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Factors Affecting Bony Impingement in Hip Arthroplasty

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Abstract: Computer modeling of 10 patients' computed tomographic scans was used to study the variables affecting hip arthroplasty range of motion before bony impingement (ROMBI) including acetabular offset and height, femoral offset, height and anteversion, and osteophyte removal. The ROMBI was compared with the ROM before component impingement and the native hip ROM. The ROMBI decreased with decreased total offset and limb shortening. Acetabular offset and height had a greater effect on ROMBI than femoral offset and height. The ROMBI lost with decreased acetabular offset was not fully recoverable with an increase in femoral offset or osteophyte removal. Bony impingement increased and component impingement decreased with decreased acetabular offset and increased head diameter. **Keywords:** acetabular offset, center of rotation, bony impingement, hip arthroplasty range of motion.

Translation of the acetabular and femoral components affects implant survival in cemented total hip arthroplasty, but their effect on the hip arthroplasty range of motion (ROM) is uncertain [1-14]. Avoiding a high hip center with cemented and uncemented acetabular components has been shown to improve implant survival [1,2,4,5,7-12,14]. Decreasing acetabular offset with cemented acetabular components also has been shown to improve implant survival [1,3,6-8,13,14]. Decreasing acetabular offset in uncemented acetabular components has been shown to be successful in hip dysplasia, but few studies have evaluated the effect of acetabular offset on uncemented acetabular implant survival in normal hip anatomy [15-17].

Many studies have shown that decreasing acetabular offset and increasing femoral offset reduce the joint reactive force and may improve the polyethylene wear rate [17-29]. Schmalzried et al [29] and Wroblewski et al [28] showed a trend of decreased polyethylene wear with a decrease in acetabular offset. Charnley [24], while discussing femoral offset, acknowledged that "with any mechanical advantage, it is inevitable that there will be some loss of motion."

Many cadaver and saw bone studies have modeled variables affecting hip arthroplasty ROM [30-36]. Chandler et al [32] described component and bony impingement and the effects of the head-neck ratio and femoral neck length on hip arthroplasty ROM. Other saw bone studies have showed that the hip arthroplasty ROM is limited by bony impingement and not component impingement with a femoral head diameter larger than 32 to 38 mm [33,36].

Many mathematical and computer studies have analyzed the variables that affect the ROM before component impingement (ROMCI) [37-44]. Yoshimine and Ginbayashi [38] outlined 5 variables affecting ROMCI: acetabular component abduction and anteversion, femoral component anteversion and neck shaft angle, and the prosthetic ROM, which is a function of the head-neck ratio and the opening angle of the acetabular liner. Widmer and Zurfluh [39] demonstrated the narrow range of acetabular and femoral component position compatible with activities of daily living (ADLs).

Component impingement has known geometric variables that facilitate mathematical and computer modeling studies; however, bony impingement varies considerably between different patients. Two previous computer modeling studies have evaluated bony and component impingement in a single pelvic model, but no study known to the authors has evaluated the variables affecting range of motion before bony

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impingement (ROMBI) irrespective of component impingement [44,45]. We aim to investigate the effects of 6 variables on ROMBI using computer modeling of 10 patients. These include the influence of acetabular offset, acetabular height, femoral offset, femoral height, femoral version, and osteophyte removal.

Materials and Methods

Ten patients (5 men and 5 women) with osteoarthritis who had undergone computed tomography (CT)–based navigated total hip arthroplasty by the senior author from 2001 to 2004 were randomly selected from the senior surgeon's CT scan database. Exclusion criteria included hip dysplasia, hip protrusio, or retained hardware. The hip arthroplasty ROMBI was simulated using the patients' preoperative CT scan and the HipNav software (CASurgica, Pittsburgh, PA) [46]. A Meridian femoral component (Stryker, Rutherford, NJ), a Versys acetabular component (Zimmer, Warsaw, IN), and a 28-mm femoral head were used for the computer simulation.

The same algorithm was used in all 10 patients to simulate hip arthroplasty ROM. First, the HipNav software generated a 3-dimensional pelvic, proximal femur, and distal femur model from the patients' CT scan. The anterior pelvic plane was determined by referencing the bilateral anterior superior iliac spines and pubic tubercles [46,47]. Hip flexion and extension were defined according to this anterior pelvic plane. Hip internal and external rotation and femoral anteversion were defined according to the posterior condylar axis of the distal femur [48]. An appropriately sized sphere was placed over the femoral head to determine the femoral head size and the anatomical hip center of rotation (COR). The acetabular component diameter was selected to be 4 mm greater than the femoral head diameter for all patients. Any acetabular osteophytes that were loosely attached to the acetabular bony rim were removed, but well-fixed osteophytes and acetabular bony rim were kept in the pelvic model until the last trial.

The *native acetabular offset* was defined as the distance between the anatomical hip COR and the inner wall of the quadrilateral plate. The *medial wall width* was defined as the native acetabular offset minus the radius of the acetabular component. The medial wall width represented how far a surgeon could ream the acetabular bone before he/she perforated the inner table. The ideal depth of acetabular reaming varies considerably between surgeons, with some surgeons consistently reaming to the medial wall and other surgeons minimizing the amount of acetabular reaming. The baseline acetabular component position compromised between these 2 philosophies by medializing the acetabular component 50% of the medial wall width from the anatomical hip COR. The femoral offset was increased by 50% of the medial wall width by selecting an appropriate femoral neck length and component size. The *native femoral offset* was defined as the offset of the femoral component minus 50% of the medial wall width. This baseline position of the acetabular and femoral components simulated a common total hip arthroplasty scenario; acetabular offset is decreased proportional to the width of the medial wall, femoral offset is increased accordingly, and total offset is unchanged. The baseline femoral component position was anteverted 15° from the posterior femoral condylar axis without consideration of the femoral prosthesis fit in the proximal femur or the native femoral anteversion. The baseline acetabular and femoral component height was identical to their preoperative height; there was no vertical translation between the anatomical COR and the baseline COR.

Each patient's baseline component position was the starting position for all series. In each series, the offset and/or height of the acetabular and/or femoral component was increased and decreased from the baseline position according to Table 1. For instance, in series 1, the acetabular component was translated in 2-mm increments a total of 1 cm medially and 1 cm laterally from the baseline position. In series 2, the femoral component was translated medially and laterally; and in series 3, the acetabular component and femoral component were simultaneously translated in opposite horizontal directions, thereby moving the COR while keeping the total offset unchanged. Series 4 to 6 involved superior and inferior translation of the acetabular component, femoral component, and both components, respectively. In series 4 and 6, the acetabular component was translated inferiorly only 6 mm because the acetabular component failed to contact the acetabular bone after 6 mm of inferior translation. Series 7 to 9 simulated modular head length and elevated liner changes with diagonal translation along the axis of the femoral neck of the acetabular component, femoral component, and both components, respectively. In series 7 to 9, the incremental change in femoral neck or acetabular liner length was 4 mm based on the available modular head lengths; the resultant change in limb length and offset was 2.5 mm. The

Table 1. Variables Studied

Horizontal Component Translation			Vertical Component Translation			Diagonal Component Translation		
Series 1	Series 2	Series 3	Series 4	Series 5	Series 6	Series 7	Series 8	Series 9
Acetabular offset	Femoral offset	Acetabular minus femoral offset	Acetabular height	Femoral height	Acetabular minus femoral height	Elevated acetabular liner	Femoral head length	Elevated liner minus femoral head

femoral component anteversion was varied at the baseline position from 0° to 30° in 5° increments.

To model ROMBI with osteophytes removed, the acetabular offset was decreased 10 mm from the baseline position, the ROMBI was tested, and any bone along the acetabular rim that contacted the femoral bone or component was removed from the pelvic model. The ROMBI with osteophytes removed was calculated as in series #1 with 2-mm incremental changes in acetabular offset and a constant femoral offset.

The maximum flexion, extension, and internal and external rotation before bony impingement were simulated for each incremental change in each series. The maximum internal rotation was simulated in 9 different hip flexion positions from 30° to 110° of flexion (10° increments), and the maximum external rotation was simulated in 11 different hip flexion/extension positions from 60° of flexion to 40° of extension (10° increments). Measurements of internal rotation at flexion less than 30° and external rotation at flexion greater than 60° were not recorded because they were consistently outside the physiologic ROM.

When component impingement occurred before bony impingement, the acetabular component abduction and anteversion were changed without translating the COR to allow the hip motion to continue free of component impingement until bony impingement occurred. Changing the acetabular component abduction and/or version did not change the ROMBI. Component-on-bone impingement rarely occurred between the femoral prosthesis and the pelvic bone, and this ROM was recorded and analyzed along with the other bone-on-bone impingement ROM. Component-on-bone impingement between the acetabular component and the femoral bone did not occur in these simulations because of the changes made to the acetabular abduction and anteversion. The total number of ROMBI simulations was 2310 for each patient and 23,100 for all 10 patients.

The locations of the acetabular rim involved in bony impingement at baseline component position were recorded using a 360° coordinate system. The coordinate system was standardized for a right hip. The 0° or 12-o'clock position corresponded to directly superior as defined by the anterior pelvic plane, and the 90° or 3-o'clock position corresponded to directly anterior. No distinction was made between pathologic osteophyte and anatomical acetabular rim. Bony impingement that occurred greater than 1 cm from the acetabular rim (ie, the anterior inferior iliac spine) was not recorded in the osteophyte location.

The maximum flexion, internal rotation, external rotation, and extension before component impingement were modeled for a 22-mm, 28-mm, 32-mm, 36-mm, 40-mm, and 44-mm head using the mathematical equations previously derived by Yoshimine and Ginbayashi [38]. The ROMCI was modeled for a hemispherical acetabular component with 45° abduction and 20° anteversion, and a femoral component with 15° of femoral anteversion, an effective neck/shaft angle of 134° (127° femoral component neck/shaft angle and 7° varus angle of the femoral component at neutral hip abduction), and a 14-mm diameter femoral neck. The femoral prosthesis modeled in the HipNav had a 14-mm–diameter femoral neck; however, many femoral prostheses have a 12-mm–diameter neck. The ROMCI is a function of the head-neck ratio; therefore, a femoral prosthesis with a 14-mm neck diameter combined with a 22-mm, 28-mm, 32-mm, 36-mm, 40-mm, and 44-mm head has the same ROMCI as a femoral prosthesis with a 12-mm neck diameter combined with a 19-mm, 24-mm, 27-mm, 30-mm, 34-mm, and 38-mm head, respectively. If the ROMBI was less than the ROMCI, then bony impingement occurred first and was recorded in Fig. 4. When ROMCI occurred first, it was recorded as the space above the bar graph in Fig. 4.

The native hip ROMBI was simulated using the patients' preoperative CT scan and the HipMotion software (Mueller Institute for Orthopedic Research, Bern, Switzerland) [49]. The native hip ROMBI was compared with the hip arthroplasty ROMBI at the baseline and anatomical COR position.

Statistical Analysis

Statistical analysis was performed using the SAS software (Cary, NC) and Microsoft Excel (Seattle, WA). The statistical analysis for series 1-9 and femoral anterversion was performed by a statistician using the SAS software and a linear mixed-effect model. The mixed model was generated using the SAS procedure PROC MIXED. A random statement with study subject as the random effect was included to account for the correlation within subjects because of the repeated nature of the data. Estimates for the change in position of the prosthesis were found by specifying it as a fixed effect. The sex differences in patient demographics were compared using a Student t test in Microsoft Excel. The effects of hip flexion on the maximum internal and external rotation were determined using the best-fit line method in Microsoft Excel. The ROMBI of the native hip and the hip arthroplasty were compared using a Student t test in Microsoft Excel.

Results

The patient demographics are listed in Table 2. The 5 women in the study had a statistically significant smaller femoral head, acetabular component, postoperative acetabular offset at baseline component position, and preoperative and postoperative femoral offset as compared with the 5 men ($P < .05$).

Fig. 1 illustrates the average ROMBI in series 3 with the acetabular component translated 1 cm medially, at

Table 2. Patient Demographics

Demographic	Average Female	Average Male	Average All	Student *t* Test (F/M)
Age	48.6 y	59 y	53.8 y	*P* = .08
Femoral head size	46 mm	51.6 mm	48.8 mm	*P* = .004
Acetabular component size	50 mm	55.6 mm	52.8 mm	*P* = .004
Medial wall thickness	13.6 mm	14.4 mm	14 mm	*P* = .35
Preoperative acetabular anteversion	22°	21°	21.5°	*P* = .42
Native acetabular offset	38.6 mm	42.2 mm	40.4 mm	*P* = .102
Postoperative acetabular offset	31.8 mm	35.2 mm	33.4 mm	*P* = .042
Native femoral offset	32.4 mm	40.4 mm	36.4 mm	*P* = .007
Postoperative femoral offset	39.2 mm	47.6 mm	43.4 mm	*P* = .002

baseline position, and translated 1 cm laterally; the femoral offset was increased and decreased accordingly such that the total offset and leg length remained constant for all 3 groups. Internal rotation before bony impingement decreased 0.80° (R^2 = 0.985) per degree of flexion from 60° to 110°, whereas external rotation decreased 0.45° (R^2 = 0.972) per degree of extension from 40° of hip flexion to 40° of hip extension.

The maximum internal rotation before bony impingement from 30° to 110° of flexion was grouped into tertiles based on low, moderate, and high hip flexion (30°-50°, 60°-80°, and 90°-110°) for analysis. The maximum external rotation before bony impingement from 60° of flexion to 40° of extension was grouped into quartiles based on moderate flexion, low flexion, low extension, and moderate extension (60°-50° of flexion, 40°-20° of flexion, 10° of flexion to 10° of extension, and 20°-40° of extension).

Fig. 2A illustrates the effects of component translation in each series on maximum internal rotation in the high-flexion tertile. For every millimeter of decrease in acetabular offset with a comparable increase in femoral offset (series 3), the average ROMBI between 90° and 110° of hip flexion lost 1.6° of internal rotation ($P <$ .0001). In series 9, the average internal rotation decreased 1.8° ($P < .0001$) per millimeter of diagonal translation of the COR, indicating that the average internal rotation would increase 7.2° more with a +4-mm lateralized acetabular liner and a 0-mm modular head than with a +4-mm modular head and a neutral acetabular liner. Fig. 2B illustrates the effects of component translation in each series on maximum external rotation in the low-extension quartile. Fig. 2C illustrates the effects of component translation on maximum flexion. The effects of component translation in each series and in each tertile/quartile are listed in the Appendix A.

Translating the acetabular component from the anatomical COR to the position where the acetabular component perforated the inner wall while maintaining a constant total offset decreased the average internal rotation in high hip flexion by 22.7° ($P <$ .0001), the average external rotation in low hip extension by 27.3° ($P < .0001$), and the maximum flexion by 13.7° ($P < .0001$).

The effects of femoral anteversion on ROMBI and ROMCI are shown in Table 3. Every degree of increased

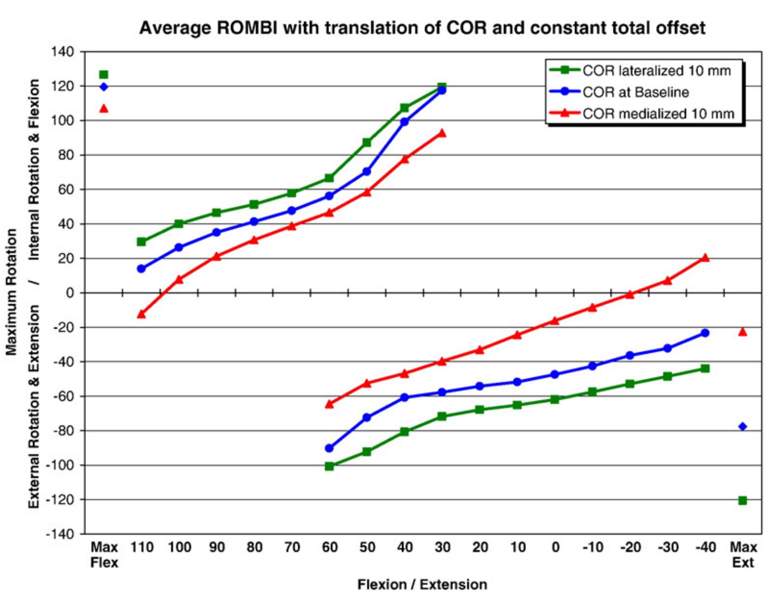

Fig. 1. Average maximum flexion, internal rotation, external rotation, and extension with translation of the COR. Total offset and leg length held constant (ie, series 3).

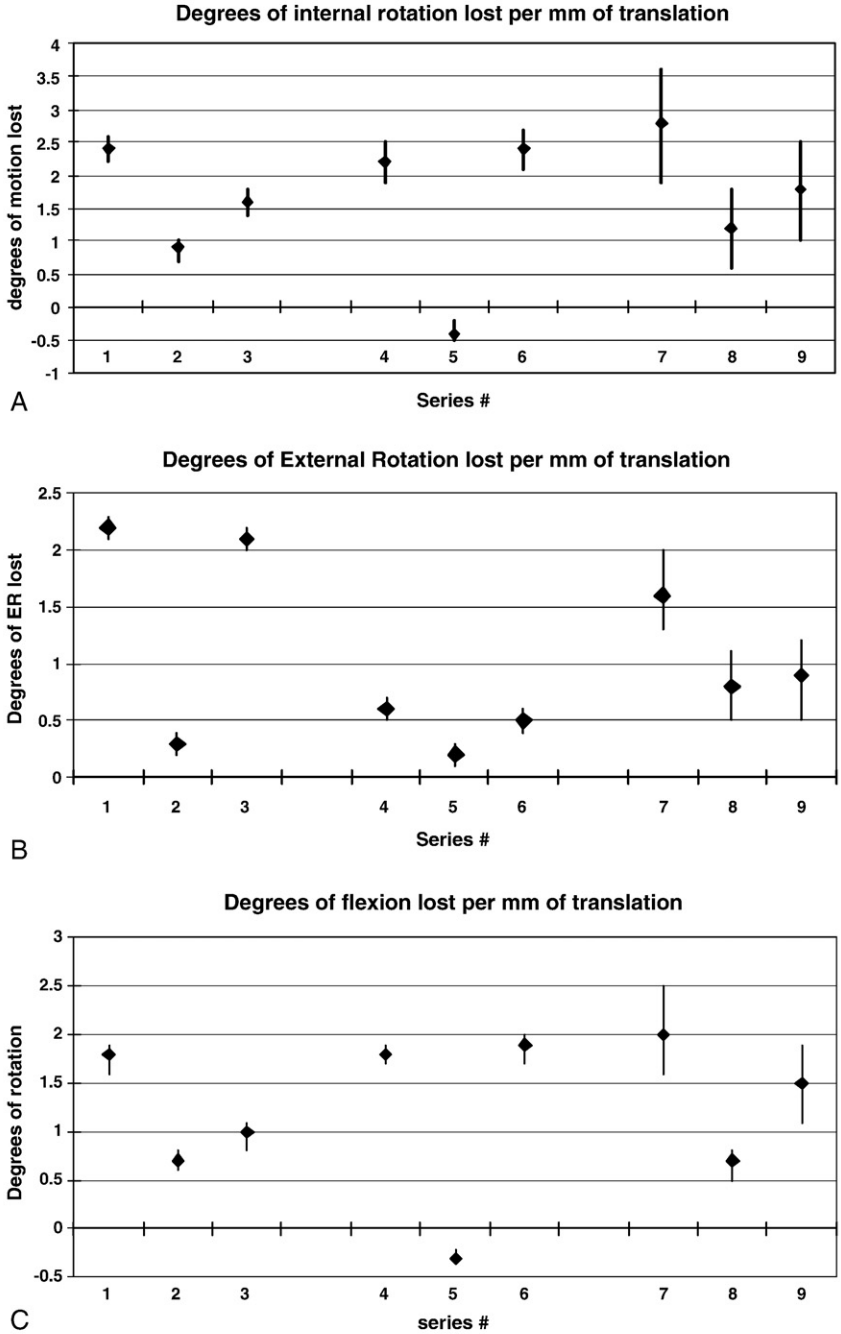

Fig. 2. (A) Degrees of internal rotation lost per millimeter of component translation. (B) Degrees of external rotation lost per millimeter of component translation. (C) Degrees of flexion lost per millimeter of component translation. 95% Confidence intervals are shown. Component variables for each series are (1) acetabular offset, (2) femoral offset, (3) acetabular offset − femoral offset, (4) acetabular height, (5) femoral height, (6) acetabular height − femoral height, (7) lateralized acetabular liner, (8) modular head length, and (9) lateralized acetabular liner − modular head length.

femoral anteversion increased the internal rotation before both bony and component impingement by 1° (*P* = .0001) and decreased the external rotation before both bony and component impingement by 1° (*P* = .0001) regardless of the amount of hip flexion simulated.

The effects of osteophyte removal on ROMBI are shown in Fig. 3. Osteophyte removal did improve the maximum internal rotation before bony impingement for a medialized acetabular component, but showed little effect on the maximum internal rotation with components at the baseline position. The effects of osteophyte removal were modest on maximum external rotation when the acetabular component was not medialized.

The locations on the acetabulum rim of the bony impingement at neutral hip abduction are listed in Table 4. The bony impingement with flexion and

Table 3. The Effects of Femoral Anteversion on ROM Before Bony and Component Impingement

ROM	Affect of Increased Femoral Anteversion on ROMBI	Affect of Increased Femoral Anteversion on ROM Before Component Impingement
Max IR from 30°-50° of hip flexion	1.1° per mm ($P < .0001$) 95% CI: (0.8, 1.4)	1
Max IR from 60°-80° of hip flexion	1.0° per mm ($P < .0001$) 95% CI: (0.9, 1.1)	1
Max IR from 90°-110° of hip flexion	1.0° per mm ($P < .0001$) 95% CI: (0.9, 1.2)	1
Maximum flexion	0.5° per mm ($P < .0001$) 95% CI: (0.5, 0.6)	0.654
Max ER from 60°-50° of hip flexion	−0.6° per mm ($P < .0001$) 95% CI: (−0.8, −0.4)	−1
Max ER from 40°-20° of hip flexion	−0.8° per mm ($P < .0001$) 95% CI: (−0.8, −0.7)	−1
Max ER from 10° hip flexion to 10° hip extension	−1.0° per mm ($P < .0001$) 95% CI: (−1.1, −0.9)	−1
Max ER from 20°-40° hip extension	−1.1° per mm ($P < .0001$) 95% CI: (−1.2, −1.0)	−1
Maximum extension	−1.5° per mm ($P < .0001$) 95% CI: (−1.7, −1.3)	−1.07

IR indicates internal rotation; ER, external rotation; CI, confidence interval.

internal rotation was typically located between the 1-o'clock and 3-o'clock positions for a right hip. The bony impingement with extension and external rotation was typically located between the 6-o'clock and 9-o'clock positions. Table 5 shows the greater trochanter with internal rotation always impacted the ilium at or greater than 60° of hip flexion and impacted the superior pubic rami at and less than 30° of hip flexion. Likewise, the greater trochanter with external rotation always impacted the superior ischium at or less than 40° of hip flexion and impacted the inferior ischium in 7 of 10 patients at 60° of hip flexion.

The effects of acetabular offset and femoral head diameter on the frequency of bony impingement are shown in Fig. 4. The baseline component position is analogous to 0 mm of acetabular offset, the average anatomical COR is analogous to 7 mm of acetabular offset, and the average inner wall perforation position is analogous to −7 mm of acetabular offset in Fig. 4. The frequency of component impingement is given as the space above the bar graph (100 − percentage of bony impingement). The frequency of bony impingement increased and component impingement decreased with a decrease in acetabular offset and an increase in head size.

The hip arthroplasty ROMBI and the preoperative ROM of the arthritic hip are shown in Fig. 5. The average hip arthroplasty ROM at the baseline component position increased 15.2° of internal rotation (P = .0002), 13.8° of flexion (P = .012), and 4.9° of extension (P = .14) and decreased 2.1° of external rotation (P = .1) compared with the native hip. The average hip arthroplasty ROM at the anatomical COR component position increased 23.0° of internal rotation (P < .00001), 19.6° of flexion (P = .013), 32.3° of extension (P < .00001), and 8.3° of external rotation (P < .00001) compared with the preoperative arthritic hip.

Discussion

Component impingement has known geometric shapes that facilitate mathematical and computer

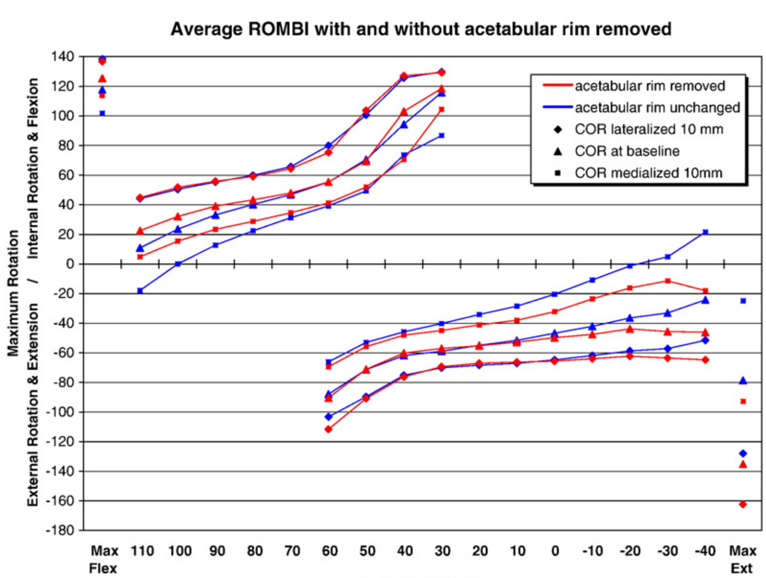

Fig. 3. Effects of osteophyte removal on ROMBI with changes in acetabular offset (ie, series 1).

Table 4. Acetabular Rim Location of Osteophytes in Impingement

ROM	Minimum Angle of Osteophyte Location	Average Angle of Osteophyte Location	Maximum Angle of Osteophyte Location
Max IR from 30°-50° hip flexion	60	91.0	115
Max IR from 60°-80° hip flexion	38	58.9	72
Max IR from 90°-110° hip flexion	31	51.6	77
Maximum flexion	33	54.8	70.4
Max ER from 60°-50° hip flexion	140	166.8	197.5
Max ER from 40°-20° hip flexion	180	204.8	224.9
Max ER from 10° flexion to 10° extension	214	229.6	250
Max ER from 20°-40° hip extension	227.5	254.3	280
Maximum extension	261.2	278.6	296.7

modeling studies. The variables that affect ROMCI, namely, acetabular abduction and anteversion and femoral anteversion, are largely determined by the surgeon; therefore, many studies have evaluated how these variables affect hip stability. Bony impingement involves more challenging geometric shapes that vary between patients. Because the variables that affect ROMBI have largely remained unknown, surgeons have traditionally relied on high offset femoral stems, longer and larger modular heads, elevated liners, and osteophyte removal to avoid hip instability from bony impingement.

Both component and bony impingement create a fulcrum about which the femoral head can sublux out of the socket and lead to hip instability [32,34]. Some studies have shown an increase in hip instability with a high hip center that could partially be due to an increase in bony impingement, but is more likely related to the higher dislocation rate associated with revision surgery [5,12]. Jolles et al [50] evaluated multiple radiographic measurements and showed no statistical significance between the final acetabular offset measurement and hip instability. No studies known to the authors have shown that a loss of acetabular offset affects hip instability; however, some studies have suggested that a decrease in acetabular offset might increase the prevalence of bony impingement [8,24,31].

Two studies have evaluated both ROMCI and ROMBI in a single pelvic computer model. Robinson [44] simulated ROMCI and ROMBI in a hip arthroplasty model and altered the ROMCI by changing the acetabular component abduction and anteversion. Kessler et al [45] studied the effects of prosthetic neck diameter, neck length, head size, acetabular abduction and anteversion, femoral anteversion, and cup medialization on ROMCI and ROMBI; their results are similar to many of the results in this study.

Table 5. Pelvic Location of Bony Impingement at Baseline Position

Hip Flexion	Average IR	Trochanter/Ilium Impingement With Internal Rotation	Average ER	Trochanter/Ischium Impingement With External Rotation
30	115°	0/10	57°	10/10
40	98°	3/10	60°	10/10
50	71°	8/10	71°	7/10
60	56°	10/10	89°	3/10

Recent studies with press fit acetabular components have shown greater postoperative acetabular offset than previous studies with cemented acetabular components [1,6,14,17,51]. Although the acetabular offset in this study was measured from the inner table on the CT scan, it is consistent with the acetabular offset in these recent studies [17,51].

When discussing the clinical importance of results shown in Fig. 2, it is important to analyze how the ROMBI shown in Fig. 1 relates to the ROM needed for ADLs [37,52,53]. Internal rotation before bony impingement at high hip flexion occurred mostly between 0° and 30° of internal rotation, well within the ROM of ADLs; and therefore, the factors affecting internal rotation at high hip flexion were discussed. In contrast, the average maximum extension before bony impingement was 78°, well outside the ROM of ADLs; and therefore, the factors affecting maximum extension have little clinical importance and were not discussed.

A decrease in offset and/or leg length decreases soft tissue tension and decreases hip arthroplasty ROM in this and other studies [30,32,33,35,45]. The study by Kessler et al [45] showed a 4.5° decrease in flexion with a 4-mm decrease in acetabular offset and a 2.7° decrease in flexion with a 4-mm decrease in neck length. This study showed a 1.8° decrease in flexion with every millimeter decrease in acetabular offset or 7.2° decrease in flexion with a 4-mm decrease in acetabular offset. This study also showed a 0.7° decrease in flexion with every millimeter decrease in neck length or 2.8° decrease in flexion with a 4-mm decrease in neck length.

Changes in acetabular offset and acetabular height had a greater effect on ROMBI than equivalent changes in femoral offset and femoral height. The positive values in series 3, 6, and 9 in Fig. 2 all demonstrated that the ROM lost from decreased acetabular offset and/or a high hip center was not recoverable with an equivalent leg length or offset compensation on the femoral side.

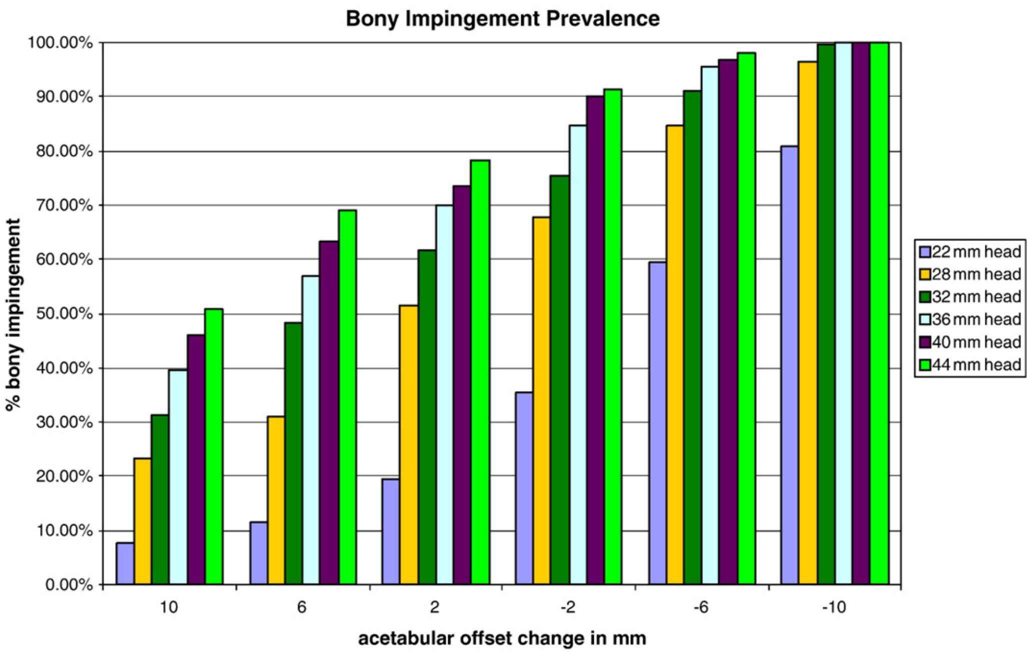

Fig. 4. Effects of acetabular offset and head diameter on bony and component impingement with a 14-mm–diameter femoral prosthetic neck.

The ROMBI was improved more with the use of a lateralized liner than with the use of an increased femoral head length.

The ROMBI lost with decreased acetabular offset is not fully recoverable with an equivalent increase in femoral offset for 2 reasons. First, the effects of femoral offset and femoral height on ROMBI are dependent on the hip flexion and rotation. For example, increasing the femoral component height translates the femur inferiorly at 0° of hip flexion but anteriorly at 90° of hip flexion. This observation helps explain the paradoxical decrease in maximum internal rotation and maximum flexion shown in series 5 (Fig. 2A and C) with increased femoral component height. Increasing the femoral offset translates the femur laterally at neutral hip rotation, but both superiorly and laterally with maximum internal rotation at 90° of hip flexion. Increasing the acetabular offset translates the femur laterally regardless of the amount of flexion or rotation of the femur. Second, a larger femoral

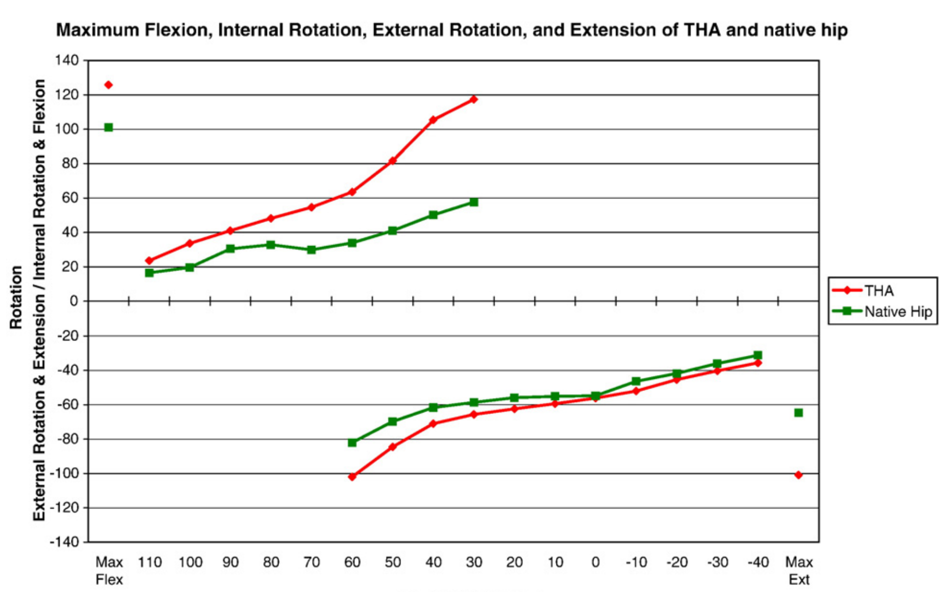

Fig. 5. Average maximum flexion, internal rotation, external rotation, and extension of native hip vs hip arthroplasty at the anatomic COR.

offset causes more femoral translation for the same degrees of rotation. Because the length of an arc is (θR), where θ is the angle and R is the radius, an increase in femoral offset (R) increases the length of the arc. Improving the hip joint reactive force though increased femoral offset sacrifices ROM, a fact that Charnley [24] acknowledged.

The effect of hip flexion on internal rotation before bony impingement (0.8°/degree of flexion) is greater than the effect of hip flexion on external rotation before bony impingement (0.43°/degree of flexion), suggesting that bony impingement with external rotation occurs over a broader range of flexion than bony impingement with internal rotation. Therefore, hip instability with internal rotation is likely more sensitive to the amount of hip flexion than hip instability with external rotation.

With maximum internal rotation, the greater trochanter impinged on the ilium at greater than 60° of flexion and impinged on the superior rami at less than 30° of flexion. Between 30° and 60° of flexion, this transition in location of impingement resulted in a large jump in internal rotation before bony impingement. Therefore, clinically relevant bony impingement with internal rotation likely begins around 60° of hip flexion and increases with increased hip flexion. Clinically relevant bony impingement with external rotation likely occurs over a broader range of hip flexion and extension.

The combined version technique as described by Ranawat and Maynard [54] allows a surgeon to optimize the ROMCI [55]. Femoral anteversion affects both ROMCI and ROMBI equally; however, acetabular anteversion affects only ROMCI, not ROMBI. Therefore, increasing the femoral component anteversion to correct for a decreased acetabular component anteversion can lessen the possibility of component impingement anteriorly but inadvertently increase the possibility of bony impingement posteriorly. This fact, also noted by Kessler et al [45], suggests that, whenever possible, a malpositioned acetabular component should be revised instead of relying on overcorrecting the femoral anteversion.

Acetabular osteophyte and/or rim removal as shown in Fig. 3 improved the ROMBI when the acetabular component was medialized 10 mm (an average of 17-mm decrease from native acetabular offset). Bony impingement often occurred between the greater trochanter and the anterior inferior iliac spine (AIIS) before it occurred between the femoral bone and the acetabular rim; therefore, removing the acetabular rim had little effect on the ROMBI when the components were not medialized 10 mm. A decrease in acetabular offset caused a decrease in ROMBI occurring both at the acetabular rim as well as the AIIS. Bony impingement between the greater trochanter and AIIS is not easily corrected intraoperatively with bony resection. Therefore, surgeons may be able to improve some of the ROMBI through acetabular rim removal when the acetabular component has been medialized; but bony impingement at the AIIS will still limit the ROMBI.

The location of bony impingement on the acetabular rim with flexion and internal rotation occurred between the 1-o'clock and 3-o'clock positions with the hip in neutral abduction. The location of bony impingement on the acetabular rim with extension and external rotation occurred between the 6-o'clock and 9-o'clock positions. These results are similar to those reported by Jaramaz et al (Computer Assisted Orthopedic Surgery meeting 2006, Montreal). This study did not record osteophyte impingement at different degrees of hip abduction or acetabular offset, which can alter the location of impingement. Generalized statements regarding osteophyte removal would require additional studies.

Previous studies and Fig. 4 show that the occurrence of bony impingement increases with larger femoral heads [33,36,45]. A larger head-neck ratio increases the ROMCI, decreases the prevalence of component impingement, and therefore increases the prevalence of bony impingement. Likewise, our study showed that an increase in acetabular offset increases the ROMBI, decreases the prevalence of bony impingement, and increases the prevalence of component impingement. Previous studies and Fig. 4 have shown that most of the improvement in ROMCI with large femoral heads occur with femoral head diameters up to 36 mm; after 36 mm, ROM is typically limited by bony impingement [33,36,45]. The improved ROMCI with a larger head-neck ratio is negated if the acetabular offset is decreased because the ROM is limited by bony impingement, which is not affected by the head-neck ratio. Maximizing overall ROM is achieved by maximizing the head-neck ratio to prevent component impingement and maximizing acetabular offset to prevent bony impingement.

Previous studies and this study have shown that hip arthroplasty ROMBI is greater than the native hip ROMBI because of the improved head-neck ratio of the femoral component compared with the native femoral anatomy [32]. This improved hip arthroplasty ROM is most pronounced with internal rotation at moderate flexion, but may not translate into improved clinic motion because the intrinsic stability of the native hip joint allows for increased pelvic tilt.

A weakness of this study is the inability to account for in vivo pelvis flexion that occurs with hip flexion. This study measures hip flexion as the relative motion between the femur and the anteroposterior pelvic plane. Hip flexion increases the pelvic flexion, increases the effective acetabular anteversion, and allows greater hip flexion before both bony and component impingement. The surprisingly limited ROMBI in the native hip underscores the importance of pelvic flexion in achieving maximum leg flexion in the native hip. The ROM before soft tissue impingement was not studied, but would likely behave similar to bony impingement. The ROMBI at different degrees of hip abduction was not studied and might have additional clinically relevancy. Component impingement has a shorter fulcrum length than bony impingement; and therefore, a greater dislocation force would likely be generated in component impingement vs bony impingement. The clinical consequences of component vs bony impingement deserves further studies.

Any clinical benefit in improved ROM and bone preservation from increasing the acetabular offset may be overshadowed by possible clinical detriments. Increasing acetabular offset could result in adverse shear forces at the bone implant interface and loosening of the acetabular component. The increased joint reactive force and increased polyethylene wear that occur with an increased acetabular offset also might supersede any benefits achieved in ROM.

The increased popularity of large femoral heads in total hip arthroplasty has decreased the occurrence of component impingement, but has inadvertently increased the occurrence of bony impingement. The widespread use of cementless acetabular components and the advent of alternative bearing surfaces and improved polyethylene may allow surgeons to increase the acetabular offset compared with previous studies of cemented acetabular components with conventional polyethylene. As patients continue to demand higher performance from their hip arthroplasties, understanding how to maximize ROM becomes increasingly important. The key clinical outcome of bony impingement is hip instability; and to date, no study has shown that acetabular offset affects hip instability. The 6 variables that affect ROMBI are acetabular offset, acetabular height, femoral offset, femoral height, femoral anteversion, and osteophyte removal, whereas acetabular abduction, acetabular anteversion, and head-neck ratio affect only ROMCI. The potential beneficial effects of maintaining acetabular offset, namely, improved ROM and bone stock preservation, must be tempered against medializing the acetabular component sufficiently to optimize the joint reactive force and to achieve appropriate acetabular component coverage.

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Appendix A

Table 6. Variables Studied

Series	1st Variable	2nd Variable	Offset and/or LL	Incremental Change	No. of Measurements
AO and FO varied/height unchanged					
1 AO	AO varied from −10 to 10 mm	FO constant	TO varied with AO	2 mm	11 Measurements
2 FO	AO constant	FO varied from −10 to 10 mm	TO varied with FO	2 mm	11 Measurements
3 AO − FO	AO varied from −10 to 10 mm	FO varied from −10 to 10 mm	TO constant	2 mm	11 Measurements
AH and FH varied/offset unchanged					
4 AH	AH varied from 10 to −6 mm	FH constant	LL varied with AH	2 mm	9 Measurements
5 FH	AH constant	FH varied from −10 to 10 mm	LL varied with FH	2 mm	11 Measurements
6 AH − FH	AH varied from 10 to −6 mm	FH varied from −6 to 10 mm	LL constant	2 mm	9 Measurements
TO and height varied–FNL vs AL length					
7 AL	AL length varied from 4 mm inset to 4 mm lateralized	FNL constant	TO and LL varied with AL length	4 mm	3 Measurements
8 FNL	AL length constant	FNL varied from −4 mm to +4 mm	TO and LL varied with FNL	4 mm	3 Measurements
9 AL − FNL	AL length varied from 4 mm inset to 4 mm lateralized	FNL varied from −4 mm to +4 mm	TO and LL constant	4 mm	3 Measurements
FA varied/offset and height unchanged					
10	FA varied from 0° to 30°	NA	NA	5°	7 Measurements

AO indicates acetabular offset; FO, femoral offset; AH, acetabular height; FH, femoral height; TO, total offset; LL, leg length; AL, acetabular liner; FNL, femoral neck length; FA, femoral anteversion; NA, not applicable.

Table 7. The Effects of Acetabular and Femoral Offset on ROMBI (Series 1-3)

ROM	Decreased AO	Decreased FO	Decreased AO With Increased FO	Average Motion Lost From Anatomical to Penetration Position
Max IR from 30°-50° of hip flexion	−2.3° per mm ($P < .0001$) 95% CI: (−2.7, −2.0)	−1.2° per mm ($P < .0001$) 95% CI: (−1.5, −.9)	−1.3° per mm ($P < .0001$) 95% CI: (−1.6, −1.0)	18.6° ($P < .0001$)
Max IR from 60°-80° of hip flexion	−1.8° per mm ($P < .0001$) 95% CI: (−1.9, −1.6)	−0.7° per mm ($P < .0001$) 95% CI: (−0.8, −0.6)	−1.0° per mm ($P < .0001$) 95% CI: (−1.1, −0.9)	14.7° ($P < .0001$)
Max IR from 90°-110° of hip flexion	−2.4° per mm ($P < .0001$) 95% CI: (−2.6, −2.2)	−0.9° per mm ($P < .0001$) 95% CI: (−1.0, −0.7)	−1.6° per mm ($P < .0001$) 95% CI: (−1.8, −1.4)	22.7° ($P < .0001$)
Maximum flexion	−1.8° per mm ($P < .0001$) 95% CI: (−1.9, −1.6)	−0.7° per mm ($P < .0001$) 95% CI: (−0.8, −0.6)	−1.0° per mm ($P < .0001$) 95% CI: (−1.1, −0.8)	13.7° ($P = .012$)
Max ER from 60°-50° of hip flexion	−2.0° per mm ($P < .0001$) 95% CI: (−2.2, −1.7)	0.6° per mm ($P < .0001$) 95% CI: (0.3, 0.8)	−2.1° per mm ($P < .0001$) 95% CI: (−2.4, −1.9)	32.3° ($P < .0001$)
Max ER from 40°-20° of hip flexion	−1.5° per mm ($P < .0001$) 95% CI: (−1.6, −1.4)	−0.2° per mm ($P < .0001$) 95% CI: (−0.3, −0.1)	−1.5° per mm ($P < .0001$) 95% CI: (−1.7, −1.4)	19.5° ($P < .0001$)
Max ER from 10° hip flexion to 10° hip extension	−2.2° per mm ($P < .0001$) 95% CI: (−2.3, −2.1)	−0.3° per mm ($P < .0001$) 95% CI: (−0.4, −0.2)	−2.1° per mm ($P < .0001$) 95% CI: (−2.2, −2.0)	27.3° ($P < .0001$)
Max ER from 20°-40° hip extension	−3.2° per mm ($P < .0001$) 95% CI: (−3.4, −3.0)	−0.6° per mm ($P < .0001$) 95% CI: (−0.8, −0.4)	−2.8° per mm ($P < .0001$) 95% CI: (−2.9, −2.6)	36.4° ($P < .0001$)
Maximum extension	−5.2° per mm ($P < .0001$) 95% CI: (−5.4, −4.9)	−0.4° per mm ($P = .0007$) 95% CI: (−0.6, −0.2)	−4.8° per mm ($P < .0001$) 95% CI: (−5.1, −4.5)	66.1° ($P < .0001$)

Table 8. The Effects of Limb Shortening Through the Acetabular and Femoral Component on ROMBI (Series 4-6)

ROM	Limb Shortening Through the Acetabular Component (High Hip Center)	Limb Shortening Through the Femoral Component (Stem Subsidence)	Acetabular Shortening With Femoral Lengthening
Max IR from 30°-50° of hip flexion	−2.3° per mm ($P < .0001$) 95% CI: (−1.8, −2.8)	−1.2° per mm ($P < .0001$) 95% CI: (−1.5, −0.8)	−1.4° per mm ($P < .0001$) 95% CI: (−0.9, −1.8)
Max IR from 60°-80° of hip flexion	−1.2° per mm ($P < .0001$) 95% CI: (−1.0, −1.4)	−0.2° per mm ($P = .0112$) 95% CI: (−0.3, 0.0)	−1.2° per mm ($P < .0001$) 95% CI: (1.0, 1.4)
Max IR from 90°-110° of hip flexion	−2.2° per mm ($P < .0001$) 95% CI: (−1.9, −2.5)	0.4° per mm ($P < .0001$) 95% CI: (0.2, 0.5)	−2.4° per mm ($P < .0001$) 95% CI: (−2.1, −2.7)
Maximum flexion	−1.8° per mm ($P < .0001$) 95% CI: (−1.7, −1.9)	0.3° per mm ($P < .0001$) 95% CI: (0.2, 0.3)	−1.9° per mm ($P < .0001$) 95% CI: (−1.7, −2.0)
Max ER from 60°-50° of hip flexion	−1.0° per mm ($P < .0001$) 95% CI: (−0.6, −1.3)	−2.00° per mm ($P < .0001$) 95% CI: (−2.3, −1.7)	−0.8° per mm ($P < .0001$) 95% CI: (−1.2, −0.5)
Max ER from 40°-20° of hip flexion	−0.5° per mm ($P < .0001$) 95% CI: (−0.4, −0.6)	−0.5° per mm ($P < .0001$) (−0.6, −0.4)	−0.1° per mm ($P = .3950$) 95% CI: (−0.1, 0.2)
Max ER from 10° hip flexion to 10° hip extension	−0.6° per mm ($P < .0001$) 95% CI: (−0.5, −0.7)	−0.2° per mm ($P < .0001$) 95% CI: (−0.3, −0.1)	−0.5° per mm ($P < .0001$) 95% CI: (−0.4, −0.6)
Max ER from 20°-40° hip extension	−1.1° per mm ($P < .0001$) 95% CI: (−0.9, −1.3)	−0.1° per mm ($P = .0122$) 95% CI: (−0.2, 0.0)	−0.9° per mm ($P < .0001$) 95% CI: (0.7, 1.0)
Maximum extension	−2.4° per mm ($P < .0001$) 95% CI: (−2.2, −2.6)	No estimate	−2.3° per mm ($P < .0001$) 95% CI: (2.1, 2.5)

Table 9. The Effects of an Elevated Liner Length and Longer Femoral Head on ROMBI (Series 7-9)

ROM	Decreased Acetabular Liner Length	Decreased Femoral Neck Length	Decreased Liner Length With Increased Femoral Neck Length
Max IR from 30°-50° of hip flexion	−2.3° per mm ($P = .0013$) 95% CI: (−0.9, −3.7)	−3.2° per mm ($P < .0001$) 95% CI: (−1.8, −4.5)	0.1° per mm ($P = .9236$) 95% CI: (−1.3, 1.4)
Max IR from 60°-80° of hip flexion	−1.5° per mm ($P < .0001$) 95% CI: (−1.0, −2.0)	−1.3° per mm ($P < .0001$) 95% CI: (−0.8, −1.8)	−0.6° per mm ($P = .0103$) 95% CI: (−1.1, −0.2)
Max IR from 90°-110° of hip flexion	−2.8° per mm ($P < .0001$) 95% CI: (−1.9, −3.6)	−1.2° per mm ($P = .0002$) 95% CI: (−0.6, −1.8)	−1.8° per mm ($P < .0001$) 95% CI: (−2.5, −1.0)
Maximum flexion	−2.0° per mm ($P < .0001$) 95% CI: (−1.6, −2.5)	−0.7° per mm ($P < .0001$) 95% CI: (−0.5, −0.8)	−1.5° per mm ($P < .0001$) 95% CI: (−1.9, −1.1)
Max ER from 60°-50° of hip flexion	−1.6° per mm ($P = .0022$) 95% CI: (−0.6, −2.6)	−1.3° per mm ($P = .0113$) 95% CI: (−0.3, −2.3)	−0.6° per mm ($P = .1989$) 95% CI: (−1.6, 0.3)
Max ER from 40°-20° of hip flexion	−1.0° per mm ($P < .0001$) 95% CI: (−0.8, −1.3)	−0.6° per mm ($P < .0001$) 95% CI: (−0.4, −0.9)	−0.5° per mm ($P < .0001$) 95% CI: (−0.8, −0.3)
Max ER from 10° hip flexion to 10° hip extension	−1.6° per mm ($P < .0001$) 95% CI: (−1.3, −2.0)	−0.8° per mm ($P < .0001$) 95% CI: (−0.5, −1.1)	−0.9° per mm ($P < .0001$) 95% CI: (−1.2, −0.5)
Max ER from 20°-40° hip extension	−2.3° per mm ($P < .0001$) 95% CI: (−1.9, −2.8)	−1.1° per mm ($P < .0001$) 95% CI: (−0.6, −1.5)	−1.5° per mm ($P < .0001$) 95% CI: (−1.9, −1.1)
Maximum extension	−3.9° per mm ($P < .0001$) 95% CI: (−3.1, −4.7)	−1.9° per mm ($P = .0022$) 95% CI: (−0.8, −2.9)	−2.8° per mm ($P < .0001$) 95% CI: (−3.6, −2.0)