International Journal of Engineering & Technology, 7 (3) (2018) 1672-1676

International Journal of Engineering & Technology

Website: www.sciencepubco.com/index.php/IJET
doi: 10.14419/ijet.v7i3.15231
Research paper

Biomechanics of hip joint: a systematic review

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Abstract

Hip joint is the second largest joint in human after knee joint. It is associated with different types of motion which helps in the movement of human body and provide stability. Biomechanics involves the study of movement of living organism. It is important to know and understand the basics of biomechanics of hip joint to define the movement of hip joint along with its load carrying capacity in different day to day activities. Many researchers are worked to know the basics biomechanics of hip joint both in in-vitro and in- vivo conditions. In this paper, it has been reported in detail to know the different biomechanical aspects involved in the hip joint during different movement and also different biomaterials used in the hip joint prosthesis. It is majorly focused on load transmitting by hip joint by upper body to lower body in different activities such as walking, running, stumbling etc. So, these basic understanding helps to understand effectively the joint reaction forces which is acting on hip joint while designing new hip joint prosthesis.

Keywords: *Hip Joint; Biomechanics; Finite Element Analysis; Joint Reaction Force; Two-Dimensional Analysis; Bones.*

1. Introduction

Biomechanics is science, which defines the movement of human body consisting of muscles, bones, tendons and ligaments which will work together for human movement. Biomechanics has been around since the inquiring ancient Greek and Roman minds began dissecting animals and vivisecting humans to discover the inner systems of our bodies. Aristotle, who wrote ”On the motion of animals” in the 4th century BC, to Leonardo da Vinci, who studied human muscle and joint function in 15th century Italy [1]. In the 19th century, Europeans were incredibly fascinated with the gait of horses and extensively studied the biomechanics of a horse's galloping motion. The overall biomechanics are classified as sports biomechanics, continuum biomechanics, bio fluid mechanics, bio tribology, comparative biomechanics, plant biomechanics, and computational biomechanics [2]. Many studies have performed to understand the biomechanics involved in human joints [3] [4].Shoulder joint has a complex biomechanics because of its degree of freedom in it [5] [6]. All the joints associated in human like arm, shoulder, knee, hip joint, ankle joint are having their own biomechanics, depending upon the load acting on these joint [7 – 10]. Bones are the vital organs in the human body which gives stability and strength. Human body consists of 270 bones at the birth and will reduce to around 206 bones at the adults where some of the bones are combines with the growth. Hip joint is the one of the key joints which will transmits the loads from upper body to lower abdomen during the activities like walking, standing, running, stumbling and other [11]. Hip joint is the body’s second largest weight-bearing joint after knee. It is ball and socket type joint which is surrounded by many well-balanced muscles [12]. The average length of femur bone varies from 42cm to 48cm in adults [13]. Hip joint consists of femoral heads, femur and lateral condyle. A healthy hip joint is shown in the figure 1. Femoral head articulates into the acetabulum of pelvis. The hip joints give stability between upper body and lower body and transmit the loads from upper body to lower body. The femoral head meshes with acetabulum and lateral condyle meshes with tibia of knee joint. The femur bone consists of different layers namely cortical bone at the outer which is harder, rigid and cancellous bone internally which is soft and spongy [14]. The femur is anisotropic in nature [15]. The density varies along with the thickness. These cortical, cancellous layers thickness vary from person to person which depends upon the age, sex [16]. At the middle of the femur it is hollow part which is bone marrow cavity [17]. With different day to day activities the joint experiences different forces acting on it which results is change is displacement, stress and strain [18].

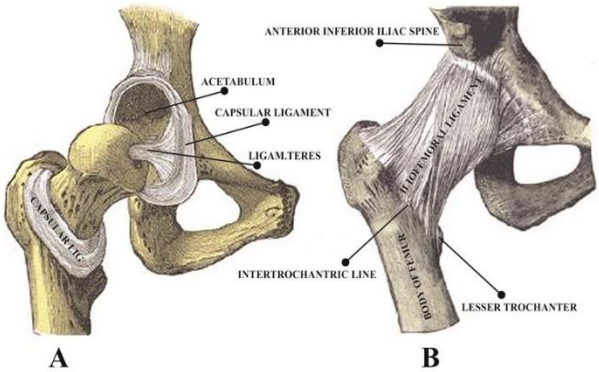


Fig. 1: The Natural Healthy Hip Joint (Right Hip). (A) Capsule Removed, Anterior Aspect, (B) Showing the Ligament [19] [20].

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Many invitro and invivo studies are performed to know the forces induced to hip joint due to various activities [21–23]. Computational models-based CT are widely used to predict the mechanical behaviour of human femurs invitro conditions [24–26]. As hip joint transfers load from upper body to lower body, the loads will be induced more in the hip joints. In this paper, it is tried to understand the different forces acting on hip joint and how these loads are transferred without affecting the human movement. Hip joint has six degrees of freedom namely flexion, extension, abduction, adduction, internal rotation and external rotation [27]. All these motions have their own degree of freedom in which they move. The overall human movement has three different motions associated namely, linear motion, angular motion and general motion. In linear motion the body moves linearly with respect to one axis and the best example is walking. In angular motion the body part moves rotationally. And general motion is a combination of both linear and angular movement [28]. The human femur has angulated in relation to the shaft in 2 planes namely sagittal and coronal planes. The neck shaft of femur has 140° at the time of birth and this angle reduces to 120° to 130° in adults. The neck shaft angle is usually around 125° in normal adults [29]. But coxa valga is a condition which is seen in some of the persons where these neck shaft angle is exceeds more than 130°, same coxa vara is a condition where neck shaft angle is less than 120° [12].

2. Materials

Femur bone is made up of cortical, cancellous bone where cortical is outer layer which is hard and cancellous is the inner bone which is comparatively softer [30]. The middle region of the femur bone is hallowed which is known as bone marrow cavity which consisting of adipose [31]. The mechanical properties of all these materials are shown in the table 1.

Table 1: Mechanical Properties of Bone [32] [33]

Sl	Material properties	Cortical bone	Cancellous bone
1.	Young's modulus	17 GPa	0.52 GPa
2.	Density	2 gm/cm^3	1.08 gm/cm^3
3.	Poisson's ratio	0.30	0.29
4.	Tensile strength	130MPa	-

The mechanical axis of the lower extremity is determined by drawing a line from the center of the femoral head to the center of the ankle joint, which corresponds to an approximately 3° slope compared with that of the vertical axis [34]. The axis of lower limb is shown in the figure 2.

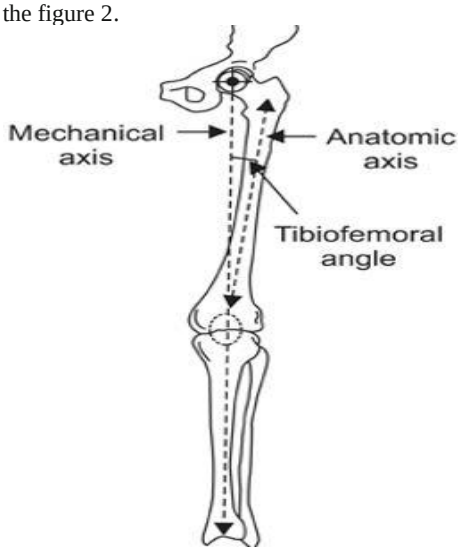


Fig. 2: Alignment of the Limb. Mechanical Axis, Anatomic Axis and Tibiofemoral Angle [35].

Levers are one of the basic tools that were probably used in prehistoric times. Levers were first described about 260 BC by the ancient Greek mathematician Archimedes (287-212 BC). A lever is a simple machine that makes work easier for use; it involves moving a load around a pivot using a force. Many of our basic tools use levers, including scissors, pliers, hammer claws, nut crackers and tongs. Lever first class, the pivot (fulcrum) is between the effort (force) and the load. Lever second class, the load is between the pivot and the effort (force) and Lever third class, the effort is between the pivot and the load [36]. Three components of lever are axis (pivot or fulcrum), resistive load (weight), force (effort). Hip joint acts as first class of lever where fulcrum is located between the applied force and the load [37]. Femoral head acting as fulcrum the abductor muscles will have joint reaction force and center of pubis the load will be acting. Joint reaction force defined as force generated within a joint in response to forces acting on the joint. In the hip, it is the result of the need to balance the moment arms of the body weight and abductor tension. [38]. Joint reaction force in normal hip as shown below in figure 3.

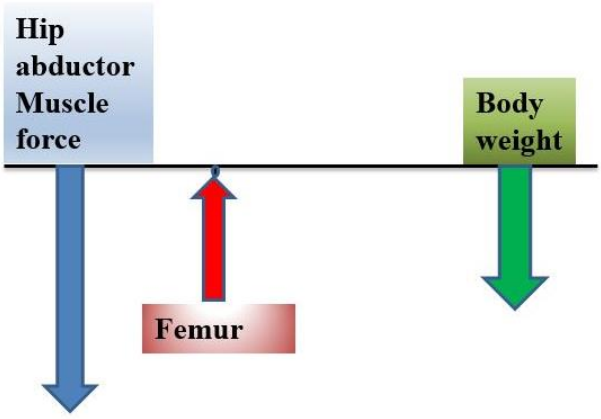


Fig. 3: Joint Reaction Force on Hip Joint.

2.1. Two-dimensional analysis of joint reaction forces at the hip joint

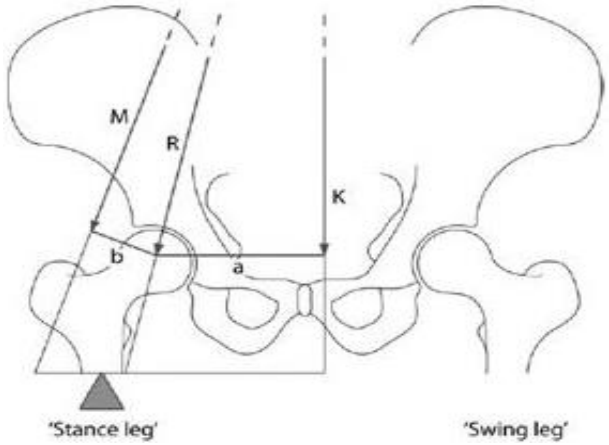


Fig. 4: Free-Body Diagram for the Calculation of the Hip Joint Force While Walking, Where K is the Body Weight (Minus the Weight Bearing Leg), M is the Abductor Muscle Force, and R is the Joint Reaction Force. [39]

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 center of gravity is centered 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 center of gravity moves distally and away from the supporting leg since the nonsporting leg is now calculated as part of the body mass acting upon the weight-bearing hip (see Fig. 4). This downward force exerts a turning motion around the center of the femoral head – the moment is created by

the body weight, K, and its moment arm, a (distance from femur to the center of gravity). The muscles that resist this movement are offset by the combined abductor muscles, M. This group of muscles includes the upper fibers 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 center 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.

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) [40]. 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 [41].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 [42].

2.2. Femoral offset in hip joint

Sir John Charnley was one of the first orthopedic surgeons to pay attention to the problem of soft tissue tension in total hip arthroplasty [43]. Charnley described the importance of restoring the femoral overhang by one of several methods: mediating the acetabular component, avoiding excessive femoral component anteversion, completing the femoral neck osteotomy at an appropriate level, maintaining a cervical-diaphyseal angle of 135°, and, when indicated, by laterally (laterally) re-routing the larger trochanter. The goal of the Charnley philosophy was to increase the abductor moment arm and restore the more "normal" biomechanics, although the concept is well understood, the precise definition of femoral overhang has varied. The simplest and generally used as a measure of the femoral overhang is the perpendicular distance between the center of the femoral head and the diaphyseal line; in the center of the femoral shaft (fig.5). Traditionally, total hip implants have had a relatively high cervical-diaphyseal angle, averaging 135° [44].

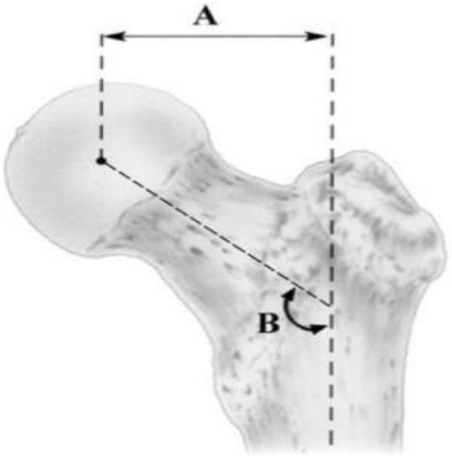


Fig. 5: Femoral Offset Angle

The femoral overhang is represented by the perpendicular distance "A" from the center of the femoral head to the long axis of the femur. The cervicodiaphyseal angle is represented by the angle "B" which forms the long axis of the femoral neck and the long axis of the femoral shaft. [44]. Normally the femoral offset varies from 30 to 60mm.

2.3. Implant model & range of motion

When total hip replacement should be carried out to a specific patient the surgeon will consider your age, weight, lifestyle and severity of joint degeneration as well gender. When matching an implant to your specific circumstances, like Range of motion, Impingement implant fixation, Tissue damage during implantation and tissue tension after THA, Component orientation (stem, cup), Bearing material [45]. There is a clear kinematic advantage to larger femoral head bearings in THR. It is known that increasing the femoral head size leads to an increased head–neck ratio, which results in increased range of motion. [46]. Chandler et al. showed that increasing femoral head size delayed contact between the femoral neck and the acetabular component, thus improving motion [47]. The implant model must be biocompatible. Many different materials are used in the such as aluminum, titanium, zirconia, ultra-high molecular polyethylene, steel, chromium cobalt [48]. The range of motion for implant model purely depend on the head diameter of the implant. With the increasing in the head diameter the range of motion increases with less prone for dislocation [49].

3. 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 [50]. 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 (stain gauges). Rydell was the first to attempt measuring direct hip joint forces using an instrumented hip prosthesis; 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 [51]. Joint reaction forces are minimal if hip center placed in anatomical position. Adjustment of neck length is important as it has effect on both medial offset & vertical offset. More extensive studies have recently been carried out, which are summarized and reported in Table 2. All these studies majorly focused on the force acting on hip joint with different activities.

Table 2: Hip Contact Forces Measured In Vivo in Patients with Instrumented Implants

Activity	Typical Peak Force (BW)	Total Number of Patients	Time Since Surgery (Months)	References
Walking, slow	1.6-4.1	9	1-30	[52][53][54]
Walking, normal	2.1-3.3	6	1-31	[53]
Walking, fast	1.8-4.3	7	2-30	[52][53][54]
Jogging, running	4.3-5.0	2	6-30	[55][54]
Ascending stairs	1.5-5.5	8	6-33	[52][53][54]
Descending stairs	1.6-5.1	7	6-30	[53][56]
Standing up	1.8-2.2	4	11-31	[53]
Sitting down	1.5-2.0	4	11-31	[53]
Knee bend	1.2-1.8	3	11-14	[53]

4. Finite element study

Many researchers studied the forces acting on the hip joint by using computational methods [57]. They used the CT scans of the bone to model the femur bone [58]. The 3D model is subjected to different types of forces which are acting on the hip joint and also normal

gait cycles are used. The table 3 shoes the different FEM studies carried out on femur to know the effects of forces acting on it.

Table 3: Finite Element Analysis Models

References	Focus	Outcomes
[11]	Different model developed, and FEM is used to know the mechanical characteristics under static and dynamic conditions	Evaluation and redesign of an artificial hip joint
[59]	Study of the effect of differently defined hip joint rotation centers on penetration of cartilage, labrum and bones	Big differences between various methods, fewer differences with abduction and external rotation
[59]	Finite volume model to study contact in hip when walking	Maximum contact pressures dependent on cartilage thickness: 0.48 mm: 34.58 MPa, 0.60 mm: 26 MPa, 0.72 mm: 21.59 MPa
[60]	Model of hip used to analyze contact stresses, geometries from sectional images of human specimens	Maximum contact pressure in acetabulum 4.94 MPa, in femoral head 4.77 MPa
[61]	To find the effects on the cup contact stress when using low stiffness Titanium alloy (Ti) as a femur head.	Von Mises stress at the UHMWPE cup decreases by increasing the femur head diameter for all types of femur head materials
[58]	Calculation of contact stresses on cartilage with test subject-specific DEA, comparison with FEA	Higher contact stresses with DEA than with FEA (9.8– 13.6 MPa vs. 6.2–9.8 MPa maximum stresses), faster computing times with DEA (7sec. vs. 65 min.)

5. Conclusion

The approach to learning and understanding hip anatomy can be undertaken in many ways as can the biomechanics. Understanding of the forces acting across 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. Hip joint falls under the first order of levers. 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 do because their pelvis must accommodate a birth canal. 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.

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