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Article

Impingement During Dislocation-Prone Activities in Acetabular Cups with Lipped and Standard Liners: A Geometric Model

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Abstract

Background/Objectives: Asymmetric acetabular liners used in Total Hip Arthroplasty (THA) are clinically successful in reducing revision associated with dislocation. The performance of an asymmetric liner is dependent on its positioning, although few studies have directly investigated the effects of variables such as cup orientation or extended rim position on outcomes such as impingement. Therefore, the aim of this study was to compare the incidence of impingement in THA with a standard and lipped liner. **Methods**: A THA was virtually implanted into a previously developed geometric model. Acetabular cups were placed in a range of clinically relevant orientations, and the model was moved through seven joint motions associated with dislocation-prone Activities of Daily Living (ADLs). The occurrence of implant–implant, implant–bone, and bone–bone impingement was assessed for the standard and lipped constructs across a total of 6,237 unique combinations of cup orientation and lipped liner apex rotations. **Results/Conclusions**: The model predicted that with both standard and lipped constructs, there were no component placement positions which avoided impingement for all ADLs. The number of impingement incidents was minimised when components were positioned at the higher end of the manufacturer's recommendations for cup inclination and anteversion. The use of a lipped liner increased the frequency of impingement events compared with the standard construct. However, for anterior impingement leading to posterior dislocation, this increase may be minimised by rotating the lip apex to a posterior-inferior position. Anterior lip apex placement tended to minimise the increase in the less critical posterior impingement.

Keywords: total hip arthroplasty; acetabular cup; lipped liners; asymmetric liners; impingement; dislocation; geometric model

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1. Introduction

Total Hip Arthroplasty (THA) is a widely used, successful surgical procedure. However, the incidence of revision is usually much higher in the first year following surgery compared with that of the 1–10-year period [1]. Dislocation is one of the most common reasons for early revision, defined as the complete and permanent loss of contact between the femoral head and cup. Alternatively, subluxation is a partial and temporary loss of contact which may lead to cup rim loading and bearing damage.

The causes of dislocation and subluxation are multi-factorial. One known risk factor is impingement, which is defined as abnormal or unwanted contact between the implant and/or bony interfaces that impedes range of motion. Three types of impingement can occur: implant–implant, bone–bone, and implant–bone. Implant–implant impingement may be influenced by design [2,3] and component placement [2,4,5]. Bone–bone impingement can be affected by both implant design and placement [6] as well as bone geometries [7]. It has been reported that subluxation and dislocation may also be related to inadequate soft tissue tension [8]. Posterior dislocation has been reported to occur more frequently than anterior dislocation following THA [9,10].

Whilst standard polyethylene liners articulating against metal or ceramic heads are a frequently used type of bearing surface, a number of acetabular components have been deployed to reduce the incidence of subluxation and dislocation. These include dual-mobility cups, larger-diameter heads, and polyethylene liners, which can be labelled generically as 'asymmetric', although several specific descriptions exist, such as lipped, augmented, hooded, elevated, face-changing, offset reorientating, and long posterior wall. Lipped liners specifically incorporate an elevated rim segment which extends beyond the standard hemispherical geometry of the liner to provide increased femoral head coverage and enhanced joint stability.

Registry data indicates that asymmetric designs comprise approximately 50–65% of liners implanted with cementless acetabular cups [11–13]. Asymmetric liners have been reported to have lower instability-related revision rates in comparison to standard designs [11–13]. Lipped liners, in particular, have been reported to have comparable rates of aseptic loosening to standard liners [13] and reduced joint instability, regardless of lip size, when used with a posterior approach [14]. However, improved outcomes do not apply to all asymmetric liners; for example, one study showed significantly better outcomes for long posterior wall components in comparison to hooded or offset reorientating liners [15].

The performance of an asymmetric liner is dependent on its positioning, which includes the cup orientation (inclination/anteversion) and the liner rotation within the cup. Only a small number of studies have directly investigated this relationship in vivo [16] or by using computer modelling [17,18]. However, the in vivo study was limited by a small cohort (14 hips in 14 patients) with variable cup orientations between patients, while the computational studies excluded bony geometries and therefore assessed only implant–implant impingement across a restricted range of cup inclination and/or anteversion angles.

Therefore, the aim of this study was to assess the incidence of impingement for standard and lipped liners during several dislocation-prone Activities of Daily Living (ADLs) across a broad range of cup orientations (inclination, anteversion) and lipped liner apex rotations using a geometric model which incorporates bony geometry.

2. Materials and Methods

2.1. Study Overview

A previously developed geometric model [19] was utilised to apply joint motions corresponding to seven dislocation-prone ADLs [20] to both standard and lipped constructs of the same diameter. The incidence and location of implant–implant, implant–bone, and bone–bone impingements were assessed across a comprehensive range of cup orientations and eight lipped liner apex rotations (Figure 1). This resulted in a total of 6237 unique impingement tests. Furthermore, the cross sections of the standard and lipped liners were compared, and the maximum range of motion (RoM) was assessed.

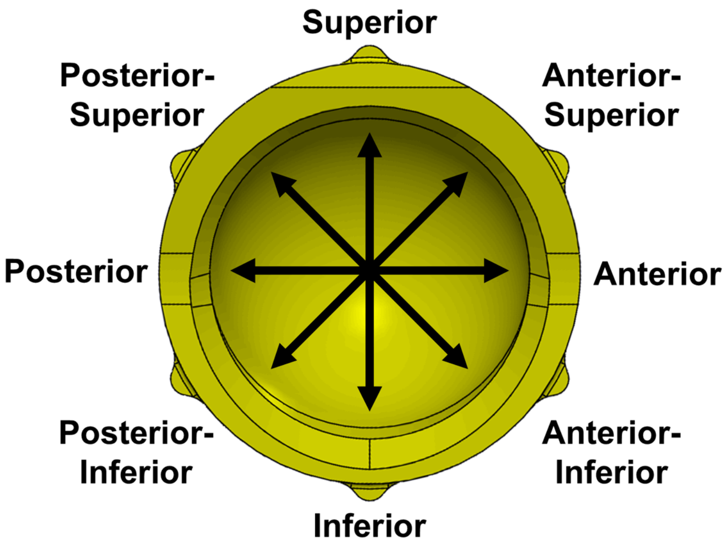

Figure 1. Nomenclature describing the eight lipped liner apex rotations investigated in this study. The arrows represent the position of the lip apex for each of the orientations considered.

2.2. Components and Component Placement

Components based on the geometries of a THA system were modelled using a commercially available computer-aided design (CAD) software package (SOLIDWORKS 2022; Waltham, MA, USA). The implants comprised a Corail® size 12 KS (collarless) stem and a 52 mm Pinnacle™ acetabular shell (DePuy Synthes; Warsaw, IN, USA) combined with either a 32 mm neutral (standard) polyethylene liner or a 32 mm lipped polyethylene liner. These were virtually implanted into a previously developed CAD model of a right hemi-pelvis and femur [19]. The femoral stem was positioned to conform with the geometry of the native femur, and the prosthetic head was aligned to the centre of the native head. After virtual reaming of the acetabulum to provide a hemispherical surface, the pelvis and femur were scaled to allow implantation of a 52 mm shell. A standard or lipped liner was then fitted. An experienced orthopaedic surgeon (T.B.) confirmed correct component positioning.

2.3. Activities Analysed

Joint motions of seven ADLs identified as being dislocation-prone following THA [20] were assessed in this study. These data described the motion of the femur relative to the pelvis. Joint motions for each of the ADLs comprised data from a single subject, which was most representative of the performance of a cohort of ten healthy subjects (five male and five female) with an average age of 49.7 years (range 44–59 years). The ADLs comprised five posterior dislocation-prone activities: bending to touch an object on the floor (STOOP), sit-to-stand from a low (SSL) or normal height chair (SSN), leg crossing whilst seated (XLG), and shoe tying whilst seated (TIE). In addition, there were two anterior dislocation-prone activities: upper body rotation whilst standing (PIVOT) and supine rolling (ROLL).

2.4. Geometric Modelling

Joint motions for the seven dislocation-prone ADLs were applied to the femur as angular rotations in three axes (flexion/extension, abduction/adduction, internal/external rotation). The model was run across a comprehensive range of cup inclination (30° to 70°) and anteversion (0° to 50°) angles in 5° increments for the standard liner and lipped liner, including each of the eight lipped liner apex rotations. Impingement was detected using the “interference detection” function in the SOLIDWORKS 2022 CAD software, which has been shown to detect low volumes of interference (>1 mm3) [19]. The type of impingement (implant–implant, implant–bone, bone–bone) was determined. Outputs were recorded in inclination versus anteversion matrices (9 × 11) describing the incidence and type of impingement for each unique combination of liner design (standard, lipped), lipped liner apex rotation, and ADL, referred to as the 'results matrices.'

For the standard liner and lipped liners, the number of ADLs resulting in impingement for a given cup position was determined. This number ranged from zero (no impingement during any ADL) to seven (impingement during all seven ADLs). Outputs were recorded in inclination versus anteversion matrices (9 × 11), referred to as the 'summary matrices.'

To compare the lipped constructs against a standard design, the difference in the number of impingement events at each cup orientation and rotation was calculated. These results were presented in a similarly formatted 'relative change matrices.' These results were further stratified by ADLs, resulting in anterior versus posterior impingement in isolation.

In all results matrices, the manufacturers' recommended range for cup angle was highlighted (inclination: 40° to 45°; anteversion: 15° to 20°) as well as a 'widened' range of more likely clinical positioning (increased by ±5°).

In each of these assessments, the model was used deterministically, with fixed increments in cup inclination, cup anteversion, and lipped liner apex rotation, with an equal weighting given to all scenarios investigated.

2.5. Range of Motion Analysis

The RoM of the standard and lipped constructs was determined in a single plane using the widest axis of the femoral neck. For the lipped constructs, RoM was calculated in a plane which intersects the apex of the lipped region.

3. Results

3.1. Geometric Modelling

A total of 6237 unique test cases were investigated, represented in 63 results matrices [21]. An example of the results matrices for the standard liner and a lipped liner orientated with a superiorly positioned (0°) lip apex is presented in Figure 2. Similar trends were observed across four of the five ADLs at risk of posterior dislocation (SSN, SSL, TIE and XLG). SSN was used as an exemplar and shows that for the standard liner (Figure 2a), implant–implant impingement occurred, but increasing inclination and, to a lesser extent, anteversion reduced the incidence of impingement. Impingement occurred during STOOP activities in all standard liner orientations, comprising implant–implant impingement at lower cup inclination and anteversion angles, which changed to bone–bone impingement as these increased. Similar trends were observed with the lipped liner during anterior impingement activities (Figure 2b), although the presence of the lip meant the impingement-free positions were noted at higher inclination and anteversion angles. The results of standard and lipped constructs were very similar when the two anterior dislocation ADLs (PIVOT and ROLL) were considered. This is because these ADLs do not involve hip flexion; hence, impingement occurs away from the lip apex when positioned superiorly. PIVOT did not result in impingement at <20° of anteversion, irrespective of inclination, above which implant–implant impingement occurred. ROLL resulted in bone–bone impingement at lower inclination and anteversion angles. Higher cup angles resulted in implant–implant impingement. There were no instances of implant-bone impingement detected in this study.

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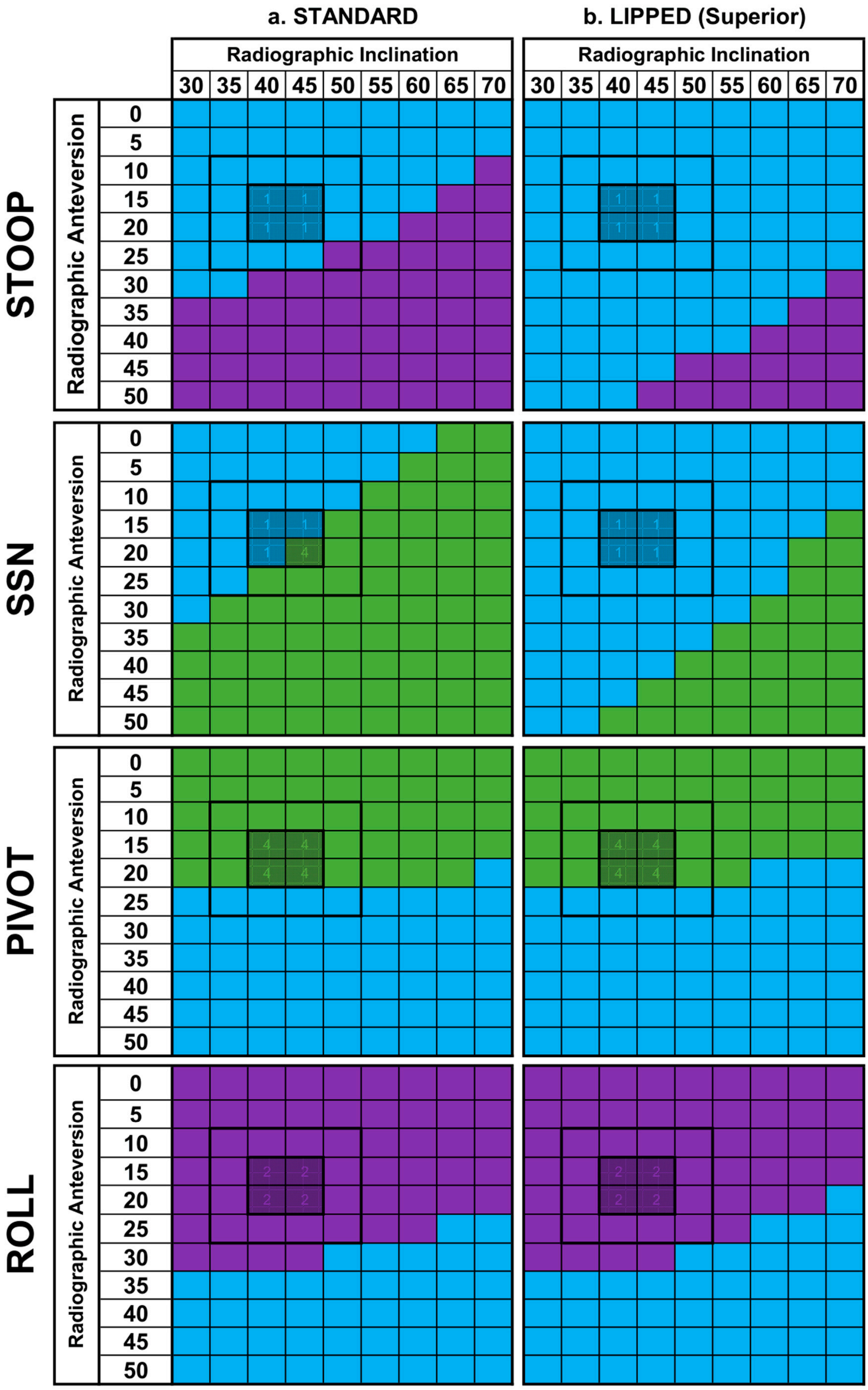

Figure 2. Results matrices demonstrating the incidence and type of impingement for (**a**) standard and (**b**) lipped construct with a superiorly positioned lipped liner apex during STOOP, SSN, PIVOT and ROLL. Cells are coloured based on the type of impingement which occurred, including no impingement (green), implant–implant (blue), and bone–bone (purple). Each matrix has a 2 × 2 shaded area representing the manufacturers' recommended range for cup orientation, as well as a 4 × 4 box for a more likely achieved, 'widened' range.

Summary matrices, which indicate the total number of impingement events at each cup orientation, for the standard liner and lipped liner at each orientation are presented in Figure 3. For a standard liner (Figure 3a), there were no cup orientations which avoided impingement across all ADLs, although a wide range of cup orientations (≥45° of inclination and ≥20° of anteversion) existed where impingement occurred in only three ADLs (STOOP, PIVOT and ROLL). When the lipped liner apex was superior (Figure 3b), the lipped construct had a greater impingement incidence compared with the standard liner, most markedly at lower inclination and anteversion angles, where between five and seven ADLs resulted in impingement in the 'widened' range. Rotation of the lip apex towards posterior resulted in a reduction in the number of impingement incidents in the 'widened' implantation range until the lip apex was rotated to inferior and anterior-inferior (Figure 3f,g), after which the incidence increased, rising to a maximum at the anterior-superior position (Figure 3i).

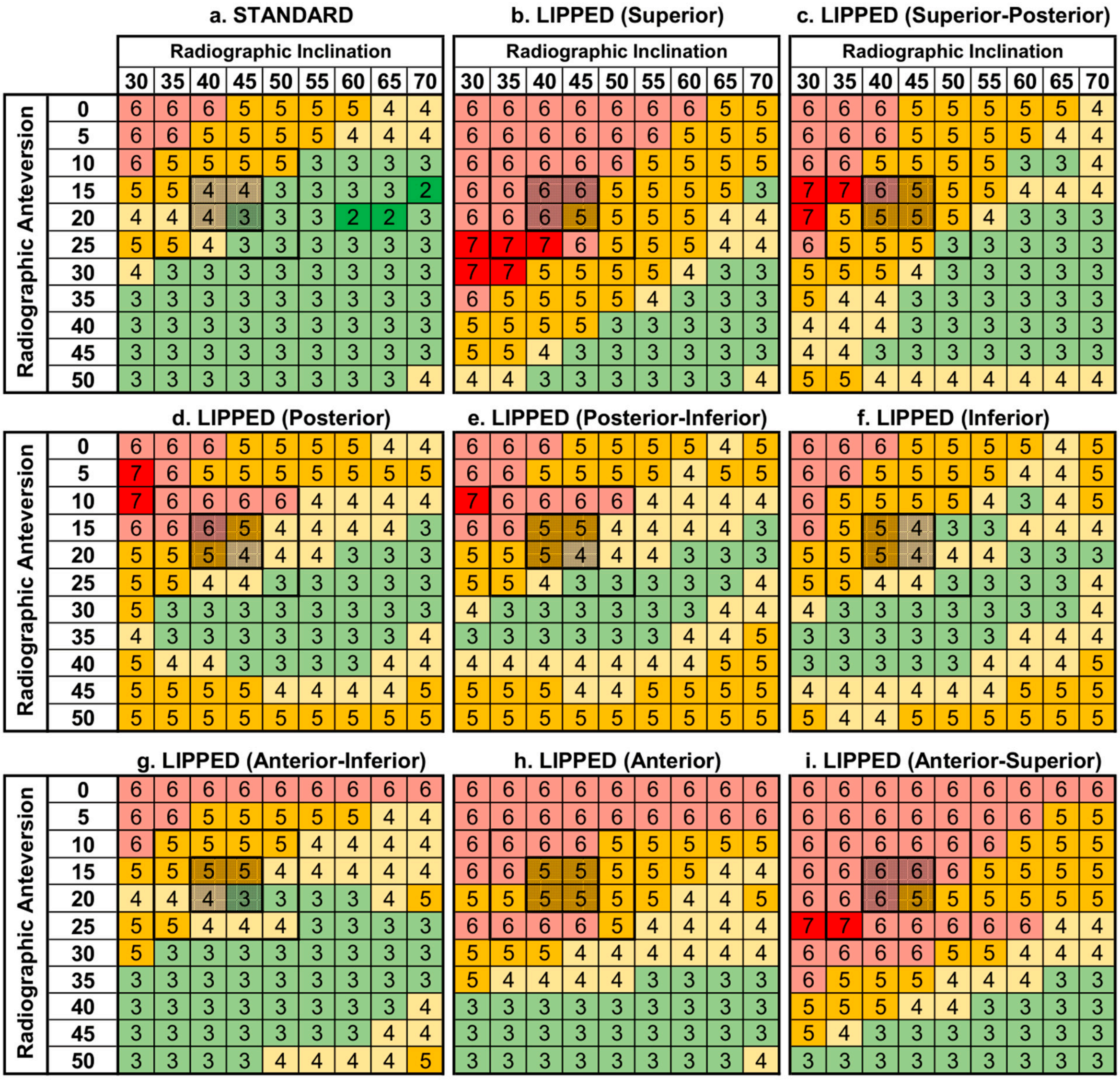

Figure 3. Summary matrices for the (**a**) standard liner and (**b**–**i**) lipped liner with the lip apex in eight orientations. Each cell comprises a number indicating the frequency of impingement events which occurred across all seven ADLs, ranging from zero (no impingement during any ADL) to seven (impingement during all ADLs). Each matrix has a 2 × 2 shaded area representing the manufacturers' recommended range for cup orientation, as well as a 4 × 4 box for a more likely achieved, 'widened' range.

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The relative change matrices, demonstrating the difference in impingement events between a standard liner and a lipped liner construct at a given lip apex position, are presented in Figure 4. The smallest relative change in the total number of impingement incidents when comparing the standard and lipped liners was when the lip apex had been rotated to the anterior-inferior position (Figure 4a), with a maximum increase in one within the 'widened' cup orientation range. The maximum increase occurred when the lip apex was rotated to the anterior-superior position (Figure 4b), where multiple cup orientations within the 'widened' range showed an increase of three impingement incidents compared with the standard case.

a. LIPPED (Anterior-Inferior)

Radiographic Anteversion	Radiographic Inclination 30	35	40	45	50	55	60	65	70
0	0	0	0	1	1	1	1	2	2
5	0	0	0	0	0	0	1	0	0
10	0	0	0	0	0	1	1	1	1
15	0	0	1	1	1	1	1	1	2
20	0	0	0	0	0	0	1	2	2
25	0	0	0	1	1	0	0	0	0
30	1	0	0	0	0	0	0	0	0
35	0	0	0	0	0	0	0	0	0
40	0	0	0	0	0	0	0	0	1
45	0	0	0	0	0	0	0	1	1
50	0	0	0	0	1	1	1	1	1

b. LIPPED (Anterior-Superior)

Radiographic Anteversion	Radiographic Inclination 30	35	40	45	50	55	60	65	70
0	0	0	0	1	1	1	1	2	2
5	0	0	1	1	1	1	2	1	1
10	0	1	1	1	1	3	2	2	2
15	1	1	2	2	3	2	2	2	3
20	2	2	2	2	2	2	3	3	2
25	2	2	2	3	3	3	3	1	1
30	2	3	3	3	2	2	1	1	1
35	3	2	2	2	1	1	1	0	0
40	2	2	2	1	1	0	0	0	0
45	2	1	0	0	0	0	0	0	0
50	0	0	0	0	0	0	0	0	0

c. LIPPED (Posterior-Inferior)
Anterior ADLs only

Radiographic Anteversion	30	35	40	45	50	55	60	65	70
0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0
25	0	0	0	0	0	0	0	0	1
30	0	0	0	0	0	0	0	1	1
35	0	0	0	0	0	0	1	1	2
40	1	1	1	1	1	1	1	2	2
45	2	2	2	1	1	2	2	2	2
50	2	2	2	2	2	2	2	2	1

d. LIPPED (Anterior-Superior)
Anterior ADLs only

Radiographic Anteversion	30	35	40	45	50	55	60	65	70
0	0	0	0	1	1	1	1	2	2
5	0	0	1	1	1	1	2	1	1
10	0	1	1	1	1	3	2	2	2
15	1	1	2	2	3	2	2	2	3
20	2	2	2	2	2	2	3	3	2
25	2	2	2	3	3	3	3	1	1
30	2	3	3	3	2	2	1	1	1
35	3	2	2	2	1	1	1	0	0
40	2	2	2	1	1	0	0	0	0
45	2	1	0	0	0	0	0	0	0
50	0	0	0	0	0	0	0	0	0

Figure 4. Relative change matrices demonstrating the minimum (**a**,**c**) and maximum (**b**,**d**) relative change in the number of impingements incidents for a lipped liner compared with a standard design, across all ADLs (**a**,**b**) and for anterior impingement/posterior dislocation ADLs only (**c**,**d**). Each matrix has a 2 × 2 shaded area representing the manufacturers' recommended range for cup orientation, as well as a 4 × 4 box for a more likely achieved, 'widened' range.

Separating out ADLs resulting in anterior impingement (posterior dislocation) showed that when the lip apex was rotated to the posterior-inferior (Figure 4c), no relative change in impingement incidence occurred compared to the standard liner within the widened cup orientation range. The maximum relative change was when the lip apex was rotated to anterior-superior, with up to three additional impingement events per component orientation compared with the standard constructs (Figure 4d). Considering only ADLs resulting in posterior impingement (anterior dislocation) showed that the lip had a much lesser effect. There was no relative change in impingement incidence in the 'widened' range when the lip apex rotation was between the superior and anterior-inferior. At other lip apex rotations, a maximum of one additional impingement incidence (PIVOT) was observed.

These observations are further illustrated in Figure 5, which plots the sum of the relative change (i.e., increase in impingement incidence for a lipped construct, compared to a standard design) within the 'widened' range across all ADLs. It highlights the small increase in anterior impingement between posterior and inferior lip apex rotations and the maximum increase between superior and anterior rotations. It also illustrates the increase in posterior impingement between posterior-superior and inferior rotations.

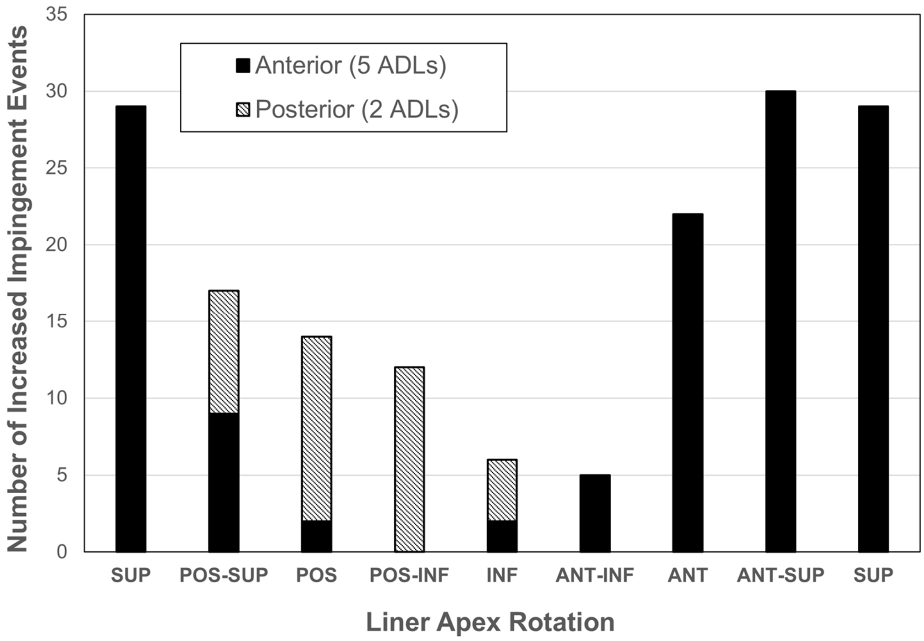

Figure 5. Number of increased impingement events for a lipped liner, relative to a standard design, summed over the 'widened' range (inclination, 35–50°; anteversion, 10–25°) across five ADLs for eight positions of the lipped liner apex. SUP, Superior; INF, Inferior; ANT, Anterior; POS, Posterior.

3.2. Range of Motion

The RoM for the standard and lipped liners was 124° and 107°, respectively (Figure 6). A similar RoM was observed when measured in the nominally hemispheric portion of the liner. However, the RoM was reduced from 62° to 45° in the half of the liner where the lip was located.

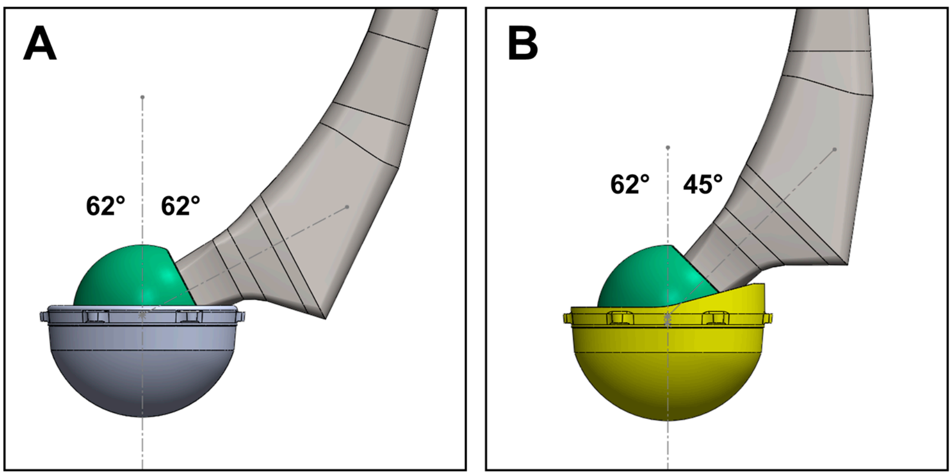

Figure 6. A cross-section of the standard (**A**) and lipped (**B**) liner constructs, including their range of motion.

4. Discussion

This study used kinematic data generated during ADLs and applied these to a geometric model; the key advantage being that, unlike in Finite Element (FE) models, it takes less than a minute to run each set of inputs. This permitted a comprehensive range of previously reported clinically relevant cup inclination (30° to 70°) and anteversion (0° to 50°) to be investigated [22,23]. In addition, systematic variation in lipped liner apex rotation was included, giving a total of 6,237 tests.

This study indicated that for the specific constructs investigated and the ADLs considered, there were no clinically appropriate component positions that avoided impingement irrespective of the liner used (standard or lipped). The elevated lip of the lipped liner reduced RoM (Figure 6) and notably increased the likelihood and frequency of impingement for individual ADLs, particularly when the lip apex is rotated anterior-superior. When considered in isolation, this would suggest that the incidence of impingement and hence subluxation and potentially dislocation would be increased when using the lipped construct to the detriment of clinical outcomes. However, clinical data indicates that the converse is more likely [11–13,15]. This suggests that a combination of cup orientation (inclination and anteversion) and lip apex rotation can minimise the risk of impingement and its consequences. This may also be a reflection of the fact that impingement does not necessarily result in either subluxation or dislocation.

When considering the standard liner, of the seven ADLs, only in one (PIVOT) would impingement incidence be more likely by increasing inclination and anteversion (Figure 2a). Hence the overall frequency of impingement across all ADLs predicted by the model was minimised when the components were placed at inclinations of ≥45° and anteversion of ≥20°. This is at the upper end of the component placement recommended by the manufacturer. The same applied to the lipped construct, but only at selected lip apex rotations (whereby the lip apex was posterior-superior through posterior to anterior-inferior, Figure 3c–g). The safest range to minimise dislocation with a standard construct has been proposed as 30° to 50° abduction (inclination) and 20° to 40° flexion from horizontal (anteversion) [24]. However, excessive inclination of the acetabular component (>50°) has been reported to increase the risk of edge loading and potentially excessive wear [25]. These conflicting requirements emphasise the need to consider multiple factors when optimising component placement, and this will vary depending on component design and the individual subject.

The incidence of impingement of the standard liner represented a 'baseline' level (Figure 3a), and it would seem reasonable to describe the impingement caused by the liner lip as a relative change from this baseline. The relative change in the incidence of impingement in the 'widened' cup placement range was minimised when the lip apex was rotated to anterior-inferior (Figure 4a). Conversely, this increase was at its most marked when the lip apex rotation was anterior-superior (Figure 4b).

Assessing the relative change in impingement incidence over baseline (standard) for anterior impingement ADLs (leading to posterior subluxation) indicated that when the lip apex was rotated to a posterior-inferior position, no increase in impingement events occurred within the likely range of acetabular orientations (Figure 4c). This was in agreement with an intra-operative clinical study [16] which concluded that a lip apex rotated to posterior-inferior was optimal to give greater stability against posterior dislocation. This agreement was not unexpected, as the study imposed internal rotation at maximum flexion, thereby simulating to a certain extent anterior impingement leading to posterior subluxation. However, it was noted in this study that average cup inclination was relatively low (31°), and the results may not be applicable to higher cup inclination angles.

There was also broad agreement with a modelling study [17] which predicted that with a cup inclination and anteversion of 40° and 15° respectively, the optimal lip rotation was posterior-inferior. There was only partial agreement with a second modelling study [18] in which it was concluded that when acetabular anteversion is relatively small (<20°), lip apex rotation to the posterior quadrant is optimal, whereas with acetabular anteversion >20°, lip apex rotation to superior or anterior is optimal to avoid early impingement. It should be noted that both these modelling studies focused on RoM about various axes rather than compound movements used in the current study to simulate ADLs.

The relative change for all ADLs was greatest when lip apex rotation is anterior-superior (Figure 4b). However, this lip apex rotation has no effect on the incidence of posterior impingement at any cup orientation positions; hence, the increase in anterior ADL impingement incidence (Figure 4d) is identical to that of all ADL impingement incidence (Figure 4b). This is further illustrated in Figure 5, showing there was no increase in posterior impingement between anterior-inferior and superior lip apex rotations when the cup is within the likely ('widened') range of cup placement. In terms of identifying component orientation and lip apex rotation that minimised impingement in this specific model, summing impingement incidence, as in Figure 3, masks the fact that avoiding posterior and anterior impingement require different solutions, as shown by Figure 4. The model considers five anterior impingement activities and two posterior events. Clinical outcomes report that anterior impingement leading to posterior dislocation is more frequent [9,10] and would suggest that minimising anterior impingement may be more important.

This study has several limitations. The model itself incorporated only one pelvic geometry, although the primary source of impingement in this study was implant–implant, which would be largely unaffected by bony anatomy. In addition, the model only included one lipped liner construct, and the findings may not be directly applicable to other asymmetric liners, as clinical studies have demonstrated outcomes are dependent on specific liner geometry [15]. The ADLs applied to the geometric model were derived from several healthy subjects and thus gave no indication of the variability across a population. However, the age range of the subjects (44–59 years) was within that expected for a THA population, and the use of healthy participants gave an indication of the aspirational level of activity for post-THA patients. The ADLs were not weighted by likelihood or frequency of occurrence. The model did not account for surrounding soft tissues, which may prevent the hip from reaching the point of impingement during activity. Furthermore, the model did not account for the severity of impingement (e.g., extent of overlap) or other factors such as joint contact forces or the resulting wear and/or deformation of the liner due to impingement. Only the effects of component orientation and lip apex position, not spatial position, were considered. However, in principle, the model could be applied to different component designs, bone geometries, and input parameters to evaluate a wider range of clinical scenarios. These limitations mean that the geometric model cannot be used to determine the likelihood of impingement occurring in a specific case. Furthermore, it cannot be used to determine the degree of subluxation or the likelihood that it will result in dislocation. However, it does efficiently provide information on the relative likelihood of impingement between standard and lipped designs across a large range of different cup positions and lip liner positions. The model did not examine the benefits of a lipped liner, such as the increased travel-to-dislocation imparted by the lip when correctly positioned, which, despite any reductions in RoM, should improve stability and reduce the likelihood of subluxation leading to dislocation, as supported by clinical outcomes [11].

Despite these limitations, unlike earlier computer-based studies [17,18], this methodology provides a comparatively simple and quick means to compare the incidence of impingement when undergoing ADLs in different THA constructs in a large number of input conditions. It showed that the reduction in RoM and the increase in the incidence of impingement of lipped compared with standard liners may be mitigated by correct lip apex rotation. For the constructs used in this study, anterior impingement leading to posterior subluxation was minimised when the liner lip apex was posterior-inferior, which is in line with clinical results [16].

5. Conclusions

This study assessed the occurrence of impingement in standard and lipped liner constructs using a novel geometric modelling approach which incorporated bony geometries and considered over 6000 unique combinations of cup orientation (inclination, anteversion) and lipped liner apex rotation. Under the input conditions used in this study, the geometric model identified no component positions which avoided impingement across all seven dislocation-prone ADLs considered for both the standard and lipped constructs. A reduced incidence of impingement was observed when the components were placed at higher inclination and anteversion angles, although this is known to increase the risk of edge loading and adverse wear, highlighting the conflicting requirements when determining optimal cup position.

For the specific components and input conditions utilised, the use of a lipped liner increased the frequency of impingement compared with the standard construct over a wide range of component placement positions. However, for anterior impingement leading to the more clinically reported posterior dislocation, this increase may be minimised by rotating the lip apex to a posterior-inferior position and orienting it at cup inclination and anteversion levels within the accepted norms. Posterior impingement, leading to the less common anterior dislocation, was minimised when the lip apex was rotated to anterior-inferior and superior. The descriptive findings from this deterministic geometric model may generate hypotheses for future clinical investigations.

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Abbreviations

The following abbreviations are used in this manuscript: THA, Total Hip Arthroplasty; CAD, Computer-aided Design; ADL, Activity of Daily Living; RoM, Range of Motion.

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