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Publication Date

2025-02-27

DOI

10.2460/ajvr.24.12.0379

AJVR

Changes in cup inclination impact impingement-free hip motion after canine total hip replacement

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Objective
To evaluate the effects of changes in prosthetic cup inclination on impingement-free hip abduction, adduction, and internal and external rotation after simulated total hip replacement in dogs.

Methods
For 6 dogs, CT scans of the hip region were used to prepare 3-D surface models of cementless total hip replacement. For each dog, 15 models with cup inclination ranging from −35° to 35° in 5° increments were prepared using computer-aided design software. For each implant position, impingement-free hip motion in abduction, adduction, and internal and external rotation was evaluated using a custom-built computer program for hip flexion/extension angles ranging from 50° to 160° in 5° increments.

Results
A total of 7,920 computer simulations were conducted. Increased cup inclination led to decreased impingement-free abduction in hip extension and increased abduction in hip flexion. Decreased cup inclination led to decreased abduction at all hip angles. Maximal inclination led to increased external rotation in full hip extension, and maximal declination led to increased internal rotation and adduction in full hip flexion.

Conclusions
During total hip replacement, changes in cup inclination influence hip abduction and, to a lesser extent, internal rotation and adduction in flexion and external rotation in extension. The assessment of intraoperative impingement should include abduction, extension combined with external rotation, and flexion combined with adduction and internal rotation.

Clinical Relevance
The inclination of a truncated cup influences impingement-free abduction. Inclination should be controlled during cup insertion to keep the prosthetic neck in the central portion of the cup truncation during abduction.

Keywords: dog, total hip replacement, computer-aided design, prosthetic cup inclination, impingement

Luxation poses a significant challenge after canine total hip replacement (THR) because it is common and debilitating. The reported incidence in the literature ranges from 1.8% to 12%.[1–3] Several risk factors for luxation have been identified, including preoperative hip joint luxation,[3] suboptimal cup position,[2,4,5] and anatomic or prosthetic impingement.[6] In human THR, the concept of the implant safe zone, defined as the angles of cup anteversion and cup inclination that minimize the likelihood of luxation, was introduced in 1978.[7] The definition of the implant safe zone has evolved to include an appropriate implant design and orientation for regular and undisturbed joint function without impingement.[8–12] Prosthetic impingement has been identified in 39% to 51% of retrieved THR implants in human patients.[13,14] Prosthetic impingement can lead to subluxation or luxation, accelerated implant wear, and poor postoperative function.[15,16] Risk factors for prosthetic impingement in human THR include extended femoral head flanges, a low

Received December 12, 2024
Accepted February 9, 2025
Published online February 27, 2025

doi.org/10.2460/ajvr.24.12.0379

ratio of head diameter to neck diameter,[13,17] elevated cup rims,[18] and excessive cup anteversion.[14,18] In silico methods, such as finite element analysis and computer-aided design (CAD) modeling, have been used to assess the impingement-free motion of various implant designs and orientations.[11,16,19] Modeling with CAD has also been used to assess the prosthetic motion of a canine THR system.[20]

During cup insertion, the angle of lateral opening (ALO), version, and inclination must be controlled.[21] Some acetabular cups have been designed with dorsal truncation to match the acetabular anatomy and improve impingement-free abduction.[22] While inclination is not relevant for hemispheric cups, it is relevant for cups with dorsal truncation. Cup orientation is determined by properly aligning the impaction axis with the cup alignment guide.[23] However, cup rotation around the impaction axis may not be controlled by the cup alignment guide. As a consequence, inadvertent cup rotation and malalignment toward cup inclination or declination can occur during cup insertion. While increased ALOs and retroversion have been identified as potential risk factors for postoperative luxation,[2,4,5] little is known about the effects of changes in cup inclination on the impingement-free motion of canine prosthetic hip joints with truncated cups.

The research presented here used CAD modeling to evaluate impingement-free hip motion following simulated THR in a group of dogs with hip dysplasia. The in silico effects of cup inclination and declination on postoperative impingement-free hip motion were assessed. The hypotheses were that cup rotation around its axis of impaction would alter measured cup inclination and truncated face version and that cup rotation would lead to a loss of impingement-free adduction, abduction, internal rotation, and external rotation of the hip joint.

Methods

Sampling

The medical records of dogs presented to the University of California, Davis from January 1, 2023, through July 1, 2023, were searched electronically to identify canine patients who had undergone CT scanning for surgical planning before THR surgery. Dogs were eligible for inclusion if their body weight ranged from 30 to 45 kg at the time of evaluation because these dogs had identical prosthetic neck and head sizes. Dogs were excluded if new bone formation obscured the cranial or caudal acetabular margins or if the proximal portion of the femur was deformed. Femoral deformity was defined as a neck-shaft angle < 140° or > 150°, femoral anteversion < 15° or > 35°, or severe (grade III or IV) trochanteric overhang.[24–26]

Computer-aided design virtual THR

Computed tomography images were obtained using a helical scanner (GE LightSpeed; GE) under IV sedation with dexmedetomidine combined with butorphanol. A 3-D surface model of the pelvis and femur was created using CAD software (Mimics, version 26.0; Materialise).[27]

Computer-simulated cup and stem implantation were performed in the right hemipelvis according to implantation guidelines.[23] Simulations were performed by 2 investigators with experience in total hip replacement and CAD (PYC and DML) who reached consensus regarding final implant positions. For prosthetic cup implantation, the cup that fit the acetabular margins was maximally medialized without penetrating the medial acetabular wall. The cup was oriented so that its ALO, retroversion, and inclination matched the anatomy.[27] For femoral stem implantation, stem size was selected as the largest implant that fit the proximal part of the femur at its recommended position without endosteal contact.[23] The stem was coaxial with the centerline of the femoral canal in the proximal half of the femur. Femoral stem anteversion matched the natural femoral anteversion by fitting the prosthetic head to the femoral head in the transverse plane.[23]

To simulate intraoperative cup malposition, multiple cup orientations were set by rotating the cup around its axis of impaction (ie, the central axis perpendicular to the open cup face). With anatomic cup position defined as 0°, the cup was rotated from −35° to +35° in 5° increments, for a total of 15 cup positions for each dog **(Figure 1)**. A positive inclination value indicated a more inclined position (counterclockwise rotation of the cup in the right hemipelvis), and a negative inclination value indicated a more declined position. Pelves with cups implanted at each rotation angle and the femur with an implanted stem were exported as surface tessellation stereolithography files for analysis.

Bone-embedded anatomical coordinate systems and measurement of cup position

All virtual THRs, cup angle adjustments, and anatomic coordinate systems were created using medical CAD planning software (3-matic, version 18.0; Materialise). Pelvic and femoral Cartesian anatomic coordinate systems (ACS) were created **(Figure 2)**. Cup position was measured after virtual THR and after each cup rotation using the pelvic ACS **(Figure 3)**.

Range-of-motion analysis

Impingement-free prosthetic hip joint motion was calculated for all simulation models using a custom computer software program generated with a commercially available simulation software (MATLAB; MathWorks Inc). Range-of-motion (ROM) analysis was formulated as a root-searching problem, with a zero-crossing point indicating the maximal hip angle. The problem formulation employed Boolean logic, in which the Boolean value was determined by assessing the occurrence of collisions between the acetabular and femoral components using a point-in-polyhedron test.[20,28] The bisection method was applied to solve this problem, with the termination set at a hip angle change of 0.1°. The allowable ROM of the THR was determined as the maximal angle of abduction/adduction and internal/external rotations of the femoral component within the acetabular component,[20,29] measured at 5° increments at hip joint angles ranging

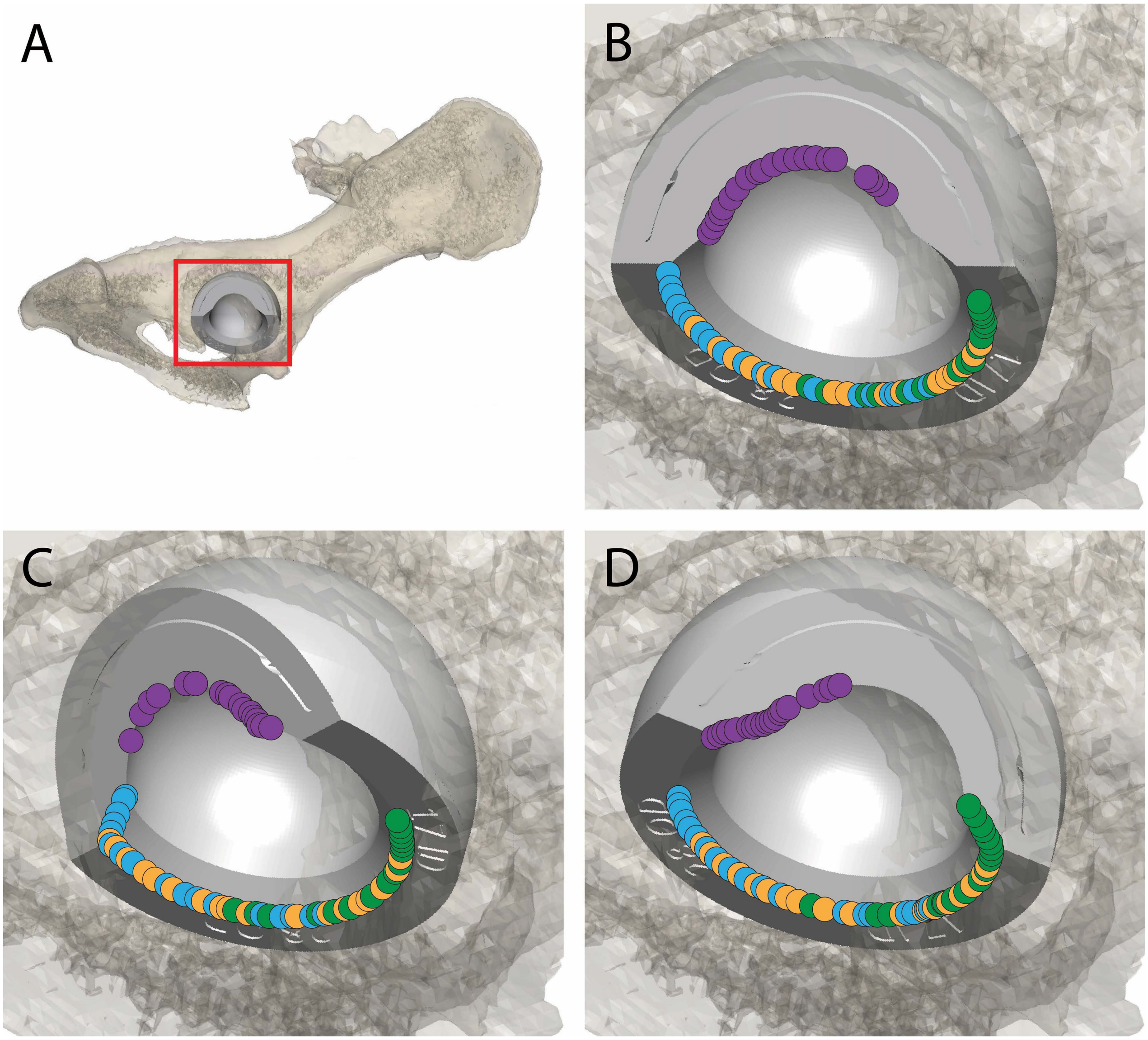

Figure 1—Rendering images showing a representative simulated right total hip replacement with varying cup inclinations. When the cup had anatomic (0°) inclination (A), the sites of impingements in abduction (purple dots), adduction (orange dots), internal rotation (green dots), and external rotation (blue dots) were evenly distributed around the cup (B). When the cup was maximally inclined (+35°), the external rotation contact points shifted caudally and dorsally onto the truncated cup face (C). When the cup was maximally declined (−35°), the abduction contact points shifted caudally and ventrally on the truncated cup face, and the internal rotation contact points shifted cranially and dorsally on the open cup face and onto the truncated cup face (D). These contact point shifts were responsible for changes in impingement-free hip motion.

from 50° to 160°, without constraints or limitations from bony structures. Regional soft tissues were not included in the assessment. The point of collision was documented for each point-in-polyhedron test.

Statistical analysis

The distribution of measured cup orientation and impingement-free joint angles was examined for normality using the Shapiro-Wilk and Anderson-Darling tests, respectively. Relationships between cup rotation and measured inclination, anteversion, and ALO were examined using general regression analysis for normally distributed data. Spearman rank correlation was used for non-normally distributed data.

To evaluate the effect of acetabular cup rotation on hip ROM after THR surgery, a mixed-model analysis was employed with cup rotation, hip flexion/extension, and their interaction as fixed effects. Measurements of hip internal rotation, external rotation, abduction, and adduction served as the dependent variables. Repeated measures and subject variability were accounted for by including individual dogs as a random effect. The significance of main effects and interactions was assessed using *F* tests. Fixed-effect parameter estimates were evaluated to determine whether cup rotation had a significant effect on ROM angle at each hip flexion/extension angle, with a *P* value threshold of .05 indicating

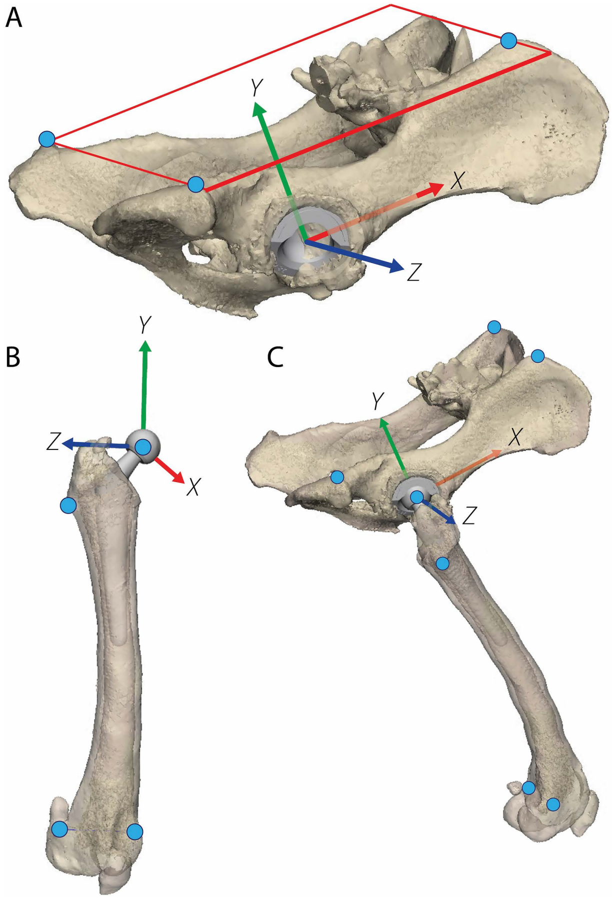

Figure 2—To create the computer rendering of the simulated total hip replacement, anatomic coordinate systems (ACS) of the pelvis (A) and the femur (B) were created. For the pelvic ACS (A), the dorsal pelvic plane was defined as the plane containing the left and right ischiatic tuberosity and the right tuber sacrale.[27,37] The dorsoventral Y-axis was the vector perpendicular to the dorsal pelvic plane, directed dorsally. The mediolateral axis (Z-axis) was the line connecting the ischiatic tuberosities, directed to the right. The craniocaudal axis (X-axis) was the line perpendicular to the Y- and Z-axes, directed cranially. For the femoral ACS (B), the femoral plane was defined as the plane intersecting the medial and lateral epicondyles and the distal aspect of the greater trochanter. The craniocaudal axis (X-axis) was the vector perpendicular to the femoral plane, directed cranially. The mediolateral axis (Z-axis) was the line connecting the lateral and medial epicondyles, directed to the right. The Y-axis was the line perpendicular to the X- and Z-axes, directed dorsally.[38] The ACS origins were the centroids of the cup and femoral head. The femoral and pelvic ACS were matched by rotating the femur about the centroid of the femoral head (C).

statistical significance. Post hoc analysis was performed to examine differences in impingement-free hip motion among cup positions using pairwise Dunnett null hypothesis tests and to determine whether these differences were > 5° using equivalence tests. The ROM at the anatomic cup position (cup rotation = 0°) was defined as a reference. After applying a Bonferroni correction, statistical significance for pairwise tests was $P < .0035$.

Results

During the study period, 26 dogs underwent CT and CAD-based virtual THR planning. Twelve dogs were excluded due to severe new bone formation (n = 7) or abnormal femoral anatomy (n = 5). Eight dogs were excluded due to weighing < 30 kg or > 45 kg. Six dogs remained, 1 each of the following breeds: Bernese Mountain Dog, Malinois, German Shepherd Dog, Golden Retriever, Labrador Retriever, and Rottweiler. Median body weight was 34.5 kg (range, 30.0 to 45.0 kg). Acetabular cup sizes were 24 mm (3), 26 mm (2), or 28 mm (1), and femoral stem sizes were #7 (2), #8 (1), or #9 (3). Prosthetic heads with a diameter of 17 mm and a neck length of +0 were fitted to the femoral stems. Testing 4 directions of hip motion at 22 hip flexion/extension angles, with 15 cup inclination positions for 6 virtual prosthetic hip joints, yielded 90 measurements of cup inclination, version, and ALO and 7,920 CAD simulations.

The median measured inclination, version, and ALO after simulated THR with anatomic cup placement were −32.0° (range, −36.3° to −20.9°), 6.1° (range, 2.93° to 10.1°), and 49.8° (range, 46.8° to 56.2°) and after all simulated cup rotations were −30.4° (range, −61.2° to −7.1°), 6.4° (range, −40.0° to 33.2°), and 49.8° (range, 46.8° to 56.2°), respectively. Measured inclinations were normally distributed, whereas measured ALO and version were not normally distributed. Cup rotation and measured inclination ($R = 0.98$; $P < .001$) and cup rotation and anteversion ($\rho = 0.98$; $P < .001$) were correlated, but cup rotation and ALO were not correlated ($\rho = 0.00$; $P = 1.000$).

Impingement-free abduction, adduction, and internal and external rotation measurements did not follow a normal distribution. The sites of impingement (neck-cup contact points) included the truncated (abduction) and open (adduction and internal and external rotation) cup faces. These sites varied based on changes in cup inclination (Figure 1).

Abduction angle

Both cup rotation and hip flexion/extension angle influenced the hip abduction angle with interaction ($P < .001$; **Table 1**). Cup rotation had a clear impact on the impingement-free abduction ROM at all hip joint flexion/extension angles except at 110° ($P = .852$). At low hip angles, cup rotation had a strong positive effect on hip abduction; that positive effect gradually decreased as hip angles increased and became negative at high hip angles **(Figure 4)**. The largest mean ± SD abduction was 117.1° ± 4.4°, with the hip flexion/extension at 50° and the cup at +35°. The smallest mean abduction was 68.9° ± 3.7°, with the hip flexion/extension at 160° and the cup at +35°. Compared with anatomic cup placement, all cup rotations at all hip flexion angles led to differences in abduction angle over 5°, except the +5° cup with the hip at 55° ($P = .002$), 60° ($P = .003$), 65° ($P < .001$), 70° ($P = .002$), and 75° ($P = .002$); the +25° cup with the hip at 105° ($P = .002$); the +30° cup with the hip at 100° ($P < .001$); the +35° cup with the hip at 95° ($P < .001$); the −5° cup with the hip at

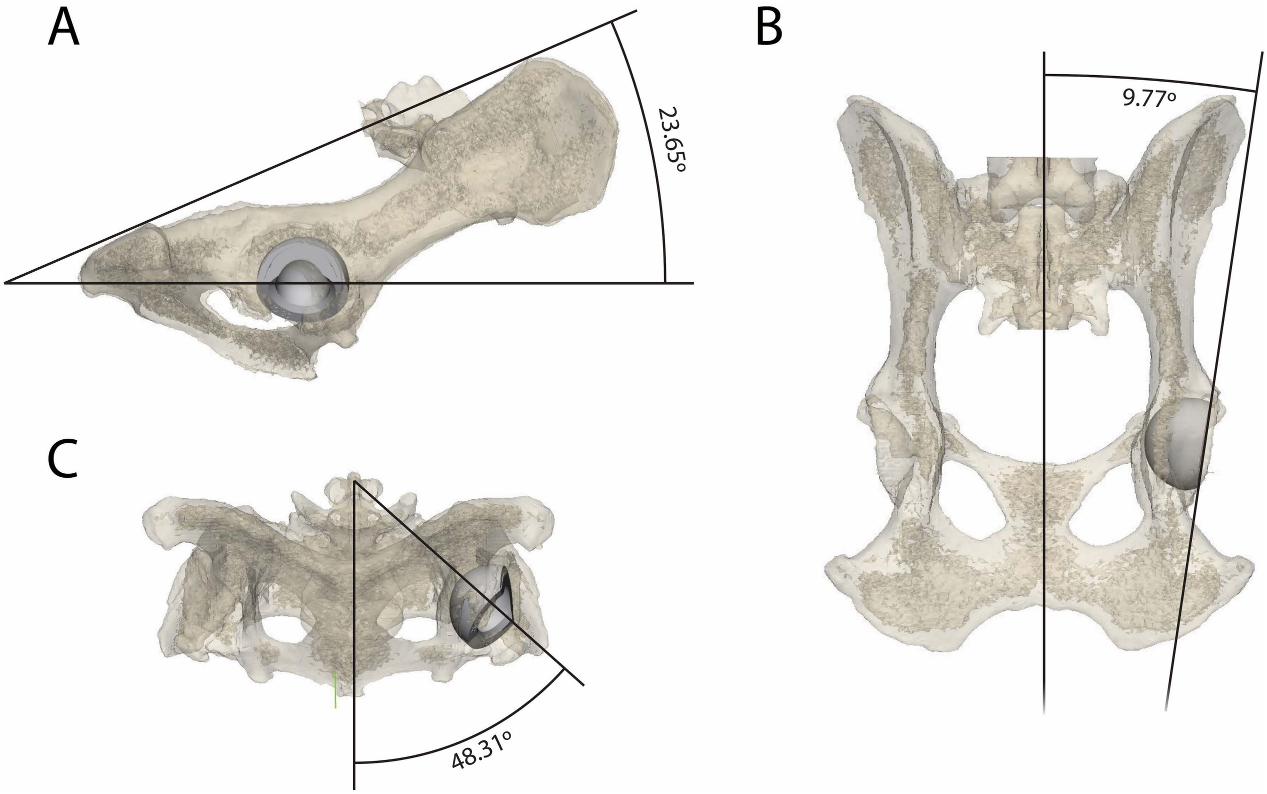

Figure 3—The measured cup inclination was the angle formed by the intersecting line of the truncated and open cup faces and the dorsal pelvic plane, projected onto the pelvic sagittal (XY) plane (A). The measured cup angle of lateral opening (ALO) was the angle between the axis perpendicular to open cup surface and the dorsal pelvic plane, projected onto the pelvic frontal (YZ) plane (B). The measured truncated face version was the angle formed by the intersecting line of the truncated and open cup faces and the bisecting plane across the right and left ischiatic tuberosities, projected onto the pelvic dorsal (XZ) plane (C). For the dog shown in the figure, the measured inclination, ALO, and truncated version were −23.65°, 48.31°, and 9.77°, respectively.

Table 1—Changes in mean ± SD impingement-free hip joint motion in abduction, adduction, and external and internal rotation at 6 angles of hip flexion/extension after total hip replacement in 6 dogs.

Motion parameter	Cup position	50°	60°	90°	120°	150°	160°
Abduction	Neutral cup (0°)	96.8[a] ± 5.3	94.8[a] ± 4.1	93.9[a] ± 2.1	92.4[a] ± 2.3	85.2[a] ± 7.3	87.8[a] ± 3.8
	Inclined cup (+35°)	117.1[b] ± 4.4	114.3[b] ± 4.0	97.5[a] ± 5.7	77.8[b] ± 6.2	69.9[b] ± 3.6	68.9[b] ± 3.7
	Declined cup (−35°)	86.8[c] ± 8.1	81.6[c] ± 6.5	74.3[b] ± 2.3	74.7[b] ± 3.5	85.2[a] ± 7.3	90.8[a] ± 7.1
Adduction	Neutral cup (0°)	7.0[a] ± 6.3	17.7 ± 5.5	40.2 ± 3.9	46.8 ± 4.3	39.4 ± 7.0	33.5 ± 8.6
	Inclined cup (+35°)	6.8[a] ± 6.0	17.4 ± 5.5	39.9 ± 4.2	46.7 ± 4.2	39.7 ± 6.7	33.9 ± 8.0
	Declined cup (−35°)	11.5[b] ± 3.5	19.2 ± 4.9	40.6 ± 3.8	47.1 ± 4.3	39.5 ± 7.4	33.5 ± 9.0
External rotation	Neutral cup (0°)	79.1 ± 12.3	87.9 ± 10.8	98.5 ± 9.4	86.6 ± 11.0	51.7[a] ± 12.7	39.1[a] ± 13.3
	Inclined cup (+35°)	78.2 ± 11.4	87.3 ± 10.3	98.5 ± 9.4	86.3 ± 11.0	54.8[b] ± 11.6	45.6[b] ± 11.6
	Declined cup (−35°)	79.8 ± 13.7	88.3 ± 11.5	99.0 ± 9.7	86.3 ± 11.2	51.3[a] ± 13.2	38.6[a] ± 13.6
Internal rotation	Neutral cup (0°)	10.8[a] ± 10.2	23.3[a] ± 11.0	59.3 ± 13.0	95.9 ± 16.6	118.1 ± 17.6	119.5 ± 17.3
	Inclined cup (+35°)	10.3[a] ± 9.6	22.8[a] ± 10.6	58.5 ± 12.3	95.37 ± 17.1	117.8 ± 18.2	119.4 ± 17.8
	Declined cup (−35°)	32.6[b] ± 6.2	37.8[b] ± 7.6	60.9 ± 13.2	96.5 ± 16.5	118.7 ± 16.8	120.0 ± 16.5

[a–c]Angles of hip flexion/extension. Within each motion parameter and within each angle of hip flexion/extension, mean impingement-free motion of cups with increased (+35°) or decreased inclination (−35°) with different superscript letters differs statistically (*P* < .0035) from mean impingement-free motion of cups in neutral position (0°).

60° (*P* < .001), 70° (*P* < .001), and 75° (*P* = .003); the −30° cup with the hip at 150° (*P* = .003); and the −35° cup with the hip at 155° (*P* = .001). The results of the post hoc analysis are shown in **Supplementary Tables S1 and S2.**

Adduction angle

Both hip flexion (*P* < .001) and cup rotation (*P* = .026) influenced hip adduction without interaction (*P* = .990). The amount of impingement-free adduction relative to hip flexion/extension followed a

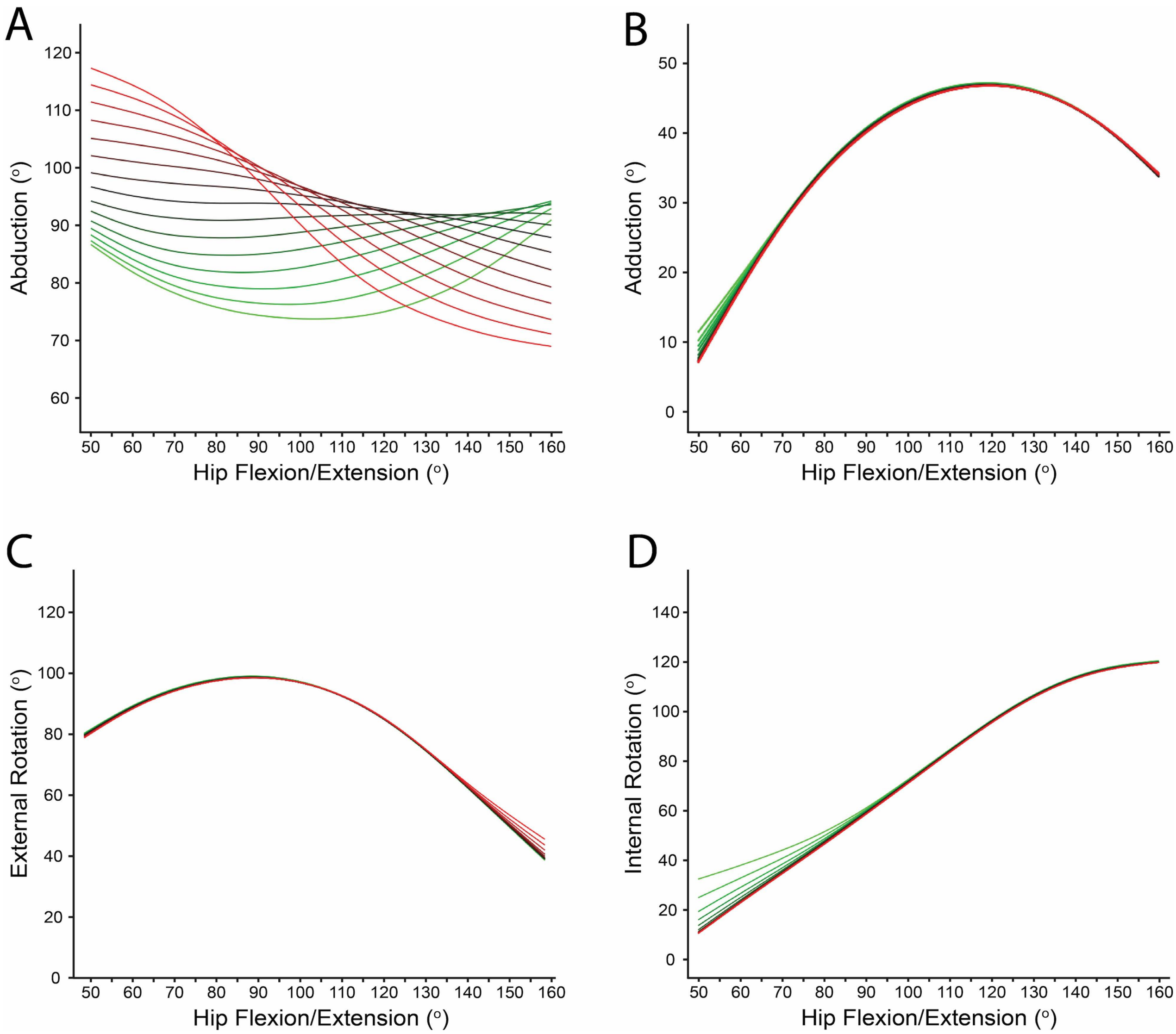

Figure 4—The mean impingement-free hip motions of 90 simulated total hip replacements from 6 dogs for hip angles ranging from 50° to 160° of flexion/extension are shown. Fifteen cup inclinations, ranging from +35° to −35° in 5° increments, are shown with a color gradient: maximal cup inclination (+35°) is shown in bright red, anatomic inclination is shown in black, and maximal cup declination (−35°) is shown in bright green. Abduction was highly affected by changes in cup inclination (A). Inclination led to increased impingement-free abduction in hip flexion and decreased abduction in hip extension. Declination led to a loss of impingement-free abduction at all hip angles. Impingement-free adduction was minimally impacted by changes in cup inclination (B). A minor increase in adduction was observed in hip flexion with maximal cup declination. Impingement-free external rotation was minimally impacted by changes in cup inclination (C). A minor increase in external rotation was observed in hip extension with maximal cup inclination. Impingement-free internal rotation was slightly impacted by cup declination (D). A minor increase in internal rotation was observed in hip flexion with maximal cup declination.

parabolic curve regardless of cup rotation (Figure 4). Minimal and maximal adduction were detected with the hip joint at 50° and 120°, respectively. With the hip flexion/extension at 50°, the mean adduction was 6.8° ± 6.0°, 7.0° ± 6.3°, and 11.5° ± 3.5° when the cup was at +35°, at anatomic cup placement, and at −35°, respectively. With the hip flexion/extension at 120°, the mean adduction was 46.7° ± 4.2°, 46.8° ± 4.3°, and 47.1° ± 4.3° when the cup was at +35°, at anatomic cup placement, and at −35°, respectively. Adduction was influenced by cup rotation with the hip at 50° (P = .013). Compared to anatomic cup position, adduction increased with the cup at −35° and the hip joint at 50° (P < .001) and 55° (P =.003) and with the cup at - 30° and the hip joint at 50° (P = .003). The adduction increase was > 5° when cup rotation was −35° with the hip joint at 50°.

Internal rotation

Both cup rotation and hip flexion/extension influenced internal rotation (P < .001) with interaction (P < .001). Cup rotation negatively influenced internal rotation. Hip extension positively influenced internal rotation (Figure 4). The influence of cup rotation on internal rotation decreased as hip angle increased, with effects observed at lower hip angles (50°, 55°, 60°, 65° [$P < .001$], and 70° [$P = .046$]). Minimal internal rotation occurred with the hip at 50°, and maximal internal rotation occurred at 160°. At 50°, the mean hip internal rotation was 10.3° ± 9.6°, 10.8° ± 10.2°, and 32.6° ± 6.2° when the cup was at +35°, at anatomic cup placement, and at −35°, respectively. At 160°, the mean hip internal rotation was 119.4° ± 17.8°, 119.5° ± 17.3°, and 120.0° ± 16.5° when the cup was at +35°, at anatomic cup placement, and at −35°, respectively. Compared to anatomic cup position, increases in internal rotation angle were detected when cup rotation was −25°, −30°, and −35° with hip angles ranging from 50° to 75° ($P < .001$), when cup rotation was −30° and −35° with the hip at 80° ($P < .001$), and when cup rotation was −35° with the hip at 85° ($P < .001$). The increase in internal rotation compared to anatomic cup position was > 5° with the cup at −35° and hip flexion/extension ranging from 50° and 75° and with the cup at −30° and hip flexion/extension ranging from 50° and 70°.

External rotation

Hip flexion/extension ($P < .001$) but not cup rotation ($P = .155$) affected the hip external rotation angle with interaction ($P < .001$). The amount of impingement-free external rotation relative to hip flexion/extension formed a parabolic curve, with maximal external rotation when the hip was at 90° (Figure 4). Cup rotation positively influenced external rotation with the hip in extension and negatively influenced external rotation with the hip in flexion. External rotation was influenced by cup rotation with the hip at 150° ($P = .021$) and 155° ($P < .001$). Minimal and maximal external rotation were detected with the hip at 160° and 90°, respectively. At 160°, the external rotation angle was 38.6° ± 13.6°, 39.1° ± 13.3°, and 45.6° ± 11.6° with the cup at +35°, at anatomic cup placement, and −35°, respectively. At 90°, the external rotation angle was 99.0° ± 9.7°, 98.5° ± 9.4°, and 98.5° ± 9.4° with the cup at +35°, at anatomic cup placement, and −35°, respectively. Compared to an anatomic cup position, increases in external rotation angle were detected with the hip at 150° and cup at +35° ($P < .001$), with the hip at 155° and cup at +30° ($P = .001$) and +35° ($P < .001$), and with the hip at 160° and cup +30° ($P < .001$), and +35° ($P < .001$). The increase in external rotation compared to an anatomic cup position was > 5° with the cup at +35° and the hip at 155°, and with the cup at +30° and +35° and the hip at 160°.

Discussion

In acetabular cups with a truncated dorsal cup surface, clockwise and counterclockwise changes in cup rotation alter the position of the truncated cup surface and influence the overall cup orientation and impingement-free motion of the prosthetic joint. In the study presented here, cup rotation around the impaction axis resulted in changes in measured inclination and truncated version angle. Also, cup rotation influenced impingement-free hip abduction, adduction, and internal rotation, whereas the position of the hip joint in the sagittal plane (flexion and extension) influenced impingement-free hip abduction, adduction, internal rotation, and external rotation. When both cup rotation angle and hip flexion/extension angle were considered, cup rotation led to significant changes in the impingement-free abduction angles at most hip joint flexion angles. Cup declination increased internal rotation and adduction in full hip flexion (50°), and cup inclination increased external rotation in full hip extension (160°).

Increased cup inclination led to increased measured inclination and truncated face retroversion, and increased declination led to decreased measured inclination and truncated face retroversion. We therefore accepted the hypothesis that changes in cup rotation led to changes in measured cup inclination and truncated face version. The observed changes in cup inclination and truncated face version resulting from cup rotation were caused by the spatial relationship between the cup and pelvis ACS. The intersecting line between the truncated and open cup surfaces was used to measure version and inclination.[21] The 2 cup surfaces are at a 45° angle to each other.[22] Changes in angulation of the truncated or open cup surface around the cup center affect the direction of the intersecting line. Because of the cup's oblique position within the pelvis ACS, changes in cup orientation around the center cup result in changes in its relative angular relationship to the pelvis dorsal plane (ie, the measured truncated face version), the sagittal plane (measured inclination), and the frontal plane (measured ALO). In the present study, cup rotation did not alter the position of the open cup surface, but it altered the position of the truncated surface, which, in turn, affected the direction of the intersecting line between the open and truncated cup faces and changed the measured inclination and truncated version. Our findings are consistent with the results of a previous study,[22] which reported that, with fixed ALO and cup rotation angle, alteration of the open face orientation along its cranial-caudal axis would lead to changes in measured version angle. These findings are particularly important during cup insertion and adjustment after insertion. The oblique position of the cup within the pelvic ACS means that adjustments of the truncated face, open face, or both during surgery will lead to changes in all measured cup orientation angles.

Based on study findings, the hypothesis that changes in cup rotation lead to a change of impingement-free abduction was accepted, and the hypotheses that changes in cup rotation lead to a loss of impingement-free adduction, internal rotation, and external rotation were rejected. Adduction and internal and external rotation had a similar pattern of change of motion for all hip flexion/extension angles that was minimally influenced by cup rotation. In contrast, impingement-free abduction had a unique pattern of change of motion resulting from cup rotation at all hip flexion/extension angles. The loss of abduction due to cup rotation seemingly resulted from the spatial relationship of the prosthetic neck and cup edge during flexion and extension. Impingement in abduction occurred at the edge of the truncated cup face, whereas impingement in adduction, internal rotation, and external rotation mostly occurred at the edge of the open cup face. The truncated face of the cup allowed additional hip motion before impingement at the central area of the truncated cup face compared to its cranial and caudal aspects. Increased cup inclination resulted in increased truncated cup face retroversion, moving the cranial aspect of the truncated surface closer to the prosthetic neck and the caudal aspect of the truncated surface away from the prosthetic neck. This resulted in an increase in impingement-free abduction in flexion and a decrease in impingement-free abduction in extension. Conversely, cup declination resulted in increased truncated cup face anteversion, bringing the caudal aspect of the truncated surface closer to the prosthetic neck. The impingement points in abduction shifted to the caudal aspect of the truncated face, near the junction of the truncated and open cup faces. Increased impingement may also have been due to differences in chamfer (polyethylene edge) geometry between the open and truncated cup face. The open cup face had less chamfer than the truncated face. Decreased cup liner chamfer has been shown to negatively impact impingement-free hip motion.[30] The loss of impingement-free abduction resulting from changes in cup inclination could increase the likelihood of hip luxation in clinical patients. The position of the truncated cup face relative to the pelvis should therefore be controlled during cup impaction. Since increases in head-to-neck ratio[12] and changes in neck geometry[12,31] also improve impingement-free motion, they should also be considered in future total hip implant designs to decrease risks of luxation regardless of cup orientation.

Impingement-free motion in internal and external rotation were only influenced by extreme cup rotation angles in full flexion and extension, respectively. At the largest cup rotations, the truncated cup surface appeared protected against impingement during internal and external rotation. It is possible that the increased and decreased cup retroversion angles at extreme cup inclination and declination protected against impingement in internal and external rotation. However, a linear relationship of truncated cup face version angle on impingement-free hip internal and external rotation was not identified. Notably, only the position of the truncated cup face changed, but the position of the open cup face remained constant. In human THR, cup version angle has been described as an important aspect of impingement-free motion in internal and external rotation.[32] In recent studies[22,27] evaluating 3-D cup positioning, version was based on open-face version rather than truncated-face version. Similarly in dogs, changes in open-face version would possibly influence impingement-free internal and external rotation more than changes in truncated-face version. That should be evaluated in future research.

Although direct comparisons between studies are not possible, the impingement-free prosthetic hip joint motion observed in the current study was less than the physiologic hip joint motion reported in the literature. In 1 study,[33] maximum angles of passive hip abduction, adduction, internal rotation, and external rotation angle in normal hip joints were 85°, 27°, 55°, and 50°, respectively. In another study,[34] the maximal abduction, adduction, internal rotation, and external rotation angle at a walk and trot were 55.1°, 15.9°, 16.2°, and 28.4°. Hip flexion angle has been reported to be 48.7° during sit-to-stand activity.[35] Impingement may be more likely to occur during flexion with hip adduction, possibly combined with internal rotation. At full hip flexion, impingement can occur at 10° of internal rotation and adduction even when the cup position is anatomic. External rotation is also limited in full extension, albeit to a lesser extent. These findings are in agreement with the authors' subjective impression that prosthetic hip joint luxation resulting from impingement most often occurs when dogs transition from a sitting to a standing position and rarely occurs when dogs are walking or trotting. Kinematic studies investigating internal rotation and adduction angles of dogs during daily activities are necessary to help improve our understanding of the prosthetic hip motion needed to minimize the risk of impingement after THR in dogs and the clinical consequences of cup malposition.

Based on the findings of the current study, testing the prosthetic joint for impingement at various joint positions during THR is recommended. Excessive cup declination is likely to lead to a loss of impingement-free abduction at most hip angles. Intraoperative impingement assessment should therefore include abduction.

This study had limitations. While implants were realistically shaped and sized and were placed anatomically, no efforts were made to reproduce the preoperative geometric relationship of the femur and pelvis. The relative position of the femur and pelvis influenced the impingement-free motion of each individual joint but most likely did not alter the findings of the study since comparisons were made between anatomically placed cups and excessively inclined or declined cups. It is also possible that impingement after THR would be anatomic (femur-on-pelvis contact) rather than prosthetic.[8,36] Anatomic impingement was not evaluated in the current study. The simulations used in the current study assessed impingement-free motion in a single direction. Simulating motion in a single plane allowed a clearer assessment of the effects of inclination on prosthetic impingement. However, since functional hip joint movements occur simultaneously in all planes, the simulations in the current study do not represent hip mobility during various activities. Reproducing hip joint positions corresponding to specific activities would provide additional information on the effects of cup malposition on prosthetic impingement. Also, no effort was made to alter pelvic extension, pelvic tilt, or pelvic rotation during ROM measurements. These factors would be expected to influence (increase or decrease) the observed impingement-free prosthetic motion. Since all prosthetic stems had identical neck geometry and all prosthetic heads had a 17-mm diameter, all implants in the current study had identical head-to-neck ratios. Since head-to-neck ratios influence impingement-free prosthetic motion, the amplitude of change observed in the current study may not be extrapolated to other head and neck sizes or neck lengths. The findings of the current study, however, would likely be consistent across all component sizes.

In conclusion, changes in cup rotation around its impaction axis (inclination and declination) resulted in changes in measured inclination and in truncated cup face version. Cup declination led to decreased abduction angles at all hip angles. Increased cup inclination led to decreased hip abduction when hip flexion was < 75°. Intraoperative impingement assessment should include abduction, flexion combined with adduction and internal rotation, and extension combined with external rotation. Inclination should be controlled during cup insertion to keep the prosthetic neck in the central portion of the cup truncation during abduction.

Acknowledgments

The authors thank Movora for providing surface tessellation stereolithography files of the implants for computer-aided design simulations; Dr. Chrisoula Toupadakis Skouritakis, University of California, Davis, for the illustrations; and the Stat Lab, Department of Statistics, University of California, Davis, for statistical guidance.

Disclosures

Dr. Marcellin-Little is a member of the *AJVR* Scientific Review Board, but was not involved in the editorial evaluation of or decision to accept this article for publication.

No AI-assisted technologies were used in the composition of this manuscript.

Funding

The authors have nothing to disclose.

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Supplementary Materials

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