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Simulation and Analysis of Leg Length Discrepancy and it's Effect on Muscles

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Abstract

Background/Objectives: Leg Length Discrepancy (LLD) after THA is the most common cause of patient's dissatisfaction. Hence, this paper aims at determining magnitude of LLD which is bearable by any person. **Methods/Statistical analysis**: It includes simulation and analysis of human musculoskeletal models in Open Sim software for various hip muscles as these muscles are more affected after THA. Firstly, muscle force results from Open Sim are cross-checked and validated with an established muscle model. Then, models of different LLDs are obtained in Open Sim and results of muscle force are plotted on graphs for various hip movements like flexion/extension, adduction/abduction, etc. **Findings:** LLD bearing capacity for different body weights of the person is found in the range of 2.0-2.5 cm. It is found that more is the body weight of the person; smaller is the range of his/her LLD bearing capacity and vice-versa. Through literature survey, it is found that person can bear LLD from 10-50 mm to avoid major problems like lower back pain, muscle or ligament injury, nerve palsy, etc. Different researchers found different values of LLD to avoid same problem. So, this range is quite large to define LLD bearing capacity of a person. From this study, a concise range of LLD bearing capacity was found. **Application/ Improvements:** Surgeon can plan his/her preoperative planning and prosthesis design in such a way that LLD will not exceed a given range after THA.

Keywords: Leg Length Discrepancy (LLD), Muscles, Muscle Force, Open Sim,Total Hip Arthroplasty (THA)

1. Introduction

THA also called as Total Hip Replacement (THR) is performed as a treatment for hip arthritis or accidental fracture of hip joint[1]. Overall satisfaction rate is higher than any other joint replacement procedure, with 97% of patients reporting improved outcome[1]. During THA, ball and socket of the hip joint are replaced with an implant, commonly made of metal and plastic[2]. When this surgery is performed, the hip joint is opened surgically. The head of the femur bone is removed and the socket of the pelvis (acetabulum) is shaped. A metal cup is placed in the acetabulum and a ball is placed as a new head of the femur. The ball is attached to a stem which is inserted into the femur for stability[2].

It is important to ensure the stability of artificial ball and socket. In order to prevent dislocation, the surgeon may alter the tension between the ball and socket by placing a larger or shorter prosthesis (implant) in the bone[3]. It results in inequality in leg lengths called as Leg Length Discrepancy (LLD) or Anisomelia, a generalized term for Limb Length Discrepancy. Ideally, surgeon wants to keep the leg lengths equal, but that is not always possible. The procedure of hip replacement and size of prosthesis will determine the length of the leg aftersurgery[3]. So, a surgeon should know how much LLD is bearable by any person. Knowing this, the surgeon can determine the expected size of prosthesis needed and how much bone can be sacrificed during the procedure keeping in mind the stability of the hip joint.

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Increased LLD affects standing posture, leg movements, gait (human walking cycle) mechanics. It also results in many problems like lower back pain, nerve palsy, muscle or ligament injury due to stretching, aseptic loosening of hip prosthesis, etc[4]. LLD causes low back pain and abnormal biomechanics of the lumbo-pelvic region[5]. LLD leads to premature fatigue of the legs in a static posture[6]. Many people studied that how much magnitude is necessary to affect subjects. Giles and Taylor[7] noticed that LLD greater than 9 mm leads to pain or arthritic changes. Ground Reaction Force (GRF) is altered for an average LLD value of 49 mm[8]. Pelvic torsion occurs for LLD greater than 15 mm[9]. Brand and Yack[10] observed that minimum 35 mm LLD is necessary to alter the forces at the hip joint. Lower back muscle activity is increased for LLD greater than 40 mm[11]. Kinetic energy is increased during walking for an average LLD of 26.7 mm[12]. Papaioannou[13] noticed LLD greater than 22 mm results in scoliosis. Rossvoll[14] stated that lower back pain occurs for an average LLD of 32 mm.

2. Leg Length Discrepancy

2.1 Classification of Leg Length Discrepancy (LLD)

LLD is subdivided into two groups: Structural LLD and Functional LLD.

2.1.1 Structural LLD (SLLD)

SLLD, also known as True LLD is defined as a difference in leg lengths due to unequal lengths ofbones. The causes of SLLD can be arthritis, bone infection, tumours', hemi atrophy or hemi hypertrophy with skeletal involvement, surgical procedures such as THA, post-polio syndrome, trauma, etc[4].

2.1.2 Functional LLD (FLLD)

FLLD, also known as Apparent LLD is a result of jointor muscle tightness in the lower extremity. The causes of FLLD can be tightness of antero-lateral soft tissues about the hip and anterior capsule, muscular imbalance due to activities such as poor training techniques, pronation or supination of one foot relative to other, knee hyperextension, scoliosis of the lumbar, etc[4].

In addition, LLD can be classified into two categories, Congenital LLD i.e., since birth/childhood and Acquired LLD (developed later in life). In terms of functional outcomes, persons with Acquired LLD are more prone to fatigue by LLD of the same magnitude when compared to persons with Congenital LLD[4].

2.2 Measurement of LLD

Following are the various methods of LLD measurement[4].

2.2.1 Clinical Methods

In these methods, distance between two reference points on the body is measured by the tailor's tape while lying flat on the ground/bed. So, the discrepancy can be easily found out by comparing the results for each leg. It includes two methods.

One method is True Leg Length Measurement. It involves measuring from the protruding pelvis bone, i.e. Anterior Superior Iliac Spine (ASIS) to the ankle joint, medial malleolus. These are good points of reference for the measurement. Both the legs are measured and their difference gives LLD.

Another method is Apparent Leg Length Measurement.It usually gives slightly less accurate results. LLD is calculated by measuring the distance from the belly button (umbilicus) to the ankle joint(medial malleolus) for both the legs.

2.2.2 Radiographic Methods

Radiography is a gold standard for measuring LLD[15]. These methods are more accurate than clinical methods. It also includes two methods.

One method is X-ray Radiography in this method, LLD is found out by marking the identical landmarks (greater or lesser trochanter, head, etc.) on the legs and measuring their perpendicular distance with respect to ground. But, the scale factor of X-ray film should be known. Nowadays, X-rays are available in digital format. The image is in the Dicom (dcm) format. These images are read invarious Dicom viewer software's like 3-D Doctor, Mimics, Scan-Doc etc.

Another method is Scanogram this method involves scanning the pelvis and legs with the use of Computed Tomography (CT) scan machine. An entire leg is visible in one image, which is not the case with X-ray. So, it is a very accurate method of measuring LLD[16].

But, these methods of measuring are generally rare as some physicians believe that the True and Apparent leg length measurement methods are accurate enough[17], apart from being quick and inexpensive to carry out.

3. Simulation using Open Sim

In this paper, behavior of different hip muscles is studied in Open Sim. Open Sim is a software for modeling, simulating and analyzing human musculoskeletal system[18]. Figure 1 shows the musculoskeletal models in Open Sim. This software is used to visualize models and to provide access to different functions.

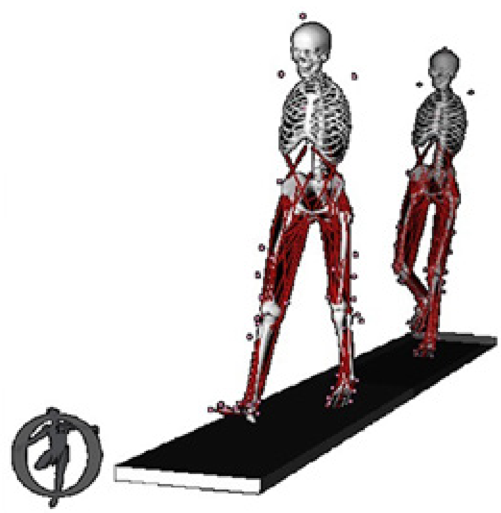

Figure 1. Musculoskeletal models in Open Sim.

Hip muscle force graphs are plotted against different hip movement angles. By observing the graphs for various LLD cases, it is determined that how much LLD is bearable by any person.

In Open Sim, it is found that gluteus maximus and gluteus medius muscles are more susceptible to various LLD cases. These muscles belong to hip abductor as well as hip flexor muscle group. It means these muscles have significant contribution in hip movements like adduction/abduction and flexion/extension. There are three muscles in gluteus maximus and gluteus medius sub-group. Out of these, gluteus maximus_1 and gluteus medius_1 develop larger muscle force than other muscles. So, graphs are plotted for these two muscles to compare the results with maximum hip muscle force as stated in hip abductor muscle model.

In the body, bones are lever arms and joints are axis/fulcrum. Motive forces for bone movements are provided by contraction and expansion of the muscles (the active component in human body). Resistive forces are supplied by bone's weight and any extra weight if any.

The results of Open Sim are compared with an established Hip Abductor Muscle Model of a person standing on the lower right leg[19] is shown in Figure 2. So, hip abductor muscles generate maximum muscle force to keep the pelvis in level.

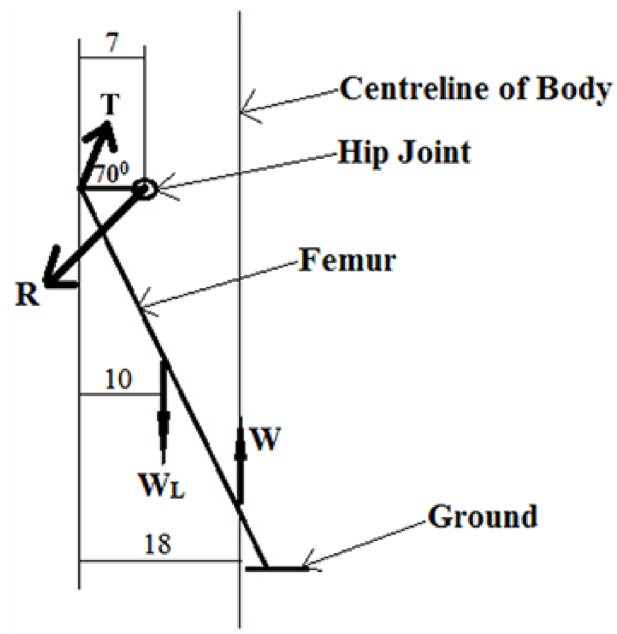

Figure 2. Hip abductor muscle model.

Forces on the leg are as follows:

- The upward vertical force acting on the foot through the centre of gravity of body equal to the body weight (W).
- The weight of one leg (W_L)which is approximately equal to W/7 and acts through the centre of gravity of thatleg.
- The reaction force (R) acting between hip and femur i.e. on the acetabulum.
- The tension or muscle force (T) in the hip abductor muscle group acting between hip and greater tro-chanter at an angle of 70^0 with respect to horizontal.

The static equilibrium condition is assumed here. Hence, summation of horizontal and vertical vector components of force is taken as zero.

$$\sum Fx = T\cos(70) - Rx = (0 \quad (1)$$

$$\sum Fy = T\sin(70) - Ry - \frac{w}{7} + W = (0) \quad (2)$$

Moment acting at the head of femur (hip joint), $\Sigma M = 0$

$$[-T\sin(70) * 7] - W\frac{10-7}{7} + W(18-7) = 0$$

$$11W - \frac{3}{7}W - 6.6T = 0$$

$T = 1.6\ W$

Equations (1) and (2) are used to determine the force acting on the acetabulum.

$$Rx = T\cos(70) = (1.6W * 0.342) = 0.55W$$

$$Ry = T\sin(70) + \frac{6}{7}W = (1.6W * 0.94) + 0.86W = 2.364W$$

$$R = \sqrt{Rx^2 + Ry^2}$$

$R = 2.4W$

Hence, a maximum force in the hip abductor muscle (T) and force on the acetabulum (R) is 1.6 W and 2.4 W respectively.

Out of the two muscles, gluteus maximus_1 and gluteus medius_1, maximum muscle force is generated by gluteus medius_1 (glut_med1) muscle. So, forces on glut_med1 for different body weights as obtained in Open Simare compared with maximum hip abductor muscle force as stated in muscle model (Table 1). The muscle forces in glut_med1 for different body weights of a person are graphically compared in Open Sim as shown in Figure 3.

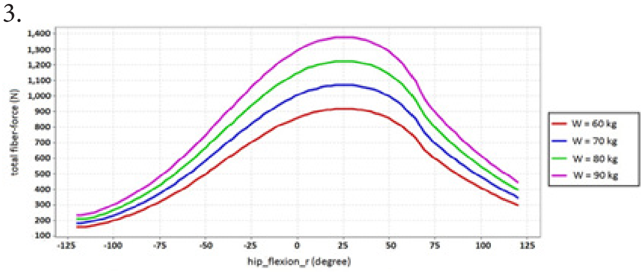

Figure 3. Muscle forces for gluteus medius_1 (glut_med1) of right hip with respect to hip flexion angle (degrees) for different body weights of a person in Open Sim.

Table 1. Results of maximum hip abductor muscle force (N) for different body weights

Body weight (kg)	Open Sim	Muscle model
60	917	942
70	1070	1099
80	1223	1256
90	1376	1413

Hence, results of maximum hip abductor muscle force from Open Sim are cross checked with the muscle model results and then validated.

4. Case Study

Subjects with different body weights are taken which possess LLD to determine their LLD bearing capacity. Table 2 shows the LLD measurement data from clinical methods (true and apparent) and X-ray method.

Figure 4. LLD measured on the X-ray film for subject with body weight of 85 kg.

Subject with body weight of 85 kg from Table 2 is shown in Figure 4 who has suffered from LLD after THA. Open Sim results for this subject are plotted on the graphs (Figure 5 and Figure 6). In these graphs, positive angles represent hip adduction and flexion, while negative angles represent hip abduction and extension respectively. From the graphs, it is found that muscle force exceeds the maximum force value after LLD of 2.3 cm and 2.2 cm in the graphs of gluteus maximus_1 (Figure 5) and gluteus medius_1 (Figure 6) respectively. So, LLD bearing capacity of this subject is 2.2-2.3 cm. As this subject possess LLD greater than it's capacity, he/she should use shoe raise or a cane during walking.

Table 2. LLD measurement by different methods

Subject's body weight (kg)	True leg length measurement (cm)	Apparent leg length measurement (cm)	X-ray method (cm)	Range of LLD (cm)
85	3.2	3.0	3.2	3.0-3.2
94	3.5	3.3	3.6	3.3-3.6
62	1.3	1.2	1.5	1.2-1.5
70	3.7	3.8	3.5	3.5-3.8

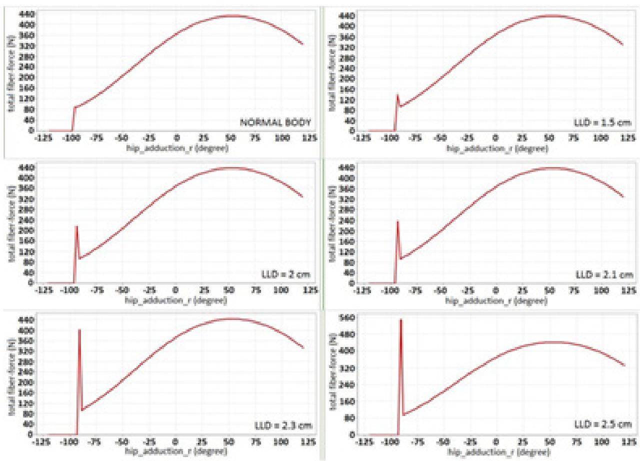

Figure 5. Graphs of muscle force (N) against hip adduction angle (degrees) of right hip for the muscle gluteus maximus_1 (glut_max1) in case of subject with body weight of 85 kg.

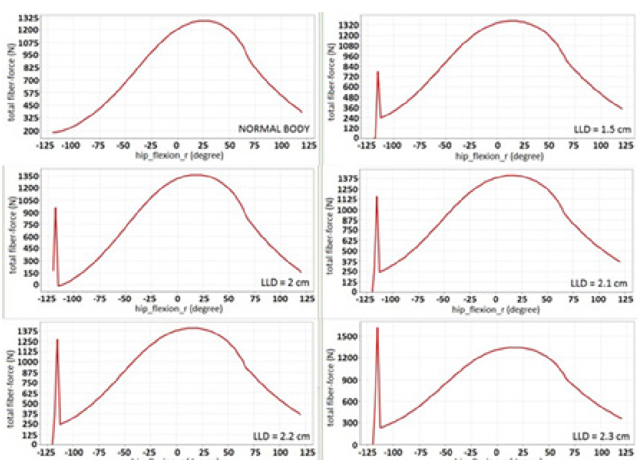

Figure 6. Graphs of muscle force (N) against hip flexion angle (degrees) of right hip for the muscle gluteus medius_1 (glut_med1) in case of subject with body weight of 85 kg.

Similarly, Open Sim results for other subjects are obtained and their LLD bearing capacity is found out (Table 3).

Table 3. LLD bearing capacity of subjects taken for a study

Subject's body weight (kg)	LLD bearing capacity (cm)
85	2.2-2.3
94	2.1-2.2
62	2.4-2.5
70	2.3-2.4

Subjects on whom THA is to be performed, preoperative planning and prosthesis design should be done in such a way that LLD will not exceed bearing capacity value after THA. Other subjects on whom THA is already performed, but possess LLD, they should use shoe raise in shorter leg or a cane during walking. In Open Sim, musculoskeletal models with different weights are taken and their LLD bearing capacity is shown in Table 4.

Table 4. LLD bearing capacity for different ranges of body weights

Range of body weight (kg)	LLD bearing capacity (cm)
50-60	2.5-2.6
60-70	2.4-2.5
70-80	2.3-2.4
80-90	2.2-2.3
90-100	2.1-2.2

5. Conclusion

From the muscle model, it is known that the force acting on the muscles is directly proportional to the weight of the person. The subjects with different weights are studied and it is found that the LLD bearing capacity of the person is in the range of 2.0-2.5 cm.

However, there is still controversy regarding the magnitude of LLD bearable by any person to avoid major problems[4]. But, careful preoperative planning and intra-operative techniques decrease the chances of patient's LLD after the operation[1]. Intra-operative techniques for leg length equalization include palpation of bony landmarks, quantification of fixed reference landmarks and production of radiographic template's images. Wong et al.[20] made the leg lengths equal in most of the cases of THA using the method of intra-operative measurement of HLTD (Head to Lesser Trochanter Distance) and neck cut. Woolson and Harris[21] have proven that leg length equality can be achieved by measuring the distance between two pins inserted into the ilium and the greater trochanter before the dislocation of true femoral head and after the reduction of the prosthetic head. Ranawatet al.[22] also stated the use of a vertical Steinmann pin which is placed into the ischium at the infracotyloid groove of the acteabulum to identify the leg length equality. Direct intra-operative measurement of pelvis to femur distance before and after THA is another method to achieve leg length equality[21,23]. Also, intra-operative measurement on a preoperative radiograph includes use of templates with known magnification factor for leg length restoration[24]. Due to LLD, gait (walk) cycle of person is affected. Mokhtarianet al.[25] developed gait rehabilitation device to improve affected gait cycle due to injury or disease. Some rehabilitation exercises should be performed to improve the functionality of lower limb. Chinnavanet al.[26] developed rehabilitation programto improve the functionality of leg in Anterior Cruciate Ligament (ACL) injury. Nowadays, navigation is a very useful tool for both prosthesis positioning and leg length equalization in THA[27,28].

It is clear that persons with Congenital LLD can bear larger magnitude of LLD than persons with Acquired LLD[4]. It is also seen that, younger persons are able to cope with larger LLD than the older persons[29,30]. The reason is that, gait and hip movement patterns differ considerably between younger and older persons. Crouch gait is generally seen in olderindividuals. Bennell et al.[31] noticed that LLD leads to lower extremity stress fracture more in female athletes. Also, activity level of the person plays an important role. Persons involved in sports or standing work are more sensitive to LLD than the less active persons[4,32]. Broadly, it can be stated that LLD bearing capacity depends mainly on the body weight, but may vary with age, sex, type of LLD and activity level of the person. Finally, it can be concluded that more body weight can bear less LLDand vice-versa.

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