covered with articular cartilage; it has a synovial membrane producing synovial fluid, and; it is surrounded by a ligamentous capsule [5]. For ease of approach we have considered the relevant anatomy under the headings ‘Bony anatomy’, ‘Ligaments and capsular anatomy’, ‘Neurovascular anatomy’ and ‘Muscular anatomy’.

BONY ANATOMY

The cup-shaped acetabulum is formed by the innominate bone with contributions from the ilium (approximately 40% of the acetabulum), ischium (40%) and the pubis (20%) [6]. In the skeletally immature these three bones are separated by the triradiate cartilage – fusion of this starts to occur around the age of 14 – 16 years and is complete usually by the age of 23 [7]. The actual articular surface appears a lunate shaped when viewed looking into the acetabulum. Within the lunate, or horseshoe shaped articular cartilage is a central area – the central inferior acetabular fossa. This fat filled space houses a synovial covered fat pad and also contains the acetabular attachment of the ligamentum teres. Inferior to this, the socket of the hip is completed by the inferior transverse ligament.

Attached to the rim of the acetabulum is the fibrocartilaginous labrum. The labrum has been closely studied as tears of the labrum are the most common indication for hip arthroscopy [8]. Although it makes less of a contribution to joint stability than the glenoid labrum in the shoulder it does serve its purpose. It plays a role in normal joint development and in distribution of forces around the joint [9, 10]. It has also been suggested it plays a role in restricting movement of synovial fluid to the peripheral compartment of the hip, thus helping exert a negative pressure effect within the hip joint [11].

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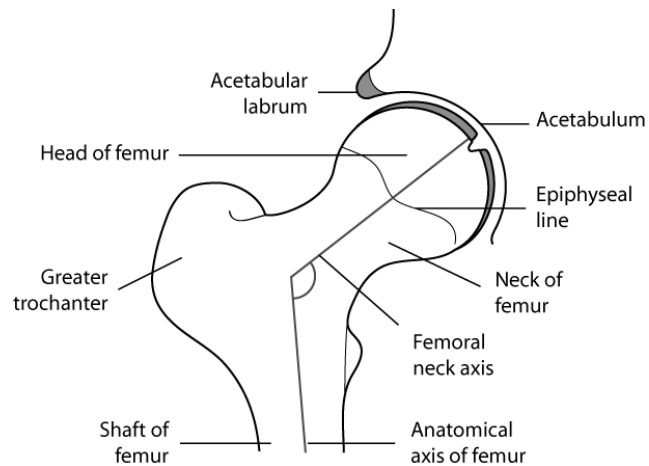


Fig. (1). Cross-sectional view of the normal hip joint.

The labrum runs around the circumference of the acetabulum terminating inferiorly where the transverse acetabular ligament crosses the inferior aspect of the acetabular fossa. It attaches to the bony rim of the acetabulum and is quite separate from the insertion of the capsule [12]. The labrum receives a vascular supply from the obturator and the superior and inferior gluteal arteries [13]. These ascend in the reflected synovial layer on the capsule and enter the peripheral aspect of the labrum. It has been observed that labral tears are most likely to occur at the junction of labrum and articular cartilage - this area has been termed the 'watershed region' [13] (Fig. 1).

The femoral head is covered with a corresponding articular cartilage beyond the reaches of the acetabular brim to accommodate the full range of motion. The covered region forms approximately 60 to 70% of a sphere. There is an uncovered area on the central area of the femoral head - the fovea capitis - for the femoral insertion of the ligamentum teres. The ligamentum teres, while containing a blood supply does not contribute to the stability of the joint. It is covered in synovium, so while it is intra-articular it is actually extra-synovial.

The head of the femur is attached to the femoral shaft by the femoral neck, which varies in length depending on body size. The neck-shaft angle is usually $125 \pm 5^\circ$ in the normal adult, with coxa valga being the condition when this value exceeds 130° and coxa vara when the inclination is less than 120° , see Fig. (2). The importance of this feature is that the

femoral shaft is laterally displaced from the pelvis, thus facilitating freedom for joint motion. If there is significant deviation in angle outside this typical range, the lever arms used to produce motion by the abductor muscles will either be too small or too large. The neck-shaft angle steadily decreases from 150° after birth to 125° in the adult due to remodelling of bone in response to changing stress patterns. The femoral neck in the average person is also rotated slightly anterior to the coronal plane. This medial rotation is referred to as femoral anteversion. The angle of anteversion is measured as the angle between a mediolateral line through the knee and a line through the femoral head and shaft. The average range for femoral anteversion is from 15 to 20° .

The neck is most narrow midway down the neck. Abnormalities in this area and the area adjacent to the articular surface, such as a prominence resulting from a slipped capital femoral epiphysis (SCFE), can upset the normal femoroacetabular articulation leading to Cam type impingement. Conversely, abnormalities of the acetabulum such as osteophyte formation, with increased cover of the femoral head can lead to Pincer type impingement.

The vascular supply to the femoral head has been well studied due to the risk of vascular necrosis of the head when it is disrupted, particularly in fractures of the femoral neck or dislocation of the hip. Three sources are noted: a small vessel found within the ligamentum teres (present in about 80% of the population), a supply from the medullary canal and an anastomosis of vessels creeping around the femoral neck. This later supply is perhaps the most important - the vessels ascend toward the femoral head in the synovial lining that is reflected onto the femoral neck. These vessels arise posteriorly, chiefly from the medial circumflex femoral artery that branches off the deep femoral artery. The lateral circumflex artery makes less of a contribution.

LIGAMENTS AND CAPSULAR ANATOMY

The joint capsule is strong. While the ball and deep socket configuration naturally gives the hip great stability the ligamentous capsule undoubtedly contributes significantly. The capsule is formed by an intertwining of three separate entities.

The iliofemoral ligament can be seen anterior to the hip in the form of an inverted 'Y' or a modified ' Δ '. It spans, in a spiralling fashion, from its proximal attachment to the ilium to insert along the intertrochanteric line. It is taught in

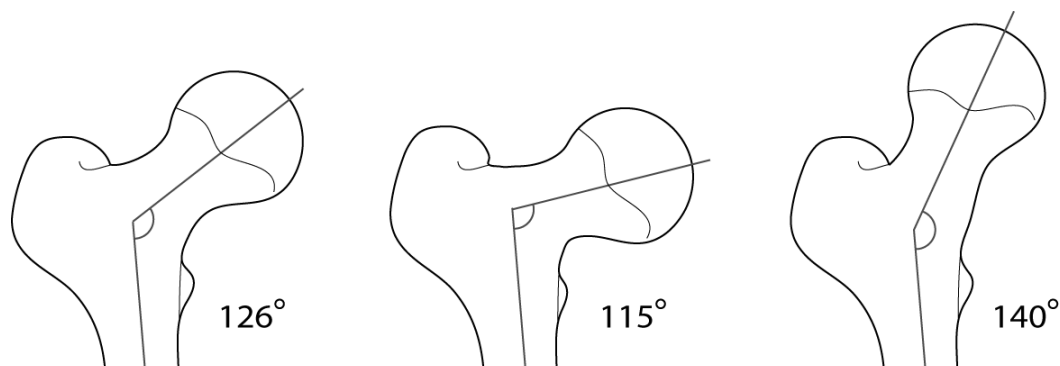


Fig. (2). (a) Normal femoral neck angle, (b) a decreased femoral neck angle (coxa vara), and (c) an increased femoral neck angle (coxa valga).

extension and relaxed in flexion keeping the pelvis from tilting posteriorly in upright stance and limiting adduction of the extended lower limb. It is the strongest ligament in the body with a tensile strength greater than 350N [6]. Inferior and posterior to the iliofemoral ligament, and blending into its medial edge, the pubofemoral ligament contributes to the strength of the anteroinferior portion of the capsule. This is perhaps the weakest of the four ligaments. Posteriorly the ischiofemoral ligament completes the main ligamentous constraints – from its ischial attachment medially it inserts laterally on superolateral aspect of the femoral neck, medial to the base of the greater trochanter.

While the ligamentous capsule is very strong, two weak points can be noted - the first anteriorly between the iliofemoral and pubofemoral ligaments, and the second posteriorly between the iliofemoral and ischiofemoral ligaments. Although dislocation is rare in the native hip, with extreme external trauma the hip can dislocate through either of these weak points [6].

There are two further ligaments at the hip joint. One, the ligamentum teres has been mentioned above – it contributes little in the way of stability to the hip and can be torn in traumatic dislocations. Some propose that it plays a role in joint nutrition [14]. Its potential for degeneration is better appreciated with the increasing utilisation of hip arthroscopy. The second is the zona orbicularis or angular ligament. This encircles the femoral neck like a button hole and again plays little role in stability.

NEUROVASCULAR ANATOMY

While hip arthroscopy is most often performed under general anaesthesia to allow sufficient relaxation and consequent joint distraction – regional blockade has been tried as an alternative. Consequently the nerve supply of the hip joint has been closely studied [15]. The anterior and posterior portions of the hip have separate innervations. Anteromedially the joint is supplied by articular branches of the obturator nerve. The anterior aspect is contributed to by branches of the femoral nerve. The posterior aspect is innervated laterally by branches off the superior gluteal nerve. Medially contributions come from articular branches from the nerves to quadratus femoris and also articular branches from the sciatic nerve.

Surgeons approaching the hip must be aware of the surrounding neurovascular structures. The key structures anteriorly include the femoral (lateral to medial) nerve, artery and vein. These run together out from the pelvis underneath the inguinal ligament. They can be located using surface anatomy in slim individuals midway between the anterior superior iliac spine (ASIS) and the pubic tubercle. Fortunately they are well separated from the hip joint by the iliopsoas muscle so should not be encountered by the practicing arthroscopic surgeon.

Posteriorly the sciatic nerve, arising from the lumbosacral plexus, emerges below the piriformis from the pelvis and enters the thigh between the greater trochanter laterally and the ischium medially. The nerve can be divided high by the piriformis in the greater sciatic foramen in approximately 10-12% of the population [6, 7].

Superior to the sciatic nerve, and also exiting through the sciatic notch, are the superior gluteal nerve and accompanying artery. These two structures supply both gluteus medius and minimus while running in a posterior to anterior direction between them. Bleeding can be encountered during the posterior approach to the hip when the rich vascular anastomosis at the lower border of quadratus femoris is encountered [5, 16]. This consists of the ascending branch of the first perforating artery, branches of the medial and lateral circumflex femoral arteries and the descending branch of the inferior gluteal artery [7].

Also prone to damage by inappropriately placed arthroscopic portals is the lateral femoral cutaneous nerve [17]. This originates from the lumbosacral plexus also and exits the pelvis under the inguinal ligament near to the ASIS [7]. It is best known in medical texts for its predisposition to compression by external forces [18]. Along the intertrochanteric line the lateral circumflex femoral artery runs after arising from the deep femoral artery.

MUSCULAR ANATOMY

The geometry of the hip permits rotational motion in all directions, necessitating a large number of controlling muscles arising from a wide surface area to provide adequate stability. The 22 muscles acting on the hip joint not only contribute to stability but also provide the forces required for movement of the hip. Approaching the muscular anatomy around the hip can be undertaken in a number of ways. They can be divided into three groups: inner hip muscles, outer hip muscles and muscles belonging to the adductor group [6]. They can be considered as superficial and deep groups [5]. Alternatively they can be divided into their main actions cross the joint.

The musculature of the hip and thigh is invested in a fibrous layer the fascia lata. This is a continuous fibrous sheath surrounding the thigh. Proximally it is attached to the inguinal ligament, lip of the iliac crest, posterior aspect of the sacrum, the ischial tuberosity, the body of the pubis and the pubic tubercle. Its inelasticity functions to limit bulging of the thigh muscles thus improving the efficiency of their contractions [7].

The major flexor of the hip joint is iliopsoas. This comprises psoas major and minor, and iliacus. Psoas major arises from T12-L5 vertebral bodies and insets into the lesser trochanter. It is joined at the level of the inguinal ligament to form the iliopsoas [6, 7]. Iliopsoas is the most powerful hip flexor but it is also aided by sartorius, rectus femoris and tensor fascia latae (TFL) [6]. Sartorius, innervated by the femoral nerve, runs from ASIS to insert medial to the tibial tuberosity. It also contributes to abduction and external rotation. Rectus femoris also arises from the ASIS and inserts into the tibial tuberosity by way of the patella ligament.

The largest and most powerful extensor of the hip is gluteus maximus. It is also the most superficial. Running from the lateral aspect of the dorsal sacral surface, posterior part of the ilium and thoracolumbar fascia it inserts into the iliotibial tract and gluteal tuberosity on the femur [6, 7]. It is also involved in external rotation of the hip with innervation from the inferior gluteal nerve. Its upper and lower fibres contribute to abduction and adduction respectively.

The principal abductors include gluteus medius and minimus. Lying beneath the fascia lata, the proximal insertion of gluteus medius into the iliac crest is almost continuous with it. From its broad based proximal attachment it appears like an upside-down triangle inserting into a relatively narrow base on the lateral aspect of the greater trochanter. Gluteus minimus is deep again to gluteus medius arising proximally from the gluteal surface of the ilium and inserting deep to the gluteus medius on the anterolateral aspect of the greater trochanter - both gluteus medius and minimus are innervated by the superior gluteal nerve.

The TFL runs from the ASIS inserting distally into the iliotibial tract. It is also a flexor of the hip joint and internally rotates it. Piriformis runs laterally from the pelvic surface of the sacrum to the apex of the greater trochanter of the femur. It also contributes to external rotation and extension of the hip.

Posteriorly, inferior to the piriformis, are the short external rotators all running in a horizontal fashion. From superior to inferior, these consist of the superior gemelli, obturator internus, inferior gemelli, and quadratus femoris. All play a role in external rotation and adduction of the hip and all receive branches from L5-S1 in the sacral plexus [6, 7].

Hip adductors include the obturator externus arising from the outer surface of the obturator membrane and inserting into the trochanteric fossa. It also contributes to external rotation and has its innervation from the obturator nerve. The remaining muscles in this group variably have their proximal origin on the pubic bone and insert distally on the femur below the level of the lesser trochanter or in the case of gracilis into the pes anserinus medial to the tibial tubercle.

Pectineus attaches at the pectin pubis and inserts into the femur along the pectineal line and linea aspera. It also contributes to external rotation and some flexion. Adductor longus attaches medial to pectineus on the superior pubic ramus and inserts distally to the pectineus along the middle third of the linea aspera - it contributes to hip flexion up to 70° [6]. Adductor brevis arises from the inferior pubic ramus and inserts proximal to adductor longus into the proximal one third of the linea aspera. Adductor magnus arises from the inferior pubic rami, ischial ramus and ischial tuberosity. It inserts distally into the medial lip of the linea aspera but also has a more tendinous insertion into the medial condyle of the femur. It contributes also to extension and external rotation. Adductor minimus runs from the inferior pubic ramus into the medial lip of the linea aspera also contributing to external rotation. Gracilis is the only adductor that inserts distal to the knee joint. It arises inferior to the pubic ramus below the pubis symphysis. All the adductors receive an innervation from the obturator nerve. Pectineus also has a supply from the femoral while the deep aspect of adductor magnus also has a supply from the tibial nerve.

As previously stated, the muscles of the hip joint can contribute to movement in several different planes depending on the position of the hip, which is caused by a change in the relationship between a muscle's line of action and the hip's axis of rotation. This is referred to as the "inversion of muscular action" and most commonly

manifests as a muscle's secondary function. For example, the gluteus medius and minimus act as abductors when the hip is extended and as internal rotators when the hip is flexed. The adductor longus acts as a flexor at 50° of hip flexion, but as an extensor at 70°.

In addition to providing stability and motion for the hip, muscles act to prevent undue bending stresses on the femur. When the femoral shaft undergoes a vertical load, the lateral and medial sides of the bone experience tensile and compressive stresses respectively. To resist these potentially harmful stresses, as might occur in the case of an elderly person whose bones have become osteoporotic and susceptible to tensile stress fractures, the TFL acts as a lateral tensioning band.

Muscle weakness around the hip is usually compensated by the individual to perform the desired task of walking. An example is the Trendelenburg gait, noted by the pelvis sagging to the contra-lateral side secondary to weakness of the abductor muscle group on the weight-bearing side. This is countered by the individual shifting their centre of gravity towards the affected joint by leaning over. This tilting reduces the force required by the abductors.

BIOMECHANICS OF THE HIP

The importance of the normal hip in any athletic activity is emphasised by the role this joint plays in movement and weight-bearing. An understanding of the biomechanics of the hip is vital to advancing the diagnosis and treatment of many pathologic conditions. Some areas that have benefited from advances in hip biomechanics include the evaluation of joint function, the development of therapeutic programs for treatment of joint problems, procedures for planning reconstructive surgeries and the design and development of total hip prostheses [19]. Biomechanical principles also provide a valuable perspective to our understanding of the mechanism of injury.

TWO-DIMENSIONAL ANALYSIS OF JOINT FORCES AT THE HIP JOINT

Basic analytical approaches to the balance of forces and moments about the hip joint can be useful in estimating the effects of alterations in joint anatomy or different treatment modalities on the hip joint reaction force [19]. The static loading of the hip joint has been frequently approximated with a simplified, two-dimensional analysis performed in the frontal plane. When the weight of the body is being borne on both legs, the centre of gravity is centred between the two hips and its force is exerted equally on both hips. Under these loading conditions, the weight of the body minus the weight of both legs is supported equally on the femoral heads, and the resultant vectors are vertical.

In a single leg stance, the effective centre of gravity moves distally and away from the supporting leg since the nonsupporting leg is now calculated as part of the body mass acting upon the weight-bearing hip (see Fig. 3). This downward force exerts a turning motion around the centre of the femoral head - the moment is created by the body weight, K , and its moment arm, a (distance from femur to the centre of gravity). The muscles that resist this movement are offset by the combined abductor muscles, M . This group of muscles includes the upper fibres of the gluteus maximus,

the tensor fascia lata, the gluteus medius and minimus, and the piriformis and obturator internus. The force of the abductor muscles also creates a moment around the centre of the femoral head; however this moment arm is considerably shorter than the effective lever arm of body weight. Therefore the combined force of the abductors must be a multiple of body weight.

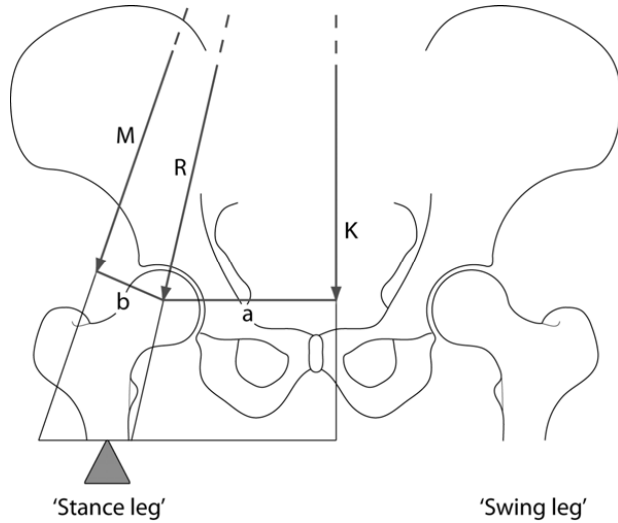


Fig. (3). Free-body diagram for the calculation of the hip joint force while walking, where **K** is the body weight (minus the weight bearing leg), **M** is the abductor muscle force, and **R** is the joint reaction force.

The magnitude of the forces depends critically on the lever arm ratio, which is that ratio between the body weight moment arm and the abductor muscle moment arm ($a:b$) [20]. Typical levels for single leg stance are three times bodyweight, corresponding to a level ratio of 2.5. Thus, anything that increases the lever arm ratio also increases the abductor muscle force required for gait and consequently the force on the head of the femur as well (see Fig. 4). People with short femoral necks have higher hip forces, other things being equal. More significantly people with a wide pelvis also have larger hip forces. This tendency means that women have larger hip forces than men because their pelvis must accommodate a birth canal [21]. This fact may be one reason that women have relatively more hip fractures and hip

replacements because of arthritis than men do. It is also conceivable that this places women at a biomechanical disadvantage with respect to some athletic activities, although studies do not always show gender differences in the biomechanics of running, particularly endurance running [22].

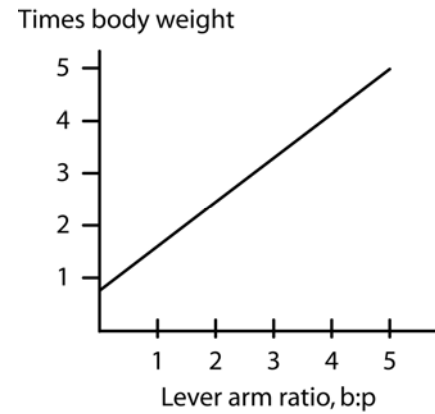


Fig. (4). Effect of lever arm ratio on the hip joint reaction force, adapted from Greenwald [23].

Normally the tissues and bones of the hip joint function without causing pain, but various diseases and injuries can damage the tissues so that the deformations associated with loading are painful [20]. Management of painful hip disorders aim to reduce the joint reaction force. Bearing in mind the basic principles outlined above, this can be achieved by reducing the body weight or its moment arm, or helping the abductor force or its moment arm. Increases in body weight will have a particularly harmful effect on the total compressive forces applied to the joint. The effective loading of the joint can be significantly reduced by bringing the centre of gravity closer to the centre of the femoral head (decrease the moment arm b). This can be accomplished by limping, however the lateral movements required take a considerable amount of energy and is a much less efficient means of ambulation. Another strategy to reduce joint reaction force involves using a cane or walking stick in the opposite hand. The moment produced from both the cane and abductor muscles together produce a moment equal and opposite to that produced by the effective body weight (Fig. 5). The two-dimensional static analysis indicates that the joint reaction force can be reduced by 50% (from 3 times

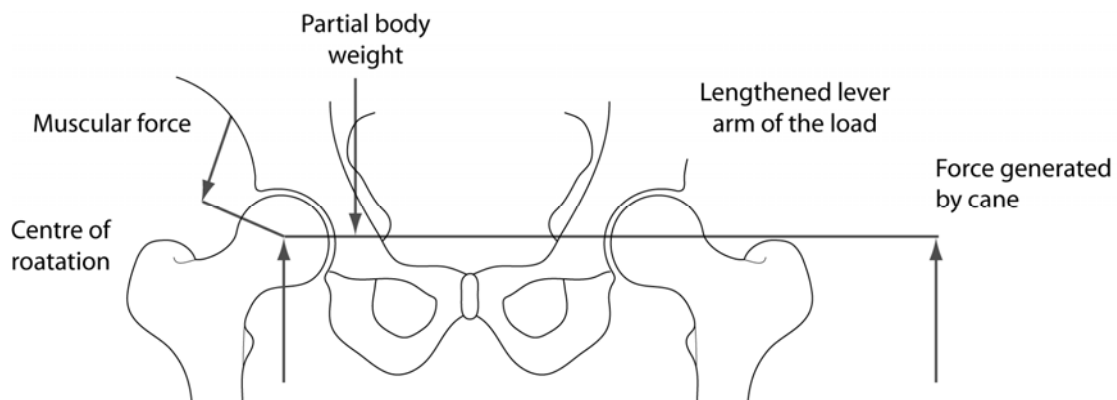


Fig. (5). Use of cane on the unaffected side. While this lengthens the level arm of the load (the partial body weight), it also provides a force (the cane) which counteracts the body load at the end of that level arm.

Table 1. Hip Contact Forces Measured In Vivo in Patients with Instrumented Implants. Adapted from Johnston *et al.* [19]

Activity	Typical Peak Force (BW)	Total Number of Patients	Time Since Surgery (Months)	References
Walking, slow	1.6-4.1	9	1-30	[24, 26-28]
Walking, normal	2.1-3.3	6	1-31	[26]
Walking, fast	1.8-4.3	7	2-30	[24, 26-28]
Jogging, running	4.3-5.0	2	6-30	[27-28]
Ascending stairs	1.5-5.5	8	6-33	[24, 26, 28]
Descending stairs	1.6-5.1	7	6-30	[24, 26, 28]
Standing up	1.8-2.2	4	11-31	[26]
Sitting down	1.5-2.0	4	11-31	[26]
Knee bend	1.2-1.8	3	11-14	[26]
Stumbling	7.2-8.7	2	4-18	[27, 29]

body weight to 1.5 times body weight) when approximately 15% body weight is applied to the cane [19]. The substantial reduction in the joint reaction force, predicted when a cane is used for support arises because the cane-ground reaction force acts at a much larger distance from the centre of the hip than the abductor muscles. Thus, even when a relatively small load is applied to the cane, the contribution it makes to the moment opposing body weight is large enough to significantly decrease the demand placed on the abductor muscles.

IN VIVO MEASUREMENTS OF JOINT FORCES AT THE HIP

Walking transmits significant body weight to the hip joint, while jogging, running and contact sports generate forces significantly greater. To verify the estimates of hip joint forces made using free-body calculations, many *in vivo* measurements have been carried out using prostheses and endoprostheses instrumented with transducers (strain-gauges). Rydell was the first to attempt measuring direct hip joint forces using an instrumented hip prosthesis [24]; which yielded force magnitudes of 2.3 to 2.9 times body weight for single leg stance and 1.6 to 3.3 times body weight for level walking [25]. More extensive studies have recently been carried out, which are summarised in Table 1.

These studies have shown that although patients in the early postoperative period can execute planned activities of daily living with relatively low joint contact forces, unexpected events such as stumbling or periods of instability during single leg stance can generate resultant forces in excess of eight times body weight [25]. It is important to remember that although the data from hip prostheses have established the magnitude of the loads acting on the hip joint, the patients in these studies have undergone total hip replacement and therefore the results cannot be directly correlated to the physiology of the normal hip.

SUMMARY

We have provided a concise review of the anatomical and biomechanical basics of the hip for the patient, clinician, physiotherapist and engineer. The approach to learning and understanding hip anatomy can be undertaken in a number of ways as can the biomechanics. Understanding of the forces

that cross the hip and of the details of the anatomy leads to a better understanding of some of the failures of the past and gives credence to current and future solutions.

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