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Original Research

An Analysis of Radiographic Leg Length Discrepancy and Hip Offset in Patients at Risk of Developing Osteoarthritis

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A B S T R A C T

Background: Leg length and hip offset are important principles in total hip arthroplasty (THA). Patients may endorse leg length differences (LLD) postoperatively that may be anatomical or functional. The objective of this study was to determine the normal radiographic variation in leg length and hip offset in a preosteoarthritic population without a THA.

Methods: A retrospective study was completed using data from the Osteoarthritis Initiative, a prospective longitudinal study. Patients at risk of developing or with early osteoarthritis without inflammatory arthritis or prior THA were included. Measurements were made from full limb length anterior-posterior (AP) radiographs. Multiple linear regression models were employed to predict side-to-side differences in LLD, Δ femoral offset (FO), Δ abductor muscle length (AML), Δ abductor lever arm, and Δ AP pelvic offset.

Results: The mean radiographic LLD was 4.6 mm, with 12 mm within 1 standard deviation. No significant differences were detected between LLD and sex, age, body mass index, or height. The median radiographic differences in FO, AML, abductor lever arm, and AP pelvic offset were 3.2 mm, 4.8 mm, 3.6 mm, and 3.3 mm, respectively. Height was predictive of Δ FO, while both height and age were predictive of Δ AML.

Conclusions: Radiographic leg length variations in a population without symptomatic or radiographic osteoarthritis exist. FO and AML are dependent on patient characteristics. Preoperative radiographic LLD is not predicted by age, gender, body mass index, or height. It should be stressed that anatomic reconstruction is one of the many goals of arthroplasty and can stand in conflict with the priority and primary goals of stability and fixation, which should be prioritized.

Introduction

An important surgical principle in total hip arthroplasty (THA) is appropriate reconstruction of leg length and hip offset, appreciating that stability and fixation remain a priority [1,2]. Postoperative THA patients may endorse the sensation of patient-perceived leg length differences (LLD). A perceived LLD may refer to anatomical or functional differences secondary to changes in biomechanical forces and the relationship between the pelvis and lumbar spine [3–6]. Preoperative LLD has also been associated with postoperative patient-perceived LLD and poor functional outcomes [3,7].

An acceptable difference in preoperative THA LLD and offset has yet to be defined in a large cohort of patients [8–10]. A wide range of differences in preoperative radiographic LLD differences have been reported, spanning from a few mm to 16 mm [11,12]. The vast majority of current literature on preoperative LLD includes patients with late-stage osteoarthritis (OA) receiving THA, in which

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increased LLD secondary to arthritis are present. Existing clinical studies that have investigated preoperative LLD in at-risk populations with minimal to no symptoms are limited by sample size [8,13]. A meta-analysis that combined these smaller studies estimated a preoperative radiographic LLD of approximately 5.2 mm [14]. A more cohesive investigation of preoperative radiographic LLD using standing leg length radiographs may be feasible with the novel use of the NIH Osteoarthritis Initiative (OAI), a publicly available 15-year prospective cohort study on OA.

The primary objective of this study was to determine normal radiographic LLD variation in preoperative patients at risk of developing or with early stages of hip OA. Our secondary objective was to determine radiographic variation in measures of hip offset, including femoral offset, abductor muscle length, abductor lever arm, and anterior-posterior (AP) pelvic offset. These parameters influence hip biomechanics and are thought to contribute to the development of hip OA [15–18]. We hypothesized that a preoperative LLD of 5 mm would be present in patients without significant radiographic signs of hip OA.

Material and methods

Study design

A retrospective study of 543 individuals (349 females and 184 males) was completed using patient data from the NIH OAI, a multicenter longitudinal study focused on knee and hip OA. Participants were recruited from 5 centers: University of Pittsburgh Medical Center (Pittsburgh, PA), University of California San Francisco (San Francisco, CA, USA), Ohio State University (Columbus, OH, USA), Brown University (Providence, RI, USA), and the University of Maryland (Baltimore, MD, USA). Inclusion criteria included patients at risk of developing or with early OA. This was defined as having a definite tibial-femoral osteophyte [Osteoarthritis Research Society International (OARSI) atlas grades 1-3] or equivalent Kellgren and Lawrence grade $\geq$2 at baseline and/or those with symptoms of pain, aching, or stiffness in either hip or knee joint on most days of a month in the past year. Exclusion criteria consisted of inflammatory arthritis, severe joint space narrowing (OARSI joint space narrowing grade 3 or bone-on-bone), or a history of THA or bilateral total knee joint arthroplasty. Participants with previous unilateral knee surgery, defined as a history of any knee surgery including meniscal or ligamentous repair as well as unilateral total knee arthroplasty, were included in the OAI study because a history of knee surgery is a strong risk factor for ipsilateral OA and because those with end-stage OA in 1 knee are at an increased risk of developing OA in the contralateral knee [19,20]. Patient demographics including age, sex, body mass index (BMI), height, and ethnicity were collected from a publicly available database (OAI) from the National Institute of Health, and thus institutional review board approval was not necessary.

Radiographic evaluation

Radiographic evaluation was conducted using full limb length AP radiographs obtained from the OAI database. Single weight-bearing AP radiographs of full length bilateral lower limbs taken at the first visit after enrollment using a 51 by 14-inch graduated grid cassette were analyzed [19]. Radiographic measurements were performed using ImageJ software (ImageJ v1.53, National Institutes of Health, Laboratory for Optical and Computational Instrumentation, University of Wisconsin).

Limb length was defined as the distance from the center of the femoral head to the tibial mid-plafond (Fig. 1A). Full limb length measurements for the study population were conducted by Duryea

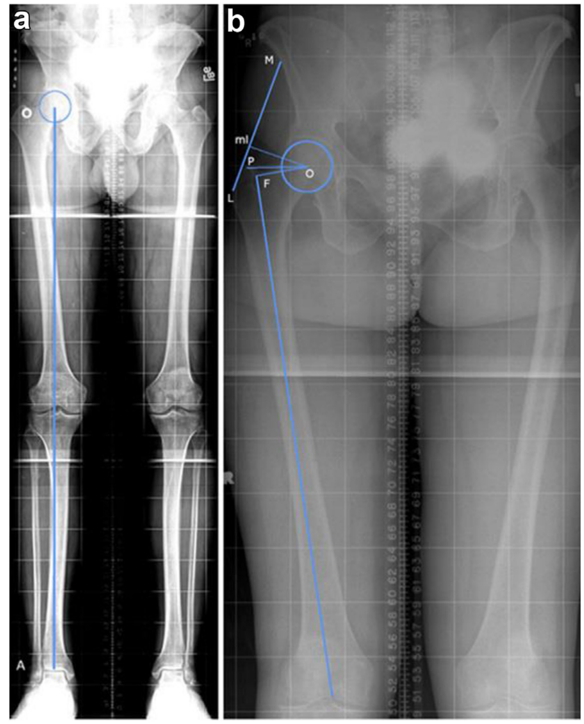

Figure 1. Radiographic evaluation of anatomic variables.

(Project #16, 29, 32) and Cooke (Project #60) and are available within the OAI database [21]. LLD data was calculated using full limb length measurements from the OAI database. A detailed description of the OAI leg length measurement protocol has been previously published, wherein limb length measurements were found to have a test-retest agreement kappa of 0.77 for presence or absence of radiographic hip OA [21–23]. Radiographic LLD was defined as the difference between bilateral full limb length measurements.

Hip offset measurements included femoral offset, abductor muscle length, abductor lever arm, and AP pelvic offset (Fig. 1B). These measurements were first described by Borja et al. [15] and later used in multiple studies evaluating abductor muscle function [16,17,24,25]. Femoral offset was measured as the perpendicular distance from the center of rotation of the femoral head to the long axis of femur. Abductor muscle length was measured as the distance between the anterior superior iliac spine and superolateral margin of greater trochanter. Abductor lever arm was measured as the perpendicular distance between the abductor muscle line and the center of the femoral head. AP pelvic offset was measured as the distance from the center of the femoral head to the superior margin of the greater trochanter.

Data and statistical analysis

Demographic characteristics, clinical characteristics, and radiographic measurements were presented with means and standard deviations for normally distributed continuous variables and with median and interquartile ranges for nonnormally distributed continuous variables. Categorical and nominal variables were presented as percentages or frequencies. LLDs and side-to-side differences in hip offset measures were analyzed and reported as absolute values. To fully compare side-to-side differences, each group was further subdivided. Specifically, age was subdivided into 4 subgroups with 10-year increments starting at the age of 40 years.

Table 1
Patient demographics and baseline characteristics.

Characteristics	Patients (N = 543)
Age (years), [mean(±SD)]	61.6 (9.1)
Gender (N, %)	
Male	184 (34%)
Female	359 (66%)
BMI (kg/m^2), [mean(±SD)]	29.4 (4.8)
Height (cm), [mean(±SD)]	166.7 ± 8.8
Race (N, %)	
White	336 (62%)
Black	197 (36%)
Other	10 (2%)

SD, standard deviation.

BMI was subdivided into 6 subgroups with 5 kg/m^2 increments starting with 15 kg/m^2. Height was subdivided into 3 subgroups with 15 cm increments, starting with 145 cm. Shapiro-Wilk test of normality was used to verify the normality of distribution. Student t-test and ANOVA tests were used for analysis of normally distributed data. Finally, multiple linear regression was performed to test whether each of the side-to-side differences were significantly predicted by gender, age category, height category, and BMI category. Data and statistical analysis were performed with R Studio (Build 382), with statistical significance set to <0.05.

Results

Demographic and baseline characteristics

A total of 543 patients were included for analysis (Table 1). The mean age was 61.6 ± 9.0 years (range 46-80 years), with a mean BMI of 29.4 ± 4.8 kg/m^2 (range 23.6-42.5) and a mean height of 166.7 ± 8.8 cm (range 148.2-190.0 cm). Patients between ages 50 and 60 years constituted the majority among the age groups (34.4% of study population). Patients with BMI between 25 and 30 kg/m^2 constituted the majority among the BMI groups (37.9% of study population). Patients' height between 160 and 175 cm was most common among the height groups (53.6% of study population). There was appropriate inclusion, variation, and representation of race as the OAI was designed to enroll a diverse population [26]. Females constituted 66% of the total population. There was no significant difference in age between male and female populations ($P = .99$).

LLD measurements

The mean radiographic LLD for the entire cohort was 4.6 ± 3.5 mm (Table 2). The mean for male and female populations was 4.8 mm ± 3.8 mm and 4.4 mm ± 3.4 mm, respectively. The regression model was not statistically significant, indicating LLD is independent of patient age, BMI, and height. LLD measurements for the cohort population followed a Weibull distribution with a shape factor of 1.23 and a scale of 4.85 (Fig. 2). An LLD of less than 7.25 mm was found in 80% of the cohort population, with an LLD of 12 mm falling within 1 standard deviation of the mean.

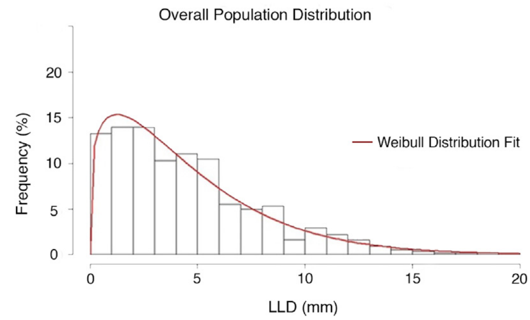

Figure 2. Distribution of study population leg length discrepancy.

Hip-offset measurements

Radiographic measurements

The mean radiographic femoral offset, abductor muscle length, abductor lever arm, and AP pelvic offset of the study population were 46.5 ± 6.8 mm, 98.3 ± 15.8 mm, 52.6 ± 6.7 mm, and 55.4 ± 6.0 mm, respectively (Table 2).

Side-to-side differences

The median side-to-side differences of Δ femoral offset, Δ abductor muscle length, Δ abductor lever arm, and Δ AP pelvic offset were 3.2 mm (range 0-17.2 mm), 4.8 mm (range 0-27.7 mm), 3.6 mm (range 0-18.8 mm), and 3.3 mm (range 0-18.4 mm), respectively (Table 3). In 95% of the cohort population, there was a Δ femoral offset, Δ abductor muscle length, Δ abductor lever arm, and Δ AP pelvic offset of 11 mm, 17.5 mm, 11.7 mm, and 11.5 mm, respectively. Regression model significantly predicted ($P < .01$) Δ femoral offset, and only height category was a significant predictor ($P = .03$ for height category 160-175 cm; $P = .02$ for height category 175-190 cm). Similarly, regression analysis significantly predicted Δ abductor muscle length ($P < .01$). Height category and age category were the significant predictors of Δ abductor muscle length ($P < .01$ for height category 175-190 cm; $P < .01$ for age category 60-70 cm; $P < .01$ for age category 70-80 cm). Δ abductor lever arm was independent of patient height and age characteristics. Regression model significantly predicted ($P = .02$) Δ AP pelvic offset, and only height category was a significant predictor ($P < .01$ for height category 175-190 cm).

Discussion

Among individuals with preosteoarthritis and minimal symptoms, the mean LLD was 4.6 mm, with 12 mm falling within 1 standard deviation of the mean. By examining a study population consisting of individuals without significant radiographic or symptomatic OA, our findings offer valuable information on the normal radiographic variations as measured on a radiograph in this at-risk group. Large radiographic variations in LLD, Δ femoral offset, Δ abductor muscle length, Δ abductor lever arm, and Δ AP pelvic offset were observed. A surgical principle in THA is an attempt at reconstruction of leg length and hip offset. These results show that

Table 2
Overall means and median of LLD and functional variables.

Measurement Type	LLD	FO	AML	ALA	APO
Mean (mm) [±SD]	4.6 [3.5]	46.5 [6.8]	98.3 [15.8]	52.6 [.7]	55.4 [6.0]
Median (mm) [IQR]	3.9 [1.9-6.2]	3.2 [1.3-5.5]	4.8 [2.1-8.9]	3.6 [1.8-6.4]	3.3 [1.4-5.8]

SD, standard deviation; IQR, interquartile range; LLD, leg length difference; FO, femoral offset; AML, abductor muscle length; ALA, abductor lever arm; APO, anterior-posterior pelvic offset.

Table 3
Median of LLD and functional variables by category.

Patient Characteristics	LLD	Δ FO	Δ AML	Δ ALA	Δ APO
Median by gender (mm) [median (IQR)]					
Male	3.9 [1.8-7.0]	3.9 [1.7-5.9]	6.2 [2.7-10.8]	4.1 [2.2-6.5]	3.8 [1.6-5.8]
Female	3.8 [1.9-6.0]	2.9 [1.2-5.2]	4.3 [2.0-7.9]	3.5 [1.6-6.2]	3.1 [1.2-5.6]
P-value	0.45	**0.03**	**<0.01**	**0.03**	0.18
Median by age group (y) (mm) [median (IQR)]]					
40-50	3.4 [1.7-5.4]	2.8 [1.2-5.2]	3.9 [1.9-7.2]	3.5 [2.2-6.6]	3.1 [1.4-6.2]
50-60	4.0 [1.8-6.4]	3.8 [1.5-6.1]	4.1 [2.0-8.1]	3.6 [1.5-6.1]	3.4 [1.3-6.1]
60-70	3.5 [1.8-6.9]	2.9 [1.1-5.2]	5.3 [2.3-9.7]	3.7 [1.8-6.5]	3.4 [1.5-5.5]
70-80	4.2 [2.0-5.9]	3.1 [1.6-5.9]	4.8 [2.4-10.4]	3.8 [2.3-6.4]	3.3 [1.2-5.5]
P-value	0.44	0.13	0.07	0.53	0.99
Median by BMI (kg/m^2) (mm) [median (IQR)]					
15-20	5.4 [3.6-10.6]	2.4 [1.1-4.6]	3.6 [0.9-5.9]	3.1 [1.8-5.0]	3.2 [1.6-4.0]
20-25	3.4 [1.7-5.6]	3.1 [1.6-5.3]	4.7 [2.8-8.4]	3.7 [1.7-5.9]	3.8 [1.2-5.3]
25-30	3.6 [1.7-6.2]	3.0 [1.0 - 5.1]	5.1 [1.9-9.4]	3.7 [1.9-6.4]	3.2 [1.3-5.3]
30-35	4.1 [2.3-6.7]	3.3 [1.4-6.0]	4.1 [1.9-8.0]	3.5 [1.8-6.7]	3.3 [1.3-6.2]
35-40	3.3 [1.7-6.2]	3.6 [1.4-7.3]	5.3 [3.0-8.5]	3.5 [1.2-6.7]	4.3 [2.2-7.2]
40-45	4.2 [1.3-7.3]	4.3 [1.6-7.0]	9.0 [4.9-12.5]	6.2 [2.9-6.9]	2.6 [1.7-4.4]
P-value	0.47	0.22	0.43	0.35	0.24
Median by height (cm) (mm) [median (IQR)]					
145-160	3.2 [1.6-6.1]	2.6 [1.0-4.5]	4.6 [1.5-8.2]	3.7 [1.8-5.7]	2.6 [1.1-5.4]
160-175	4.0 [2.0-6.0]	3.2 [1.4-5.6]	4.3 [2.2-7.9]	3.3 [1.6-6.2]	3.3 [1.4-5.8]
175-190	3.9 [1.9-7.4]	4.1 [1.6-6.1]	7.6 [3.3-12.2]	4.5 [2.3-7.0]	4.1 [1.8-6.4]
P-value	0.17	**0.04**	**<0.01**	**0.04**	0.05

LLD, leg length difference; FO, femoral offset; AML, abductor muscle length; ALA, abductor lever arm; APO, anterior-posterior pelvic offset; IQR, interquartile range.
Significance is denoted in bold.

considerable variation exists in preoperative patients at risk of developing hip OA. It should be emphasized that stability and fixation should remain a priority goal in THA.

A mean radiographic leg length LLD of 4.6 ± 3.5 mm and a range of 0-12 mm were observed in 95% of the study population without a THA. There exists a broad range of normal radiographic LLDs within established literature, with maximum limits ranging from 10-20 mm [8,23,27]. The current investigation corroborates previous studies, however, with higher power. A meta-analysis on pooled data of 573 patients represents a comparatively powered study and demonstrated a mean radiographic LLD in asymptomatic patients of 5.2 ± 4.1 mm, with 78.7% of the analyzed population falling within a 9 mm LLD [14]. Additionally, radiographic LLD in patients without a THA was not affected by age, gender, BMI, or height [14]. The results of this study, which examined a population of pre-osteoarthritic patients with minimal symptoms, offer insight into the radiographic variations of LLDs in patients without a THA.

Functional parameters contributing to hip biomechanics include femoral offset, abductor muscle length, abductor lever arm, and AP pelvic offset [16–18,28]. Studies on femoral offset demonstrate that restoration of both LLD and femoral offset is critical in restoring normal hip function. Both increased and decreased femoral offset adversely impact implant longevity and cause side-to-side imbalance of abductor muscle strength [29,30]. This strength imbalance is a plausible explanation for the postoperative patient-perceived LLD. The current study found 95% of prearthritic individuals to have a range of Δ femoral offset of 0-12 mm with a mean of 4.0 ± 3.3 mm. Individuals' height was found to be correlated with Δ femoral offset. Specifically, individuals with a height greater than 175 cm had a greater Δ femoral offset range compared to those with a height between 145 and 175 cm ($P < .01$). Postoperative Δ femoral offset is generally accepted at <5 mm [31]. However, the significant interaction with height may suggest a need to establish an individualized postoperative Δ femoral offset with regard to a patient's height.

The normal range of Δ abductor muscle length and Δ AP pelvic offset was 0-17.5 mm and 0-11.5 mm, respectively. Δ Abductor muscle length is correlated with height and age, and Δ AP pelvic offset is correlated with height. Prior studies have demonstrated that use of the ipsilateral diseased hip is more accurate in preoperative digital templating than using the contralateral healthy hip in patients with unilateral OA [32]. However, using the contralateral healthy hip may be useful in instances where measurements of the diseased hip are not discernible or reflect pathological biomechanics [33]. Given that THA affects LLD and alters the surrounding biomechanical environment of the abductor muscles, consideration of a patient's contralateral hip may provide guidance in preoperative planning when appropriate and once stability through range of motion has been established [16]. Establishing individualized Δ abductor muscle length and Δ AP pelvic offset with respect to parameters such as patient height or age may improve templating by providing information in addition to the contralateral hip.

The current study is not without limitations. This study is retrospective in nature. However, the large sample size, in conjunction with collecting data from a prospective cohort, allowed for a high-powered analysis of reliable data. Further, there was missing data on abductor muscle strength as well as correlations between abductor muscle strength and LLD. Abductor muscle strength has been shown to have an inverse correlation with LLD. Considering the study population did not have functional limitations or clinical symptoms, we assumed that abductor muscle strength was symmetric. The use of single AP plane radiographs has limitations. Compared to three-dimensional imaging techniques, there is a less accurate measurement of leg length. Using a single standing leg length AP image as a measure of true leg length discrepancy may not be entirely valid due to variances in anatomy, positioning, and alignment. However, single AP plane pelvic radiograph is the common method in the clinic to assess leg lengths. Multiple studies have used single AP plane radiographic images to assess how preoperative LLD may impact patient perceived-LLD, functional outcomes, and patient satisfaction postoperatively [3,34]. Additionally, clinical outcome measures were not available, thus prohibiting comparisons between those with and without LLD and subsequent analysis of clinical outcomes. Future investigations are needed to demonstrate associations between LLD and clinical outcomes in order to fully elucidate an acceptable range of LLD following THA.

Conclusions

There are considerable radiographic variations in LLD in a population without symptomatic or radiographic OA. Population-wide variations in LLD, femoral offset, abductor muscle length, abductor lever arm, and AP pelvic offset were observed. During preoperative planning, surgeons consider a multitude of factors to properly template the femur, acetabulum, and reestablish leg length equality and hip offset. Preoperative variation highlights the challenge in postoperative reconstruction. The authors stress that reconstruction of the biomechanics is one of many goals in THA. The primary goal is stability and fixation, which is the priority. Leg length differences may be needed to establish the primary goal of stability.

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Conflicts of interest

Smith Nephew, APT, Peptilogics, ORS, AAOS, ASTM.

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