Computer-assisted versus Manual Alignment in THA

A Probabilistic Approach to Range of Motion

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Abstract Dislocation remains a major complication after THA, and range of motion before impingement is important in joint stability. Variability in implant alignment affects resultant range of motion. We used a probabilistic modeling approach to assess the effects of implant alignment variability based on manual and computer-assisted surgical (CAS) techniques on resultant range of motion after THA. We implemented a contact detection algorithm within a probabilistic analysis framework. The normally distributed alignment variables (mean $\pm$ 1 standard deviation) were cup abduction (manual = $45^\circ \pm 7.6^\circ$, CAS = $45^\circ \pm 5.7^\circ$), cup anteversion (manual = $20^\circ \pm 9.6^\circ$, CAS = $20^\circ \pm 4.5^\circ$), and stem anteversion (manual and CAS = $10^\circ \pm 1.5^\circ$). The outcomes of the probabilistic analysis were range of motion distributions with 1% and 99% bounds. The upper bounds of motion for manual and CAS alignment were similar because bony impingement was the limiting factor. The lower bounds of range of motion were substantially different depending on the type

of surgical alignment; manual alignment produced a smaller range of motion in 3% to 5% of cases. CAS implant alignment produced range of motion values above minimum acceptable levels in all cases simulated.

Introduction

Dislocation remains a major complication after THA [4, 6, 19, 27, 39]. Reported dislocation rates range from 0.6% to 11% after primary THA [2, 10, 30, 34], and the rate can double after revision surgery [7, 21]. Impingement between the implants and/or bones is an important causative factor in dislocation [1, 16, 23, 26], making range of motion (ROM) an indicator of joint stability. Implant design affects ROM, but patient-specific factors such as anatomy and surgical alignment, naturally, are also critical [25]. Safe zones have been proposed for implant alignment [9, 18, 22], but even these guidelines permit reasonable variation in practice. There is also natural variability in how precisely a surgical plan can be executed [20]. Computer-assisted surgical (CAS) techniques reduce but do not eliminate this variability [13–15]. However, the effect of reduced variability on a clinical outcome such as ROM has not been fully determined.

To better understand the issue of dislocation, it is important to understand how variability in implant alignment affects ROM. Mathematical modeling has been used previously [31, 32] to compute the optimal combination of implant alignment parameters for maximum hip ROM, but patient-specific factors, such as potential bony impingement, were not considered. One recent study did consider the effect of bony impingement on hip ROM for varying orientations of cup abduction, cup anteversion, and femoral anteversion [16], and bony impingement reportedly

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preceded component impingement in 44% of the cases considered. This latter study, however, did not account for the combined effects of multiple alignment variables, the interaction of which may further limit the zone of acceptable implant function.

A probabilistic modeling approach has the potential to account for interactions in alignment parameters and to predict the likelihood of bony impingement for different levels of alignment variability (e.g., manual versus CAS). Any mathematical model can be made probabilistic by treating each input parameter as a statistical variable with a mean and standard deviation [5, 8, 36]. Outcome metrics may then be predicted for many individual trials in which the input parameters are randomly sampled from each of their respective statistical distributions. Each of the trials will result in a slightly different predicted outcome since the inputs are randomly sampled. When the results from all trials are pooled, one may also form a normal distribution for each outcome metric (for example, ROM in each rotational degree of freedom at the hip). In this way one can see how variability in the input parameters (implant alignment) leads directly to variability in outcome metrics (hip ROM).

Accordingly, we formulated a probabilistic model to compare hip ROM outcomes following THA with manual and CAS alignment. We sought to answer the following specific questions: (1) What are the upper and lower bounds of resulting hip ROM associated with normal variation in implant alignment parameters corresponding to manual and CAS surgical techniques? (2) How are the bounds of hip ROM affected by bony impingement?

Materials and Methods

We developed a probabilistic hip ROM assessment platform by combining a contact detection model [16] with NESSUS[®] probabilistic software (Southwest Research Institute, San Antonio, TX). Our probabilistic analysis included variability in the component alignment parameters and predicted the variability and bounds of resultant hip ROM.

The femoral and pelvic surface geometries for a male subject were extracted from CT scan data [28]. The slice interval was 0.7 mm in the hip and 2 mm in the diaphyseal region. The CT image three-dimensional reconstruction has a reported accuracy of 1.5 mm [29]. Implant geometry was provided by the manufacturer (Stryker, Mahwah, NJ) in the form of CAD files. The cup (Trident[®]) had an outer diameter of 56 mm with an 11.9-mm-thick press-fit liner, corresponding to a 28-mm head size. The femoral component (HipStar[™]) had a 12-mm neck diameter, 135° neck angle, and 40-mm stem offset, defined as the horizontal

distance between the center of the head and a vertical line through the center of the stem. The implant sizes and the locations of the cup relative to the pelvis and the stem relative to the femur were chosen by an experienced total hip arthroplasty surgeon. The equivalent of preoperative templating was used to select prosthetic size and initial implantation position. The goal of the reconstruction was to preserve the center of rotation of the hip and the limb length while aligning the long axis of the stem with the long axis of the intramedullary canal of the femur [16]. Before implantation, the anatomic femoral neck-shaft angle was 124° and femoral anteversion was 9°. The abduction of the anatomic acetabulum was measured at 41° and the acetabular anteversion was 8°. After implantation the prosthetic femoral head center was located 0.9 mm proximal to the natural head center. The natural offset of the femur was 4 mm less than that of the implant. Therefore, after implantation, this resulted in a 4 mm lateral displacement of the femoral shaft from its native position. The acetabular center was unchanged since the center of the acetabular cup was lined up with the center of the natural acetabulum during the simulated implantation. Consequently, the acetabular cup was slightly (approx. 1 mm) inset in the native acetabulum. Once the locations of the components were set, only the orientation of the components was changed (cup inclination, cup anteversion, and femoral stem anteversion) as prescribed by a Monte Carlo simulation [8]. The Monte Carlo simulation involved the treatment of each input parameter as a statistical distribution with a mean and standard deviation. Hip ROM was predicted for many trials in which the input parameters were randomly sampled from their respective distributions. Hip ROM predictions for all trials were then pooled and it was possible to quantify the statistical variation in hip ROM resulting from variability in the alignment parameters.

The implants were aligned nominally at 45° cup abduction, 20° cup anteversion, and 10° femoral anteversion. The global coordinate system was located at the center of the femoral head [35]. The anatomic definition of cup orientation described by Jaramaz et al. [11] was used to perturb the cup position: abduction rotation was applied first about the anterior-posterior axis and anteversion rotation was applied second about the inferior-superior axis. The contact detection model, implemented using C++ [16], determined the ROM in each degree of freedom (flexion/extension, abduction/adduction, internal/external rotation) and the type of contact that occurred (implant-implant, implant-bone, or bone-bone). Bony impingement was defined as implant-bone or bone-bone contact. To evaluate the likelihood of bony impingement and the associated reduction in ROM, analyses were performed with the implants alone (implants only) and with the implants and bone geometry combined (combined).

Probabilistic analyses were performed at two levels of alignment variability based on manual and CAS surgical techniques. Each alignment parameter was modeled as a normal distribution with the mean based on the nominal alignment. Cup alignment variability levels were based on a comparison of manual and CAS techniques [24] in which standard deviations of manual abduction and anteversion were 7.6° and 9.6° , respectively. Standard deviations of CAS alignment variables were 5.7° for cup abduction and 4.5° for cup anteversion. While variability in femoral anteversion has been reported with standard deviations of up to 11.1° [33], this variability is largely due to anatomic differences and was not considered representative of the variability in implant placement for a single patient. Femoral anteversion was therefore assigned a standard deviation of 1.5° for both manual and CAS alignment.

A 1000-trial Monte Carlo simulation was performed to predict the distribution of ROM for all three independent rotational degrees of freedom at the hip, and the likelihood of bony impingement was computed for each direction of motion. ROM distributions were described by 1%, 50%, and 99% bounds.

Results

For all degrees of freedom, ROM results exhibited narrower distributions (tighter bounds) for the CAS levels of alignment variability compared to manual (Fig. 1). When bone surfaces were excluded from the contact detection algorithm (implants only cases), the ROM results were normally distributed with the 50th percentile ROM values centrally located between upper and lower bounds of motion.

When bone surfaces were included in the contact detection algorithm (combined cases) bony impingement caused a reduction in the upper bound of ROM for all hip rotations except extension (Fig. 1). The likelihood of bony impingement after CAS compared to manual alignment was also lower for all hip motions except adduction (Table 1). The unaffected bounds of extension rotation and the low likelihood of bone contact in this degree of freedom indicate ROM was controlled by the implant design for this motion. For all other directions of motion, bony impingement limited ROM in 30% to 88% of trials simulated (Table 1). Overall, bony impingement preceded prosthetic impingement in 43.7% of conditions tested with manual implant alignment and in 39.2% of cases with CAS alignment. The effect of bony impingement was to increase the frequency of ROM values occurring at the upper bound of motion. The 50th percentile ROM values were, generally, unaffected by bone contact; the one exception was

Fig. 1A–C Graphs show ROM (1%, 50%, and 99%) for (A) flexion and extension, (B) abduction and adduction, and (C) internal and external rotation. For all degrees of freedom, ROM results exhibited narrower distributions (tighter bounds) for the CAS levels of alignment variability compared to manual. When bone surfaces were excluded from the contact detection algorithm (implants only cases), the ROM results were normally distributed with the 50th percentile ROM values centrally located between upper and lower bounds of motion. When bone surfaces were included in the contact detection algorithm (combined cases) bony impingement caused a reduction in the upper bound of ROM for all hip rotations except extension. Horizontal dotted lines indicate minimum acceptable levels of ROM [3].

Table 1. Likelihood (%) of bone impingement affecting ROM for the different directions of motion at the hip

Technique	Flexion	Extension	Abduction	Adduction	Internal	External
Manual	0.513	0.072	0.378	0.799	0.422	0.437
CAS	0.498	0.002	0.319	0.875	0.358	0.297

adduction for which bony impingement caused a drastic reduction in the upper bound of motion, thereby also pushing down the 50th percentile ROM value. The sites of bony impingement varied with the direction of hip motion. In general, flexion generated bony impingement between the anterior intertrochanteric region of the femur and the anterior rim of the acetabulum; in abduction, the tip of the trochanter impinged on the outer face of the ilium above the superior lip of the acetabulum; and in external rotation, the posterior intertrochanteric ridge tended to impinge on the ischium (posterior and inferior to the acetabulum).

Discussion

Dislocation remains a major complication after THA, and range of motion before impingement is important in joint stability. Variability in implant alignment influences resulting hip ROM. The purpose of this study was to use a probabilistic model to compare hip ROM outcomes following THA between manual and CAS levels of alignment variability. This approach enabled us to identify the upper and lower bounds of resulting hip ROM associated with normal variation in implant alignment and to compare the effects of manual and CAS surgical techniques. In addition, we determined the effect of bony impingement on the bounds of hip ROM.

The probabilistic analysis was limited to a representative bone geometry from a single male subject and included only one implant design. The implant was, however, a common design with a standard neck angle, neck diameter, and offset. Although the relative incidence of dislocation is higher in females, the main purpose of the study was to compare CAS to manual implant alignment—a purpose for which use of male anatomy was reasonable. The rationale for including bone geometry was to determine the extent to which hip ROM computed with implants only was reduced by bony impingement. Limitation to a single subject was reasonable for this comparison. Additional limitations are that only one head size, one neck angle, and one offset was modeled, although the values chosen were, again, common in clinical practice. With a larger head size, the ROM using impingement of implants only would shift higher. When analyzing the ROM with combined implants and bone, the lower limit is also likely to be shifted up. However, the upper limit would not change substantially since bony

impingement was almost always the limiting factor when the implants were at or near optimal orientation. While this model only analyzed the effects of prosthetic or bony impingement, other factors that are important in hip dislocation are leg length inequality, pelvic obliquity, soft tissues (capsule and muscles) and patient-related factors. The probabilistic platform is robust and the model could be expanded to account for additional sources of variability. Inclusion of additional input variability, however, is likely to only increase observed variability in resultant ROM. Femoral anteversion was assumed to have a modest standard deviation level in this study, primarily because wider variation was observed to cause the stem to protrude from the anterior surface of the proximal femur in some cases. Including variation of femoral anatomy in the model would allow for greater variation in femoral anteversion. ROM results were also limited to primary motions, which enabled easier comparison to earlier studies [16, 31, 32]. It would be interesting and relevant to expand the contact detection algorithm to consider composite motions typical of common activities at risk for dislocation [23].

We implemented a probabilistic contact detection model to assess how variability in implant alignment affected ROM after THA. Input parameters included cup abduction and anteversion, as well as anteversion of the stem, and variability levels were assigned based on a previous study of CAS compared to conventional THA techniques [24]. The computer model accounted for bony impingement and interactions among alignment parameters, which were perturbed simultaneously to characterize probability distributions of potential ROM outcomes. To the authors' knowledge, a similar probabilistic evaluation of the effects of implant alignment on resulting ROM has not previously been reported, although mathematical models for hip ROM have been previously described [12, 17, 31, 32, 37, 38]. One recent study of optimal implant alignment focused on prosthetic impingement only but stressed the importance of considering the impact of patient-specific factors at the time of surgery [32]. For similar ranges of implant alignment, we found median ROM values similar to those cited previously [32], but our predicted ROM values for implants only were substantially reduced by bony impingement for all hip motions except extension. Predicted ROM values also varied by 24° to 53° (1%–99% bounds) around their median levels, depending on the direction of motion considered. Our findings agree with that earlier work and

reinforce the assertion that optimal implant alignment for a specific patient depends heavily on surgical technique and patient anatomy.

Although several previous studies have applied mathematical models to compute optimal implant position for hip ROM following THA [12, 17, 31, 32, 37, 38], most have not accounted for bony impingement. The contact detection model reported here [16] was used previously to incrementally evaluate hip ROM as a function of implant alignment parameters (cup abduction, 35°–55°; cup anteversion, 0°–30°; stem anteversion, 0°–30°), as well as implant size. Bony impingement limited ROM in 44% of conditions tested. In the present study, we varied implant alignment over similar ranges but using a probabilistic analysis technique and a fixed implant size. We found bony impingement occurred before implant impingement in 43.7% of hip motions with manual implant alignment and 39.2% of conditions with CAS alignment. The likelihood of bony impingement was lower with CAS alignment for all motions except adduction. In the case of adduction, the likelihood of bony impingement was 87.5% for CAS compared to 79.9% for manual alignment. This phenomenon is easily explained by the greater standard deviation associated with the model input parameter for manual cup inclination compared to CAS. The probabilistic model allowed the cup to rotate into abduction to a greater extent for the manual cases, thus causing the implant to protrude from the acetabulum more often on the adduction side. Consequently, the adduction ROM for manual alignment was limited by the implant more often than for CAS alignment. This means the CAS alignment cases were more likely to contact the bone on the adduction side, but the adduction ROM was also greater for the CAS alignment compared to manual as shown by the combined results (Fig. 1B).

The probabilistic analysis provided quantitative evaluations of the effects of different component alignment variability levels on hip ROM. As expected, the distribution of ROM was tighter for CAS than it was for manual alignment. This result was evident when comparing the outcomes for the various implants only configurations (Fig. 1). The ROM results for the implants only cases highlighted the potential ROM that could be achieved based solely on prosthetic impingement, which is controlled by the implant design. The inclusion of bone surfaces in the contact detection algorithm then demonstrated the impact bony impingement had on the upper and lower bounds of ROM. For all hip motions except extension (for which bony impingement was relatively unlikely), CAS and manual alignment exhibited the same upper bounds for hip ROM due to the limiting effect of bony impingement. The critical difference between CAS and manual alignment was observed in the lower bounds of the

resultant ROM distributions, which gave an indication of how often ROM fell in an undesirable range. Poor hip ROM can be defined by the following limits: flexion < 90°, extension < 15°, adduction or abduction < 30°, and external rotation < 30° (internal rotation is not typically limited by prosthetic or bony impingement) [3] (Fig. 1, horizontal dotted lines). Our results indicate, with CAS levels of alignment variability, hip ROM was always in the acceptable range for all hip motions. Considering ROM outcomes associated with manual alignment, hip extension, adduction, and abduction exhibited acceptable levels for all cases, but hip flexion fell below the 90° threshold 5% of the time and external rotation was less than 30° in 3% of the cases studied. These data suggest a clinically relevant improvement in hip ROM associated with CAS implant alignment. Probabilistic analysis enables one to assess the expected variability in a system outcome metric given the variability of various input parameters is known. Such an approach has advantages over more common DOE (design of experiments) studies. Namely, the probabilistic approach automatically accounts for variable interactions and predicts a probability distribution of possible outcomes. In our study, we observed a clinically relevant probability (3%–5%) that hip ROM would fall below acceptable levels with manual implant alignment. Within the level of variability considered here, CAS alignment produced resultant ROM that was always within acceptable limits. While CAS techniques decrease variability in implant alignment [13–15, 24], this study provides quantitative support for the ability of CAS methods to decrease the probability of hip dislocation compared to conventional techniques.

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