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Determining and Achieving Target Limb Length and Offset in Total Hip Arthroplasty Using Intraoperative Digital Radiography

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ABSTRACT

Background: Achieving appropriate limb length and offset in total hip arthroplasty (THA) is challenging. Target limb length and offset may not always mean equal radiographic measurements bilaterally. The goal of this study is to introduce a method for determining as well as achieving target limb length and offset using digital radiographic measurements.

Methods: One hundred and two consecutive patients with unilateral hip osteoarthritis undergoing primary THA in the lateral decubitus position were included. Limb length and offset were measured on anterior-posterior pelvic radiographs preoperatively, intraoperatively, and postoperatively. Offset was defined as the length of a line parallel to the inter-teardrop line, extending from the edge of the ischium, at about the lower border of the ipsilateral obturator foramen, to the edge of the femoral cortex, usually at, or just below, the neck resection level. Target limb length was determined for each patient based on patient perception and severity of disease. Target offset equaled the contralateral limb. Using intraoperative digital radiography, adjustments were made until targets were achieved and the hip was stable. Patients were followed for an average of 4.2 years postoperatively.

Results: Limb length was within 5 mm of target measurements in 100% of patients and offset was within 5 mm of targets in 97.1%. Target measurements differed by >5 mm from the contralateral side in 2.0% of limb length and 2.9% of offset measurements. There were no significant differences between intraoperative and postoperative limb length ($P = .261$) or offset ($P = .747$) measurements. At final follow-up, there were no dislocations or reoperations and average Hip disability and Osteoarthritis Outcome Score for Joint Replacement was 95.78.

Conclusion: Target limb length and offset goals can be determined for most patients undergoing THA. Targets are not always equal to the contralateral side. Intraoperative digital radiography can allow surgeons to accurately achieve target limb length and offset to within 5 mm in a homogenous cohort of patients with unilateral hip osteoarthritis with excellent clinical outcomes.

Achieving appropriate limb length is essential to success in total hip arthroplasty (THA). Limb-length differences can lead to limp, functional deficits, pelvic obliquity, need for shoe lift, instability, and low back pain, all potentially leading to significant patient dissatisfaction [1,2]. Limb-length inequality is one of the most common causes for litigation after THA [3]. The limb is typically lengthened during surgery but acceptable limb lengthening goals are unclear [2]. Furthermore, several studies have shown that patient perception of limb-length differences do not always correlate with measurable differences [1,4]. Complicating this further are epidemiological studies showing that 90% of the population have an anatomic limb-length inequality measuring on average approximately 5.2 mm [5]. Therefore, although the general inclination is to make hips equal with regard to measurable hip morphology, neither overall limb-length equality nor symmetric hip morphology may be the correct goal for all patients.

Achieving appropriate offset in THA is critical to restoring the function of the hip abductors and avoiding impingement [6–8].

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Femoral offset in THA refers to the lateralization of the femoral shaft compared to the center of rotation of the hip in the acetabulum. In addition, acetabular offset is the position of the acetabular component and hip center of rotation from the pelvis. Global offset is an overall assessment of the lateralization of the femoral shaft from the pelvis [6,7]. Inadequate offset can be associated with poor gait patterns, poor functional outcomes, impingement, pain, increased muscle force and fatigue, increased joint reactive forces, and dislocation [6,9–12]. Too much offset has been associated with increased pain as well as increased wear and apparent limb-length inequality [13,14]. Generally speaking, the goal is to make offset as symmetric as possible with the opposite side. Due to implant design, it is not always possible to change offset without changing limb length. Consequently, achieving desired offset is not always possible [15].

Researchers have shown that achieving limb length and offset within 5 mm results in acceptable outcomes [16–18]. Although target limb length and offset may be decided upon during preoperative planning, achieving these with traditional instrumentation in the operating room can be challenging [2]. We recently described a method for accurately obtaining target acetabular cup position using intraoperative digital radiography (DR) [19]. In that study we also showed the significant effect of pelvic position on the acetabular component measurements [19]. Several previous studies have also shown the importance of patient positioning on radiographs for THA templating and shown how positioning can affect both limb length and offset [20,21]. Very little, however, has been described on methods of patient positioning intraoperatively in regards to limb length and offset.

In the present study, we first aim to introduce a method for determining target limb length and offset. We further propose a technique for accurately achieving those targets using intraoperative DR. We hypothesize that using this method will allow us to accurately achieve target goals within 5 mm. Finally, we have created a computer simulation illustrating the impact of limb positioning when determining limb-length and offset measurements.

Materials and Methods

Cohort

A cohort of 369 consecutive THA cases collected for a previous study [19] was examined in the present study. To simplify the process of determining target limb length and offset, only patients undergoing primary THA for unilateral hip osteoarthritis (OA) were included. Exclusion criteria were contralateral hip pathology or THA. One hundred and two patients met these criteria. The study was approved by the Institutional Review Board.

Limb-Length and Offset Calculations

Limb length was measured as described in previous studies [22]. First, a horizontal line was made at the level of the tear drops. Limb length was measured from this horizontal line to the level of the center of the lesser trochanter bilaterally. A spot was chosen on the lesser trochanter that appeared equivalent bilaterally. Offset was measured from the level of the predicted neck cut to the ischium (Fig. 1). Patient positioning was considered critical to obtaining accurate measurements. Measurements will change with flexion, abduction, adduction, internal rotation, and external rotation of the hip. Video 1 was created using anatomic models to illustrate these points. Figure 2 illustrates case examples of these effects.

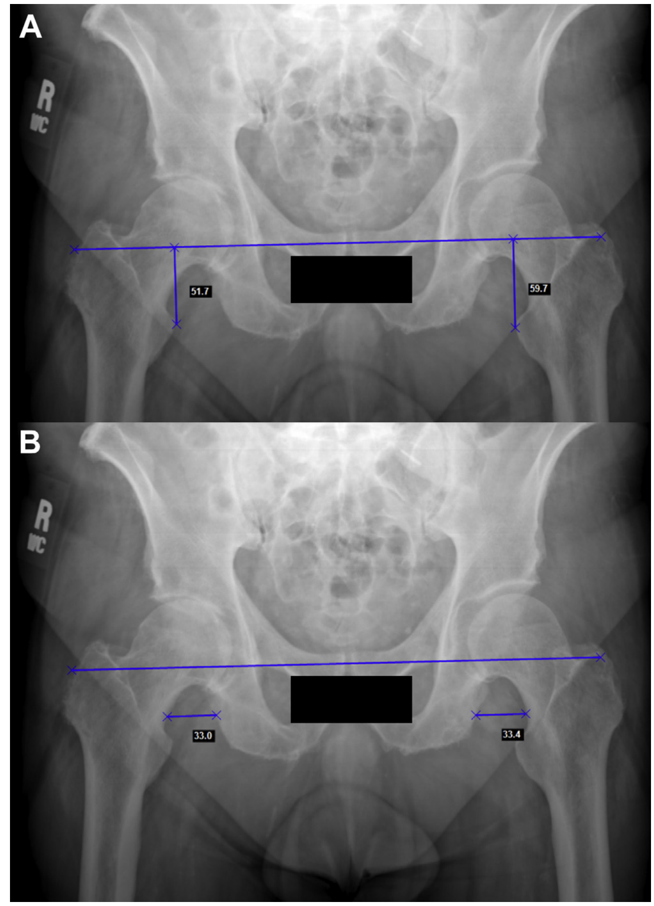

Fig. 1. Steps for measuring limb length and offset. First, it is essential to obtain an anterior-posterior (AP) pelvic radiograph in neutral rotation using the following criteria: the center of the sacrum should be aligned with the center of the pubic symphysis and the pelvic tilt should not differ significantly from the patient's standing AP radiograph. Both femora should rest in comparable degrees of rotation indicated by similar lesser trochanteric profiles. Both lower extremities should show comparable abduction and should rest in the same degree of flexion. A horizontal line is then drawn connecting the lowermost edges of both tear drops. For limb length, a point on the lesser trochanter that is equivalent bilaterally is chosen and connected perpendicularly to the horizontal (Fig. 1A). To determine offset, a point on each femoral neck at about the level of the anticipated neck cut is then chosen. A line is drawn from this point on the neck, parallel to the inter-teardrop line to the border of the ischium (Fig. 1B).

Algorithm for Determining Target Limb Length and Offset

Target limb length was determined based on the amount of joint disease and patient perception of limb-length differences. Multiple studies have shown that the articular cartilage of the femoral head and acetabulum ranges between 1 and 2 mm [23–26]. Therefore, if there is partial joint spacer narrowing, the limb has likely shortened between 2 and 3 mm. If there is complete joint space narrowing, then the limb has likely shortened between 4 and 5 mm. Determining limb shortening based on bone loss depends on the quantity of bone lost. Researchers have shown the thickness of subchondral bone to be less than 1 mm [27]. Therefore with either femoral or acetabular subchondral bone loss, the limb likely shortened between 5 and 6 mm, and, with both femoral and acetabular bone loss, the limb likely shortened by greater than 6 mm. For the purposes of the present study, the severity of OA was classified into mild joint space narrowing, complete joint space narrowing without bone erosion, femoral or acetabular bone loss, and combined femoral and acetabular bone loss. Patients with more severe OA or greater structural loss were assigned higher target limb lengthening. Target

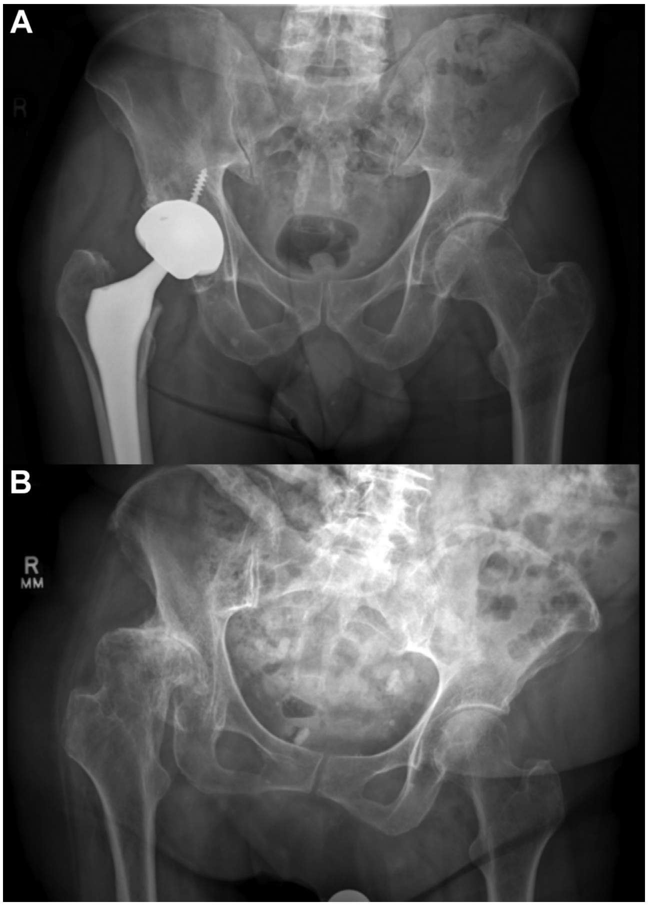

Fig. 2. (A) The effects of adduction and internal rotation on offset on the right hip. This creates a sense of reduced offset compared to the left hip. (B) The effects of pelvic tilt on limb length and offset by decreasing offset and limb length on the hip that is elevated and causing an opposite effect on the hip that is rotated down.

limb lengthening was 2-3 mm for mild joint space narrowing, 4-5 mm for complete joint space narrowing, 5-6 mm for complete narrowing with femoral head flattening or acetabular bone erosion, and 6 mm or greater for erosion of both femoral head and acetabulum (Fig. 3). Offset of the normal, nonoperative limb was chosen as the target offset in all cases. Intraoperatively, priority was given to limb length and stem canal fit over offset (if necessary) when choosing stem size. Consequently, in some cases, the final offset was allowed to remain asymmetric with a difference of greater than 5 mm due to limitations in stem design.

Surgical Steps

All THAs were performed by the senior author (B.L.P.) using an iliotibial band sparing superoposterior approach [28] in the lateral decubitus position.

1. All patients obtain a preoperative anteroposterior (AP) weight-bearing pelvic radiograph with 25-mm marker for magnification scale. This is used to determine target limb length and offset as described above, as well as targets for component size and positioning.
2. During patient positioning, the nonoperative limb is secured in neutral extension and is allowed to rest in unadjusted natural rotation (Fig. 4). The pelvis is secured using a pegboard with radiolucent pegs.
3. A femoral broach equal to or 1 size smaller than templated size is placed at a depth determined by preop templating.
4. The acetabulum is reamed and the actual cup is inserted with a trial liner.
5. Head and neck trial sizes are estimated based on preoperative templating for limb length and offset, as well as tissue tension and relative knee height compared to opposite knee height (palpated through drape).
6. The hip is reduced and range of motion/impingement testing is carried out to determine the stability of the joint. The hip is put through a full range of motion with a finger over the femoral head in order to identify subluxation or frank dislocation resulting from impingement. We first test for posterior stability or anterior impingement. This includes maximum flexion with neutral abduction-adduction and rotation (ie, bringing the thigh to the chest). The hip is then tested at 60° flexion, 30° adduction, and 80°of internal rotation. We then test for anterior stability or posterior impingement. The limb is brought to maximal extension, external rotation, and adduction while assessing the proximity of the neck to the acetabular rim or to posterior osteophyte. Pressure is then applied to the posterior neck as the final part of the test for anterior instability.
7. Components are changed as deemed necessary to achieve appropriate tensioning and stability of the hip.
8. Intraoperative imaging: During the above steps the portable X-ray unit and the flat panel detector are positioned. All radiographs are taken in AP orientation using a digital flat panel detector and a portable DR processing system that immediately collects the images within the software program (Radlink, El Segundo, CA). Appropriate positioning for DR is as follows (Fig. 4):
   a. The bed is tilted until the pelvis is in neutral rotation.
   b. The operative limb is brought to 0° flexion/extension.
   c. The operative limb is brought to 0° abduction/adduction by placing 1-2 padded supports between the knees.
   d. The operative hip is rotated to neutral by placing a padded Mayo stand under the ankle.
9. The first radiograph is examined for appropriate positioning. In almost all cases, small positioning adjustments are made until the image resembles positioning in the preoperative film (ie, reference radiograph). Additionally, trajectory of the X-ray beam can be adjusted until pelvic inlet/outlet orientation matches the preoperative film. The entire process takes approximately 1 minute.
10. The imaging software is then used to measure acetabular orientation as described previously [19], as well as limb length and offset as described above. Canal fit and orientation of the femoral stem are also assessed. Canal fit is assessed based on the size of the stem relative to the inner cortex of the proximal femur. Ideally, the stem is sized so that the canal of the proximal femur is completely filled with the femoral stem. The orientation of the femoral stem in the coronal plane is assessed for varus/valgus position. Ideally, the stem is placed neutral but if adequate fill was felt to be present, slight varus was accepted.
11. Modifications to implant position and sizing are then made in order to achieve the target goals. After each change, the hip is again put through a full range of motion with impingement testing.
12. If neck/cup impingement is identified and limb length and offset are at the upper limits of acceptance, then cup version is adjusted. These cup adjustments in the presence of radiographic confirmation of target limb length and offset are chosen rather than adding length using longer heads.
13. Final radiographs are obtained with all implants in place prior to closure.

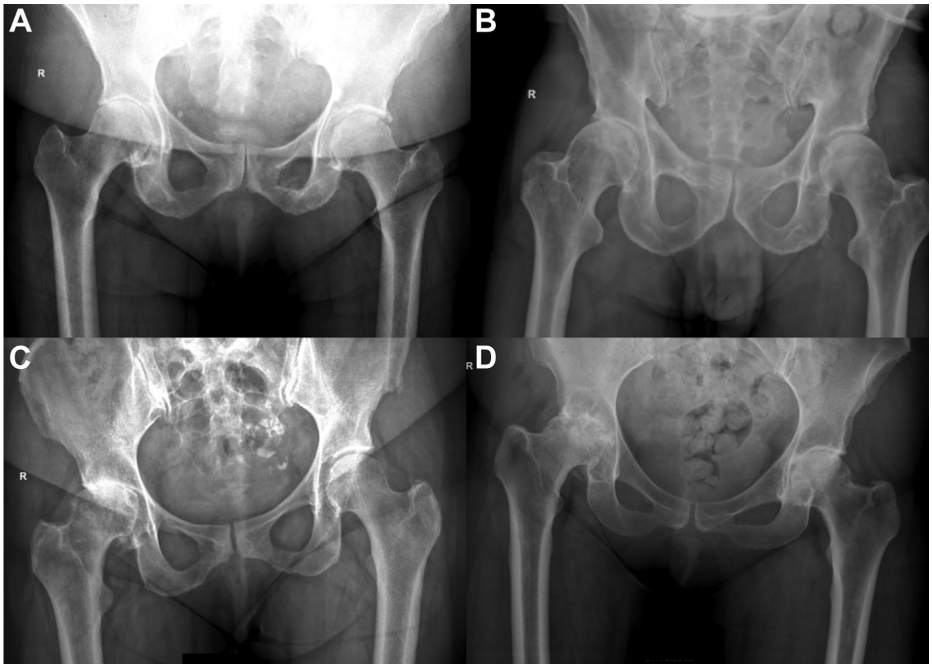

Fig. 3. Grading of arthritis severity for target limb lengthening. (A) Mild joint space narrowing is targeted for 2-3 mm lengthening. (B) Complete joint space narrowing is targeted for 4-5 mm lengthening. (C) Femoral head flattening or acetabular bone erosion is targeted for 5-6 mm lengthening. (D) Erosion of the femoral head and acetabular is targeted for 6 mm or greater lengthening.

Postoperative Assessment

All patients underwent standard weight-bearing AP postoperative radiographs at 2-3 weeks. Radiographs were measured to determine postoperative limb-length and offset differences compared to preoperative measurements. Magnification was scaled off of known femoral head implant size. Data were also collected on limb-length perception, dislocation, and revision surgery. The Hip disability and Osteoarthritis Outcome Score for Joint Replacement (HOOS JR) was collected on long-term follow-up [29].

Statistical Analysis

Limb-length and offset differences were measured preoperatively, intraoperatively, and postoperatively for all patients by 2 observers. Postoperative limb length and offset were compared to

Fig. 4. Intraoperative positioning. (A, B) Positioning of the patient in the lateral decubitus position. (C, D) Position of the hip during intraoperative imaging. The hip is positioned in zero extension by placing the ankle over a bump on a posterior mayo stand. An anterior mayo stand is placed to prevent the hip from flexing. The hip is positioned in neutral rotation by elevating the posterior mayo stand accordingly. The hip is positioned in zero abduction/adduction by placing a bump under the thigh.

preoperative measurements, intraoperative measurements, and target goals. A *t*-test was used to compare differences between intraoperative and postoperative measurements. Interobserver agreement was assessed by calculating Pearson correlation coefficients. This was applied to final intraoperative and postoperative measurements for observers 1 and 2. SPSS software (IBM v24) was used to perform statistical analysis. Statistical significance was set as $P < .05$.

Results

One hundred and two patients are included in the present study. All patients underwent a primary THA for unilateral hip OA with a normal contralateral hip. Forty-two patients were male and 60 were female. Average (standard deviation) body mass index was 28.2 (5.8) and age was 66.0 (11.0).

Postoperative limb-length measurements were within 5 mm of the target goal in 100% of patients (mean difference 2.1 mm, range 0-8.7). All patients were either maintained at their preoperative limb length or lengthened slightly. Of note, targets did not always require radiographic measurements equal to the opposite side, but were set based on assumption of the amount of preoperative shortening. 98.0% of patients were within 5 mm of the contralateral limb postoperatively. Basing the target range on the criteria above resulted in 2.0% (N = 2) of patients with greater than 5 mm postoperative limb-length differences from the contralateral side (6.7 and 8.7 mm, respectively). However, neither of these patients had complaints of leg-length discrepancy. Furthermore, the patient 8.7 mm longer on the operative side was 5.8 mm longer on the operative side preoperatively. There were no significant differences between intraoperative and postoperative measurements of limb length ($P = .261$) and there was excellent interobserver agreement with a Pearson's correlation coefficient between observer 1 and 2 of 0.95 for limb length.

Postoperative offset measurements were within 5 mm of the target goal (equal to the contralateral side) in 97.1% of patients (mean difference 2.8 mm, range 0-14.7). The remaining 2.9% (N = 3) of patients were knowingly left greater than 5 mm (7.5, 13.0, and 14.7 mm, respectively) higher than target offset due to prioritization of limb length and fit of the femoral stem. However, none of these patients had complaints of perceived discrepancy or pain. There were no significant differences between intraoperative and postoperative measurements of offset ($P = .747$) and there was excellent interobserver agreement with a Pearson's correlation coefficient between observer 1 and 2 of 0.93 for offset.

All patients were followed for a minimum of 2 years. At 2-year follow-up, there were no complaints of perceived limb-length discrepancy, dislocations, reoperations, or clinically significant trochanteric bursitis. About 63.7% (65 patients) had further follow-up at 4.9-6.1 years. At this final follow-up there were 0 dislocations. Two patients (3.0%) felt long on the operative side but did not feel the need to use a contralateral shoe lift. In addition, both these patients' measured limb lengths were within 5 mm of the contralateral side. As noted above, the 2 patients who measured more than 5 mm limb-length differences from the contralateral side (6.7 and 8.7 mm, respectively) did not complain of perceived leg-length inequality at any point. Six patients (5.9%) had undergone contralateral THA at the time of last follow up. Average HOOS JR score was 95.78.

Discussion

The purpose of the present study is to introduce a method for choosing and achieving limb length and offset targets in THA. Our technique for determining limb-length goals is based on the severity of OA as well as patient perceived preoperative limb-length differences. All limbs are shortened by the disease process but we almost never know a patient's natural limb-length difference prior to the development of OA. Epidemiological studies have shown that more than 90% of the population has limb-length differences which average approximately 5.2 mm [5]. Therefore, individuals with similar severity of OA can have different radiographic limb-length measurements. There are also a significant percentage of patients who preoperatively measure longer than the uninvolved side (17% in the present study). On this basis, our goal is to restore premorbid limb length based on the estimate of shortening caused by disease rather than defaulting to limb-length equalization compared to the normal side. One patient in particular demonstrated this point. Preoperative analysis showed the patient's operative limb started 5.8 mm longer (compared to the nonoperative limb) even with mild joint space narrowing secondary to OA. Based on this disease severity, the target goal was to lengthen by 2-3 mm, ultimately resulting in a limb-length discrepancy of 8.7 mm as measured on postoperative radiographs. However, this patient clinically felt symmetric as the premorbid length had been restored.

After determining initial limb-length differences based on erosion caused by hip disease, all patients were either lengthened or left unchanged. In a patient with OA and a normal opposite side, it is rarely a consideration to shorten the operative limb as this can lead to instability. The critical determination is how much to lengthen for each person. Using our method, patients with severe joint narrowing and/or with erosive bone loss were lengthened more than those with incomplete or complete cartilage loss but with no bone erosion.

Our target offset begins with attempting to restore offset that is equal to the contralateral, normal side. The ability to reach this target can be limited, however, based on implant design. Changing neck/head length results in changes to both limb length and offset. Using a smaller femoral component and allowing it to rest deeper into the upper femur can allow increased offset with no increase in limb length. Restoring appropriate limb length is given priority and asymmetric offset outside a ±5-mm range is accepted as necessary to maintain that goal. In the authors' experience and in this cohort, asymmetric offset in the ranges described appear to have no adverse clinical consequences.

Using DR in the operating room is not novel [19,30,31]. DR, or fluoroscopy, has been used routinely for many years in anterior THA. Use in the lateral decubitus position is less common. We have described our methodology especially focusing on patient positioning as the importance of this can be overlooked or underappreciated. Patient position and table position are modified as described above until an AP pelvis radiograph, comparable to the preop, is obtained, with equal abduction/adduction, flexion/extension, and rotation. Obtaining these standard radiographs is essential to the accuracy of THA just as a perfect mortise ankle, perfect lateral elbow, and perfect Grashey shoulder radiographs are important for other surgeries in orthopedics. It is important to emphasize that images with incorrect limb or pelvis position were never used for making measurements in the present study.

In an effort to illustrate the importance of proper positioning, we created a three-dimensional (3D) model to illustrate the direct impact of limb position on limb-length and offset measurements. First, 3D models of the pelvis, left femur, and right femur were downloaded from BodyParts3D, a human anatomy project funded by The Integrated Database Project, Ministry of Education, Culture, Sports, Science and Technology of Japan [32,33]. This is a publicly available database for 3D anatomical models [32,33]. The models were downloaded in Wavefront format (.obj) and opened with the 3D modeling program SketchUp Make (Trimble, Sunnyvale, CA, v2016). This software is used to capture and display parallel projection images of the 3D model of the pelvis and hip joints. For the purposes of the present study, frontal parallel projection images were used. The right 3D femoral segment was then moved relative to the 3D pelvic segment around the center of rotation of the right femoral head using the rotation tool provided by the software. The femur was rotated in the 3 planes of motion: internal/external rotation about the central axis of the femoral shaft, flexion/extension, and abduction/adduction. The femur was rotated from 30° internal rotation to 30° external rotation in the transverse plane, 20° abduction to 20° adduction in the coronal plane, and 45° flexion to 45° extension in the sagittal plane. The movement within each plane was performed independently. At various points throughout these movements, the limb length and offset were measured using the measurement tool. The movements and corresponding measurements were then compiled into a 3D video illustrating the effects of positioning on limb-length and offset measurements (Video 1). This technique was similar to a previously published model on the effects of pelvic position on acetabular cup measurements [19]. We found that there were associated changes in the linear measurements of limb length and/or offset with rotation of the femur in every plane. The exact relationship between the movement of the femur and change in limb length and/or offset are beyond the scope of the present study. Future studies should attempt to determine a mathematical equation between the rotation of the femur in the 3 planes of motion and the linear changes in limb length and offset.

The present study introduces 2 separate concepts. First is a method of determining limb length that differs slightly from standard. Normally, the standard target in patients with unilateral hip OA is equalization of limb lengths [34,35]. Several extensive literature reviews describe the technique and guides for achieving target limb length but generally the target has been equalization [2,35]. The present study uses severity of arthritis and patient perception to determine targets with excellent long-term outcomes of function and patient perception of limb length. Nevertheless, future large prospective studies are needed to determine if this method is superior. In addition, the present study introduces a method for achieving target limb length using intraoperative digital radiographs. The literature review identifies many studies using different techniques for intraoperative assessment of limb length using landmarks and other devices, but there is very little describing the use of intraoperative radiographs [2,35]. There are few studies that describe intraoperative radiographs. One study by Ezzet and McCauley [31] showed that intraoperative radiographs allowed them to achieve satisfactory limb length in 86% of cases and femoral alignment in 99.5% of cases, and that any outliers were known and accepted as such at the time of surgery. There is, however, no clear discussion about standardized patient positioning protocol. The results of the present study show that using intraoperative DR allowed us to keep 100% of our patients within 5 mm of our preoperative target limb-length goals. This is critical as previous studies show that deviations of greater than 5 mm are associated with worse functional outcomes [16–18]. At final follow-up functional outcomes were high with a HOOS JR of 95.78. We believe that DR is a simple, inexpensive, and rapid tool that is invaluable to the surgeon and should be used in all THA procedures.

There were several limitations to the present study. First, the study presents a unique method of determining limb-length targets using the quantity of cartilage and bone loss as well as patient perception. It is critical to state that it is impossible to know if this theory is correct without pre-arthritic radiographs of each patient. Nevertheless, we believe that this is a viable method of calculating target limb length instead of targeting the limb length of the uninvolved extremity. The present study was also limited to patients with unilateral hip OA for the purpose of simplifying determinants of limb length and offset. Understandably, patients with fixed pelvic obliquity, gross deformity, bilateral OA, contralateral THA, and revisions make determination of correct limb length and offset more complex. However, our principles remain the same in these cases as much as hip stability and implant constraints allow. An additional limitation is that the study compares one cohort of patients. Further studies should consider adding a comparative group using traditional limb-length and offset targets or a group in which intraoperative DR was not used. In addition, consideration was not given to spine disease and fixed pelvic obliquity, the effects of which can impact limb length. Another important limitation of this study is our ability to determine the precise effect of poor limb or pelvic positioning on limb-length and offset measurements. Images with incorrect limb or pelvis position were never used for making measurements in the present study and therefore we are unable to calculate the exact effect of poor positioning on measurements. In an attempt to illustrate these effects, however, we created the 3D simulation (Video 1).

In conclusion, this study presents a novel method of determining target limb length and offset in THA that focuses on disease severity and patient perception. Furthermore, we present a method of obtaining accurate intraoperative radiographs and illustrate the importance of limb and pelvic position on these measurements. Finally, this study has shown that, in a homogenous cohort of patients with unilateral hip OA, intraoperative DR allows accurate achievement of target limb-length and offset goals as well as excellent functional outcomes.

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