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Evaluation of a New Leg Length Measurement Algorithm in Hip Arthroplasty

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Leg length inequality after hip arthroplasty is a major source of patient dissatisfaction and dysfunction. Despite numerous reported methods to intraoperatively determine leg length change, it remains a challenge. We developed a reliable and reproducible method to measure leg length change using surgical navigation. The method measures the change in position of the femur relative to the pelvis and the pelvic coordinate system without the need to establish a femoral coordinate system. We replaced 112 hips using the new leg length measurement algorithm. Leg length change measured at surgery was compared with leg length change as measured on magnification-corrected pre- and postoperative radiographs. Compared with radiographically measured leg length change, the leg length changes measured intraoperatively had a mean difference of −0.5 ± 1.77 mm (range, −5–3.9 mm). We found no difference between radiographic data and navigation data. Leg length change measured using surgical navigation, measuring the change in position of the femur relative to the pelvic coordinate system, without establishing a femoral coordinate system is easy and reliable.

Level of Evidence: Level IV, therapeutic study. See the Guidelines for Authors for a complete description of levels of evidence.

Leg length inequality is a major source of dysfunction and dissatisfaction after THA.HA[4,6,8,17] In symptomatic patients, a substantial difference in leg length causes gait asymmetry and may exacerbate hip and back pain. A substantial postoperative leg length discrepancy may lead to revision surgery.[14] Accurately measuring changes in leg length during surgery is difficult. Small changes in adduction-abduction, flexion-extension, or internal-external rotation between pre- and postreconstruction measurements can lead to substantial errors in assessing leg length changes during surgery and can lead the surgeon to make poor decisions based on this inaccurate information. Physically measuring leg length change using landmarks and a ruler becomes even more difficult as incisions become smaller.

Various methods of measuring leg length change during surgery include comparing the dimensions of the resected bone with the dimensions replaced by the prosthesis,[23,24] comparison of surgery with the detailed preoperative surgical plan,[10] and the use of mechanical jigs and tape measures.[15,18] However, these methods are susceptible to error and mean postoperative leg length was reported within a range of 1 mm to 9 mm.[3,8,10,15,24] Two prior computer-assisted methods[17,22] of measuring leg length change during surgery have disadvantages. The first method[17] uses only a pelvic reference frame and digitizes a landmark on the femur before and after reconstruction. Although easy, the measurements can be just as inaccurate as mechanical methods because any difference in positioning of the leg between the pre- and postreconstruction assessments will lead to large errors. The second method[22] is to establish coordinate systems for both the pelvis and the femur to allow for more accurate measurement. However, there are two problems with this method. First, establishing a femoral coordinate system involves calculating the center of the femoral head, which is difficult and often impossible as a result of the asphericity of the arthritic hip joint. Second, entering the additional data required to properly establish a femoral coordinate system, including data points around the knee, is time-consuming.

To address these problems, we developed a method in which the femoral reference frame is tracked in the pelvic coordinate system before and after reconstruction. This method ensures the leg is placed in the exact same orientation relative to the pelvis before and after reconstruction and eliminates the need to calculate the center of the hip or

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to establish a femoral coordinate system. This method may potentially be applied regardless of whether optical or electromagnetic tracking is used and whether the navigation is image-free or image-based. We report the reliability and reproducibility of this simplified method of measuring leg length during THA.

MATERIALS AND METHODS

We performed 112 THAs in 107 patients through a tissue-preserving superior capsulotomy[11] with the assistance of computed tomography-based surgical navigation. The new leg length measurement algorithm was used in all the procedures. Sixty-one procedures were performed in female patients and 51 in male patients (Table 1). Mean patient age was 56.3 ± 12.7 years (range, 19.1–85.3 years). There were 50 left and 62 right hips operated on. All patients consented to the procedure according to Institutional Review Board protocol.

We assessed preoperative leg length discrepancy both physically by measuring from the anterior-superior iliac spines to the medial malleoli and radiographically on the anteroposterior pelvis radiograph by using the interteardrop line as a horizontal reference and measuring the distances from the most proximal point of the lesser trochanter to this line (Fig 1). This assessment of the preoperative leg length discrepancy was incorporated into the preoperative goal of leg length change to achieve during surgery. During surgery, pelvic and femoral skeletal reference frames were applied before excision of the femoral head, and the leg was initially placed in a clinically neutral and straight position. The position of the femoral reference frame relative to the pelvic reference frame was stored (BrainLAB Prototype CT based Hip Build 274, Heimstetten, Germany). After excision of the femoral head, the pelvic coordinate system was established by registering the pelvic anatomic landmarks relative to the three-dimensional computed tomography data set. The THA procedure was then performed as usual.[11,12] After reconstruction, the system guided the surgeon to return the leg into the exact same orientation it was in before reconstruction. With the leg in the same orientation, any changes in position of the femoral reference frame relative to the pelvic reference frame could be resolved in linear translations allowing calculation of change in leg length. The change in leg length of the final reconstruction was calculated and stored three times for reproducibility. The mean of these three calculations was used as the leg length change measured at surgery (Fig 2).

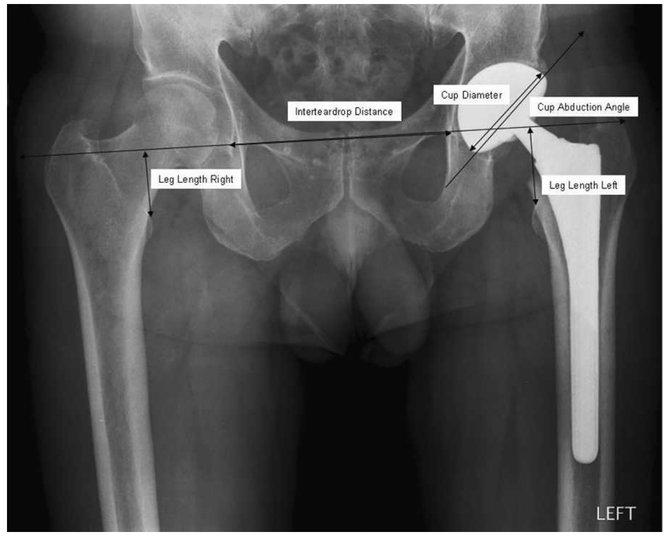

Fig 1. The interteardrop line serves as a horizontal reference on pre- and postoperative radiographs. The measurement method on a postoperative radiograph is shown.

TABLE 1. Demographic Data of Study Group

Parameter	Results
Total number of hips	112
Total number of patients	107
Gender	
Men	51 (45.5%)
Women	61 (54.5%)
Height (m)	1.72 ± 0.1* (1.47–1.93)
Weight (kg)	81.3 ± 17* (43.2–149.5)
Body mass index (kg/m^2)	27.5 ± 4.9* (17.5–46.3)
Age (years)	56.3 ± 12.7* (19.1–85.3)
Side	
Left	50 (44.6%)
Right	62 (55.4%)
Diagnosis	
Osteoarthritis	80 (71.4%)
Posttraumatic osteoarthritis	4 (3.6%)
Osteonecrosis	6 (5.4%)
Dysplasia	14 (12.5%)
Slipped capital femoral epiphysis	2 (1.8%)
LCDP	5 (4.5%)
Rheumatoid arthritis	1 (0.9%)
Implant type	
Ceramic-ceramic	98 (87.5%)
Co-Cr polyethylene	10 (9%)

*Mean ± standard deviation (range); LCDP = Legg Calve Perthes disease

The measured change in leg length using computer assistance in surgery was then compared with the change in leg length measured radiographically. Leg length change was measured radiographically (TME) by measuring change between the leg length difference on the postoperative radiographs and the leg length difference on the preoperative radiographs. This was accomplished by drawing a horizontal line between the teardrops and then measuring down orthogonally to the most proximal points on the lesser trochanters (Fig 1). The postoperative radiograph magnification was normalized using the known diameter of the acetabular component. The preoperative radiograph magnification was normalized by comparing the interteardrop distance on the preoperative and postoperative radiographs when magnification was known. The changes in leg length discrepancy between both legs allowed for calculation of the actual change in length on the operated side. These values were subsequently

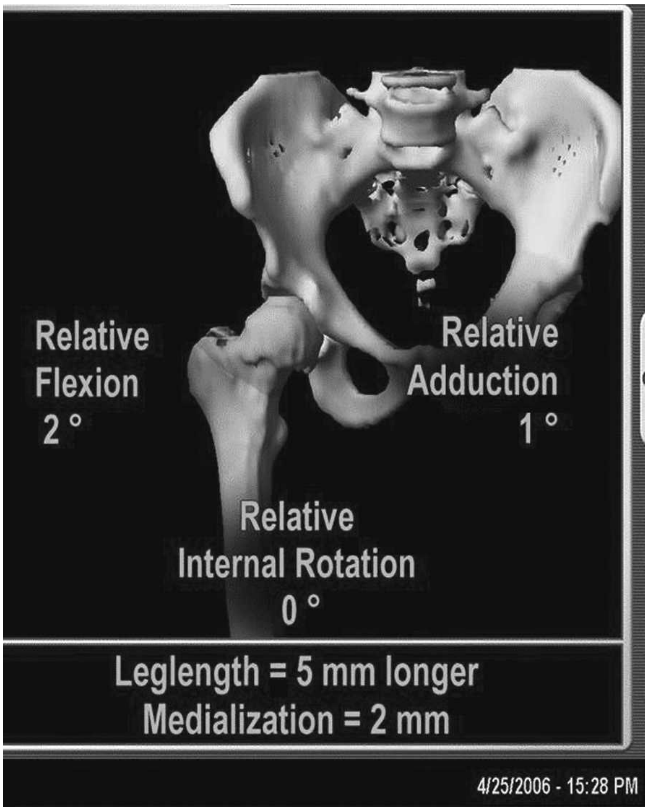

Fig 2. The intraoperative leg length measurement obtained with the navigation system is shown. As a result of elimination of positional errors, the only changes measured are linear changes.

compared with the values measured by the navigation system during surgery.

To determine whether the use of the algorithm would affect surgical time, we compared the operative time in the 112 consecutive cases using the leg length algorithm with 70 consecutive cases using the exact same surgical technique and computer-assisted cup navigation but without leg length measurement.[11]

We analyzed the difference between leg length change measured radiographically and calculated by the navigation system using the independent t-test after normal distribution had been established. We presumed a probability value of $p < 0.05$ would be significant.

RESULTS

We found no difference between the results of the radiographically measured change compared with the calculation of the navigation system. The mean registration accuracy was 2 ± 0.6 mm (range, 0.7–3 mm) (Table 2). The preoperative leg length discrepancy measured on the radiographs was −5.2 ± 5.7 mm (range, −29.8–9.6 mm). Measured on postoperative radiographs, the mean leg length change was 6.18 ± 4.33 mm (range, −5–20 mm). This resulted in a mean remaining postoperative leg length difference of 1 ± 5.2 mm (range, −20–15 mm). The mean leg length change calculated intraoperatively with the navigation system was 6.68 ± 4.2 mm (range, −2–22 mm). Comparing the difference between the computer-assisted leg length change measurement and the radiographic leg length change measurement, the mean difference between the two was −0.5 ± 1.77 mm (range, −5–3.9 mm).

The surgical time for the procedures performed with the addition of the leg length algorithm was similar to that for the procedures performed without the use of the leg length algorithm (136.9 ± 22.2 minutes; range, 62–202 minutes versus 139.4 ± 18.6 minutes; range, 105–199 minutes, respectively). The mean incision length was 7.8 ± 1 cm (range, 5.5–12 cm).

TABLE 2. Leg Length Measurements: Radiographic versus Navigated Methods

Parameter	Results
Leg length change measured radiographically (mm)	6.18 ± 4.33 (−5–20)
Leg length change measured using intraoperative navigation (mm)	6.68 ± 4.2 (−2–22)
Difference between leg length change and intraoperative navigation (mm)	−0.5 ± 1.77 (−5–3.9) p = 0.382
Registration accuracy	2 ± 0.6 (0.7–3)

Mean ± standard deviation (range)

DISCUSSION

Our goal was to investigate reliability and reproducibility of a new simplified computer-assisted measurement algorithm in hip arthroplasty in which the femur is tracked in the pelvic coordinate system, eliminating the need to define the center of rotation or to establish a femoral coordinate system. We hypothesized this method would be easy to use and would demonstrate leg length changes similar to those measured on pre- and postoperative radiographs. Our data demonstrate this method of measuring leg length change during surgery is efficient, reliable, and reproducible.

There are, however, several limitations of this study. First, measurements from plain radiographs have limitations.[16] These limitations include variation in positioning of the pelvis relative to the plane of the film and centering of the xray beam.[20,21] We used the acetabular component to correct for magnification using anteroposterior pelvis radiographs, but the xray beams are not perpendicular to the cup on an anteroposterior pelvis radiograph in which the source of the beam is centered on the midline of the pelvis. The divergence of the xray beams can reduce the accuracy of the magnification correction. Furthermore, several authors[2,5,7,13,19,21,25] have described the influence of pelvic tilt and rotation on the reliability of measurements performed on conventional radiographs. Different solutions to this issue have been described in the literature. Jaramaz et al[7] used a combination of preoperative computed tomography and postoperative plain radiographs to correct for pelvic malposition. Tannast et al[21] described a software algorithm to correct for tilt and rotation. Yet, these studies primarily addressed the effect of pelvic malposition on angular measurements of component abduction or inclination and do not specifically address the effect of pelvic tilt on linear measurements. Our study attempts to reduce the effect of pelvic tilt on linear measurements by measuring the difference in length between the two hips on each radiograph. We did this because although change in pelvic tilt between radiographs can substantially affect linear measurements, it is likely to affect measurements of both hips similarly. Thus, leg length difference between the two hips was measured and the change in leg length difference between the two sides before and after surgery was measured because this method is likely to greatly reduce the influence of variation of pelvic tilt on the linear measurements used in this study. Second, the method and accuracy of determining the pelvic coordinate system[1,9] may also be a source of error. Fortunately, even if the orientation of the pelvic coordinate system was achieved with an error of 5°, this error would only affect leg length measurement by 1%. With a change in leg length of 5 mm, the system error resulting from this effect would only be 0.05 mm, so this potential error does not appear important. Third, although our study demonstrates the method is reliable and reproducible, the study design does not allow for determination of the method's true accuracy because we do not have an exact method of knowing the actual change in length that occurred as a result of the surgery.

Comparing our results with the literature, our method was reliable and more reproducible than other studies of measuring leg length change without navigation. Comparing intraoperative measurements with postoperative radiographs, Woolson et al[24] had similar results reporting on a mean postoperative difference of 1 mm. Ranawat et al[15] reported a mean difference of 1.9 mm, Konyves and Banister[8] reported a mean of 9 mm, and Matsuda et al,[10] comparing a new nonnavigated method against a historical control group, reported mean differences of 2 mm and 4 mm, respectively. Bose,[3] using a carpenter's level as a tool in a study group, against a control group without a measurement device, reported mean differences of 3.4 mm and 8.8 mm, respectively.

Our simplified method of measuring leg length changes during surgery appears reliable and reproducible. It eliminates the need to calculate the center of rotation of the arthritic hip joint, which is often not possible to do or might lead to measurement errors as a result of the decreased reliability of the estimated center of rotation in a deformed arthritic hip. The method also eliminates the need to establish a femoral coordinate system. The method may be applied to all types of hip surgery, whether joint-preserving surgery or prosthetic arthroplasty, and can potentially be applied regardless of the method used to develop the pelvic coordinate system, whether image-based or image-free. We believe the reliability of the method is especially important because the average incision length was less than 8 cm and traditional physical methods of measuring leg length change become progressively difficult as incision length decreases. Thus, reliable computer-assisted methods of measuring leg length may be even more important to allow the benefits of accelerated recovery with tissue-preserving, less invasive arthroplasty techniques[12] without creating larger difficulties with management of leg length change.

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References

1. Amiot LP, Poulin F. Computed tomography-based navigation for hip, knee, and spine surgery. *Clin Orthop Relat Res*. 2004;421: 77–86.
2. Anda S, Svenningsen S, Grontvedt T, Benum P. Pelvic inclination and spatial orientation of the acetabulum: a radiographic, computed tomographic and clinical investigation. *Acta Radiol*. 1990;31: 389–394.
3. Bose WJ. Accurate limb-length equalization during total hip arthroplasty. *Orthopedics*. 2000;23:433–436.
4. Cuckler JM. Limb length and stability in total hip replacement. *Orthopedics*. 2005;28:951–953.
5. Goergen TG, Resnick D. Evaluation of acetabular anteversion following total hip arthroplasty: necessity of proper centreing. *Br J Radiol*. 1975;48:259–260.
6. Gurney B, Mermier C, Robergs R, Gibson A, Rivero D. Effects of limb-length discrepancy on gait economy and lower-extremity muscle activity in older adults. *J Bone Joint Surg Am*. 2001;83: 907–915.
7. Jaramaz B, DiGioia AM III, Blackwell M, Nikou C. Computer assisted measurement of cup placement in total hip replacement. *Clin Orthop Relat Res*. 1998;354:70–81.
8. Konyves A, Bannister GC. The importance of leg length discrepancy after total hip arthroplasty. *J Bone Joint Surg Br*. 2005;87: 155–157.
9. Langlotz F, Nolte LP, Tannast M. The foundations of computer assisted surgery. [in German]. *Orthopade*. 2006;35:1032–1037.
10. Matsuda K, Nakamura S, Matsushita T. A simple method to minimize limb-length discrepancy after hip arthroplasty. *Acta Orthop.* 2006;77:375–379.
11. Murphy SB. Tissue-preserving, minimally invasive total hip arthroplasty using a superior capsulotomy. In: Hozack W, ed. *Minimally Invasive Total Hip and Knee Arthroplasty*. Heidelberg, Germany: Springer Verlag; 2004:5.
12. Murphy SB, Ecker TM, Tannast M. THA performed using conven-

tional and navigated tissue-preserving techniques. *Clin Orthop Relat Res*. 2006;453:160–167.
13. Murray DW. The definition and measurement of acetabular orientation. *J Bone Joint Surg Br*. 1993;75:228–232.
14. Parvizi J, Sharkey PF, Bissett GA, Rothman RH, Hozack WJ. Surgical treatment of limb-length discrepancy following total hip arthroplasty. *J Bone Joint Surg Am*. 2003;85:2310–2317.
15. Ranawat CS, Rao RR, Rodriguez JA, Bhende HS. Correction of limb-length inequality during total hip arthroplasty. *J Arthroplasty*. 2001;16:715–720.
16. Robb JE, Rymaszewski LA, Bentley HB, Donnan PT. Reliability of the acetabular teardrop as a landmark. *Surg Radiol Anat*. 1991;13:181–185.
17. Sarin VK, Pratt WR, Bradley GW. Accurate femur repositioning is critical during intraoperative total hip arthroplasty length and offset assessment. *J Arthroplasty*. 2005;20:887–891.
18. Shiramizu K, Naito M, Shitama T, Nakamura Y, Shitama H. L-shaped caliper for limb length measurement during total hip arthroplasty. *J Bone Joint Surg Br*. 2004;86:966–969.
19. Siebenrock KA, Kalbermatten DF, Ganz R. Effect of pelvic tilt on acetabular retroversion: a study of pelves from cadavers. *Clin Orthop Relat Res*. 2003;407:241–248.
20. Tannast M, Murphy SB, Langlotz F, Anderson SE, Siebenrock KA. Estimation of pelvic tilt on anteroposterior x-rays—a comparison of six parameters. *Skeletal Radiol*. 2006;35:149–155.
21. Tannast M, Zheng G, Anderegg C, Burckhardt K, Langlotz F, Ganz R, Siebenrock KA. Tilt and rotation correction of acetabular version on pelvic radiographs. *Clin Orthop Relat Res*. 2005;438:182–190.
22. Wixson R, MacDonald M. Total hip arthroplasty through a minimal posterior approach using imageless computer-assisted hip navigation. *J. Arthroplasty* 2005;20:51–56.
23. Woolson ST. Leg length equalization during total hip replacement. *Orthopedics*. 1990;13:17–21.
24. Woolson ST, Hartford JM, Sawyer A. Results of a method of leg-length equalization for patients undergoing primary total hip replacement. *J Arthroplasty*. 1999;14:159–164.
25. Yao L, Yao J, Gold RH. Measurement of acetabular version on the axiolateral radiograph. *Clin Orthop Relat Res*. 1995;316:106–111.