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Optimizing stability and motion in reverse shoulder arthroplasty with a 135° neck-shaft-angle: a computer model study of standard versus retentive humeral inserts

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Background: There has been a trend to shift from a 155° and 145° neck-shaft-angle (NSA) to a more "anatomical" reverse shoulder arthroplasty with less distalization and a 135° NSA. Multiple studies have shown that a 135° NSA is beneficial for motion. There are some concerns about primary implant stability with a 135° NSA. When instability is detected, increasing the tension with thicker inlays or changing the NSA to 145° are possible solutions. A retentive 135° (Ret135) inlay may be an alternative to avoiding increased distalization; however, retentive liners are widely regarded as salvage options reducing range of motion (ROM) and avoided by most surgeons. The hypothesis of this study was that a retentive 135° insert of the tested implant system may not have drawbacks for impingement-free ROM compared to a standard 145° insert (Sta145).
Methods: In this computer model study, 22 computed tomographic scans (11 males/11 females) were used to create models with a constant humeral stem (Perform/Stryker) and +3 mm lateralized baseplate +36 mm glenosphere for females and +6 mm lateralized baseplate +39 mm glenosphere for males using Blueprint software (Imascap, Brest, France). A Ret135, standard 135° (Sta135), and Sta145 (+10°) insert were compared for adduction (ADD), extension (EXT), external rotation (ER), and internal rotation (IR) all with the arm at the side as well as for combined IR (CIR = EXT + IR) and combined notching relevant (CNR) ROM (EXT + ER + IR + ADD).
Results: Sta135 showed significantly better ROM for ER, IR, ADD, EXT, CNR ROM, and CIR compared to Ret135 ($P < .05$) and significantly better EXT and ADD compared to Sta145 ($P < .0001$). Comparison of Ret135 and Sta145 showed equivalent ROM performance, which was slightly better but nonsignificant for ADD ($P = .16$), EXT ($P = .31$), CNR ROM ($P = .7$), and CIR ($P = .54$) in favor of Ret135. Isolated IR ($P = .39$) and ER ($P = .32$) were slightly better but nonsignificant in favor of a Sta145.
Conclusion: For this implant system tested in a computer model, a 135° standard liner offers the best ROM. A 135° retentive liner maintains at least equivalent CIR and motion to prevent notching compared to a standard 145° liner. 135° retentive liners are more than salvage options and may help to prevent distalization and overtensioning by increased liner thickness.

Reverse shoulder arthroplasty (RSA) has gained popularity in recent decades due to excellent patient outcomes.[28] The initial Grammont-type RSA was designed with a medialized and distalized center of rotation (COR) and a 155° neck-shaft-angle (NSA). This design has had good clinical performance restoring active forward elevation but is associated with some important perioperative complications.[6,13] During follow-up, the prototype Grammont arthroplasty showed restriction of rotation, extension (EXT), decreased deltoid wrapping, instability, and notching.[8,12] In an attempt to overcome these drawbacks, lateralization of the COR was at first promoted by Frankle with a nonhemispherical glenosphere (GS) and 6-10 mm of inbuilt lateralization of the COR.[20] Boileau alternatively proposed using humeral head autograft for glenoid baseplate lateralization, which he coined bony-increased

This study was approved by the institutional ethics committee (Commission cantonale d'éthique de la recherche sur l'être humain, CER-VD protocol number 2023-01051), with waiver of patient informed consent.

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offset RSA.[11] Initially, the bony-increased offset RSA was coupled with a 155° stem, resulting in a distalized and lateralized lever arm.[10] Later, the NSA was gradually decreased to 145° and 135° with the introduction of the Aequalis Ascend Flex stem (Tornier, Bloomington, MN, USA) in 2012[14] and now many other implant systems. Although reducing the NSA decreases impingement, the risk of instability due to decreased distalization and a more vertical joint line remains a common complication, ranging from 2.4% to 31%, according to different studies.[15,16,22,23,38]

Several solutions have been proposed to treat instability after RSA. On the glenoid side, options include increasing the GS diameter and using a lateralized or eccentric sphere. On the humeral side, solutions include increasing the NSA, building up tension with thicker polyethylene inserts, and using retentive liners to provide more constraint. Retentive inserts increase stability by increasing the socket depth either by a deeper dish with less lateralization or the same depth with higher borders of the inlay without changing the amount of lateralization. This creates a more constrained implant, which has significantly affected the force required to dislocate the RSA in biomechanical studies.[1,22,35] On the other side, a more constrained design theoretically leads to less range of motion (ROM) and, hence, more impingement and notching. However, in one retrospective clinical study, there was no statistical difference in ROM between patients with retentive and standard inserts.[22] Studies on optimizing RSA have focused on impingement-free adduction (ADD) and EXT, aiming to prevent scapular notching.[24,30,34] The effects of these modifications on ROM relevant for notching and internal rotation (IR) with the hand to the back are not clearly understood.

When performing RSA with a 135° stem of the implant system tested in this study, superolateral instability associated with the lower NSA may occur without or even after increasing the thickness of the insert. In this situation, after implantation of the GS, the surgeon can either use a retentive 135° liner or change the NSA to 145° with a nonretentive +10° standard insert.

In this computer model study, 3 different liners with identical configurations of the stems and glenoid implants were compared: a standard 135°, a retentive 135°, and a standard 145° insert. Assessment of isolated ROM, combined IR (CIR) and EXT (IR + EXT), and combined notching relevant ROM (CNR ROM) as the sum of IR, external rotation (ER), and EXT with the arm at the side and ADD (IR + ER + EXT + ADD) were performed. The hypothesis was that the ROM with the arm at the side for the 135° retentive inlay has no major drawbacks compared to the 145° insert.

Materials and methods

Study design and population

In this computer model study, we used deidentified computed tomographic (CT) scans of 22 patients (11 males and 11 females with a mean age of 72.9 years; females 74.6 years, males 71.1 years; range 62-83), with massive cuff tears, and the CT was done for routine preoperative planning. Approval from the local ethics committee was granted before the commencement of the study (Ethics committee approval was obtained from the Commission Cantonale d'éthique de la Recherche sur l'être Humain, study no. 2023-01051). Inclusion criteria were Hamada grade 1-2 cuff tear arthropathies with Sirveaux E0-type glenoid without any joint space narrowing, degenerative wear, and bony deformity, which were considered exclusion criteria.

The Digital Imaging and Communications in Medicine images of the CT scans were analyzed using Blueprint software (version 3.0.1; Imascap, Brest, France). After a computed segmentation sequence, the software automatically calculates both version and inclination of the glenoid as previously described and automatically calculates a neutral reference scapular plane based on automatic 3-dimensional reconstruction of all 3-dimensional points of the scapula body. The automated measurement process, reference points, axis, and planes have previously been validated and published in detail.[9] The software was used to simulate the rigid body motion (RBM) in a virtual RSA model for the PERFORM RSA system (Stryker, Kalamazoo, MI, USA), based on impingement detection between the bony anatomy and the prosthesis.

The glenoid configuration consisted of a standard PERFORM reverse base plate with a diameter of 25 mm. According to the computed scapular plane, the software automatically positions a selected implant baseplate in a standardized neutral position with 0° inclination and 0° version. In this standardized plane, virtual glenoid preparation was performed with a 25 mm baseplate (PERFORM reversed) positioned flush with the inferior border of the glenoid. The baseplate was +3 mm lateralized for females and +6 mm for males. The GS size was 36 mm for females and 39 mm for males.

The humeral configuration consisted of a PERFORM 135° inlay stem using 3 different inserts as shown in Fig. 1 (Fig. 1): A standard symmetric 135°, a retentive symmetric 135°, and a standard +10° insert (NSA of 145°). The difference between the standard symmetric 135° and retentive symmetric 135° insert is that the latter has an all-around increased lip height of +2 mm for 36 mm and 39 mm as shown in Fig. 2 (Fig. 2). The radius of curvature of the insert remains the same as for regular inserts; however, the constraint ratio is increased by changing the height of the insert. The constraint ratio is defined as d/R (depth of the poly articulation parallel to the NSA / radius of the glenosphere). The thickness of the polyethylene was set to be 3 mm. Using the patient's physiological humeral retrotorsion, the osteotomy was performed at the anatomical neck level calculated by the software (height of the osteotomy at +0 mm). A size 2 short stem of 34 mm metaphyseal diameter (Perform, Stryker) was selected for females and a size 3 stem of 38 mm metaphyseal diameter for males (Fig. 1). Medial, lateral, inferior, and anteroposterior arm changes were documented as calculated by the software. All configurations were tested for impingement-free ROM in 3 planes computed by the software with the arm at the side: ADD/abduction (ABD), IR/ER, and EXT/flexion (FLE) at 0° of ABD.

ER, IR, ADD, and EXT computed as RBM as well as CIR (CIR = IR + EXT) and CNR ROM (CNR ROM = EX + IR + ER + AD) were the outcome variables.

Statistical analysis

The statistical and graphical analysis was performed with R language 4.3.1 (R Foundation for Statistical Computing, Vienna, Austria). Descriptive statistics were used to analyze the distribution of ROM illustrated by box plots. The 1-way analysis of variance was used to examine the differences between the 3 insert groups, with post-hoc pairwise comparison conducted using the *t*-test. Significance was set at $P < .05$.

Results

The results are shown in Figs. 3-7 and Table I.

Unidirectional range of motion

Concerning unidirectional ROM (Table I), the 135° standard insert had a significantly better ROM in IR and ER compared to the 135° retentive inlay ($P = .046$ and $P < .001$, respectively, Fig. 3), but no statistically significant difference compared to the 145° stem ($P = .34$ and $P = .13$, respectively). The 135° standard insert had a

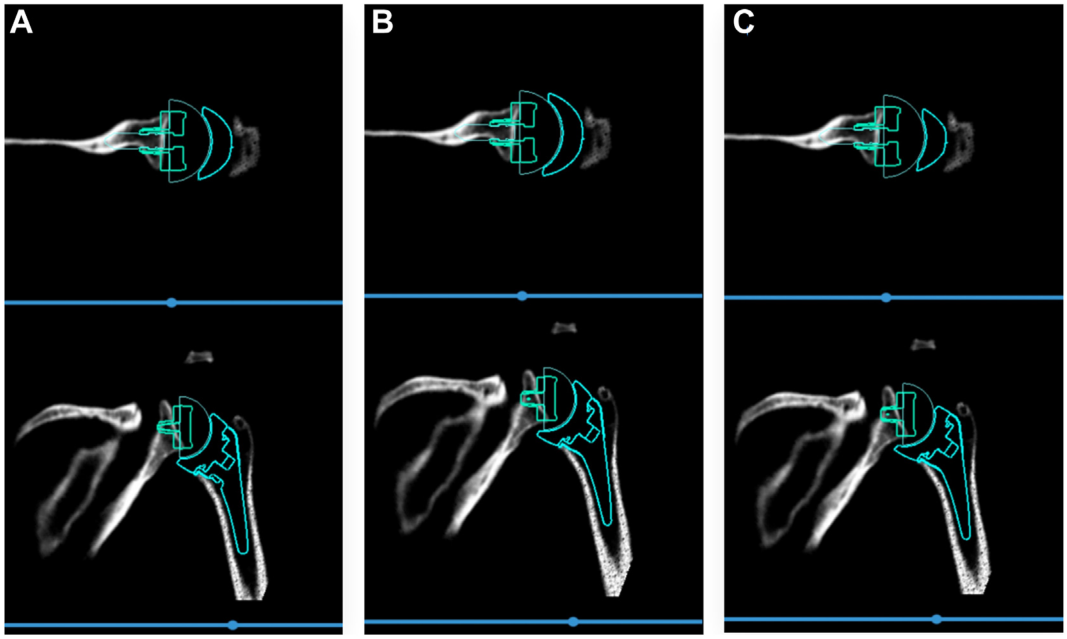

Figure 1 Illustration of axial images (*Top*: antero-posterior constraint) and coronal images (*Bottom*: inferior constraint and distance to posterior scapular pillar). Baseplate placement was flush at the inferior glenoid border, and with +3 mm lateralization for this female patient. Three different inserts and their distance from the posterior pillar of the scapula are shown; 135° standard (**A**), 135° retentive (**B**), and 145° standard (**C**).

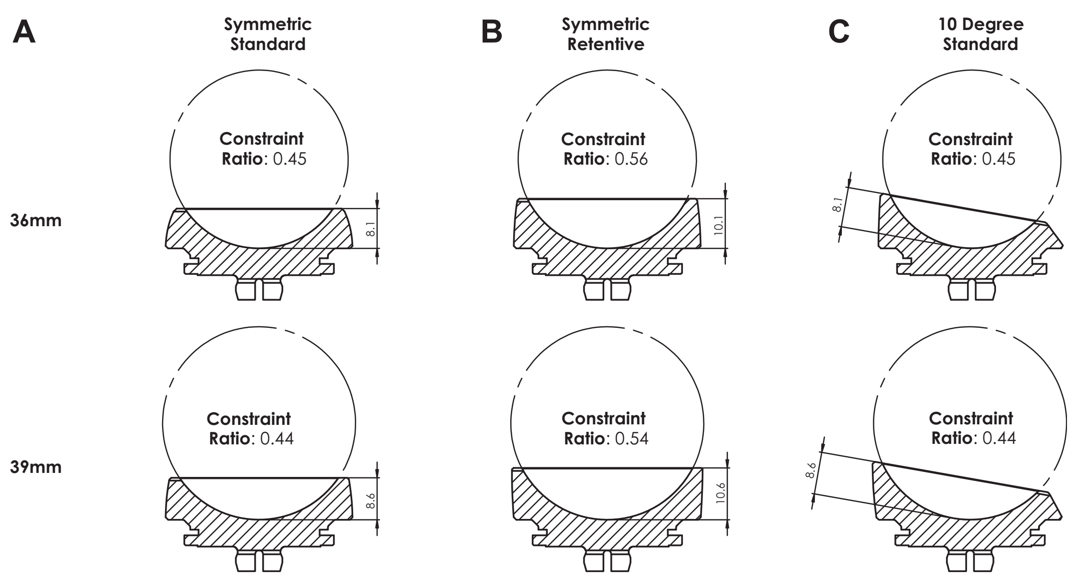

Figure 2 Schematic illustration of different inserts with their constraint ratios: 135° standard (**A**), 135° retentive with a 2 mm all-round higher lip (**B**), and 145° standard (**C**) (*Top*: 36 mm collar diameter, *Bottom*: 39 mm collar diameter). Courtesy of Stryker.

statistically significantly better ROM in ADD and EXT compared to both the 135° retentive inlay and the 145° standard insert, as expected ($P = .0021$, $P < .001$, $P = .0021$, and $P < .001$, respectively, Figs. 4 and 5). Concerning ABD and FLE (Figs. 4 and 5), there was no statistically significant difference between the 3 groups ($P = .96$, $P = .78$). When comparing the 135° retentive and the 145° standard insert, there was no statistically significant difference in any unidirectional ROM.

Combined range of motion

For the combined ROM (Table I), the 135° standard insert has shown statistically better ROM in both CIR (CIR = EXT + IR) (Fig. 6) and CNR ROM (ADD + IR + ER + EXT) (Fig. 7) compared to the 135° retentive insert and the 145° standard insert (all $P < .001$). When comparing the 135° retentive to the 145° standard insert, there was no significant difference.

Discussion

The key finding of this study is that there is no statistically significant difference between the ROM of the 135° retentive insert and the 145° standard insert of the tested implant system. The 135° retentive insert does not lead to a specific reduction of ROM and is a good alternative compared to increasing the NSA. It may also help to avoid thicker 135° inserts commonly used in cases with concerns

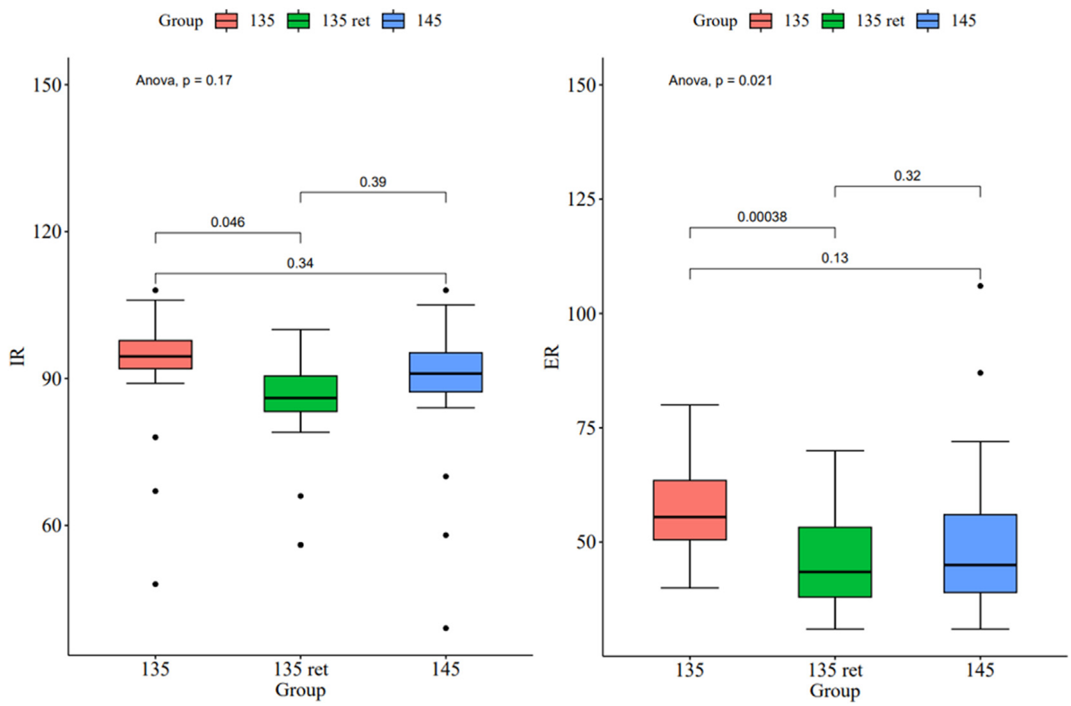

Figure 3 Box-plot comparison of internal rotation (IR) and external rotation (ER) between the 3 groups.

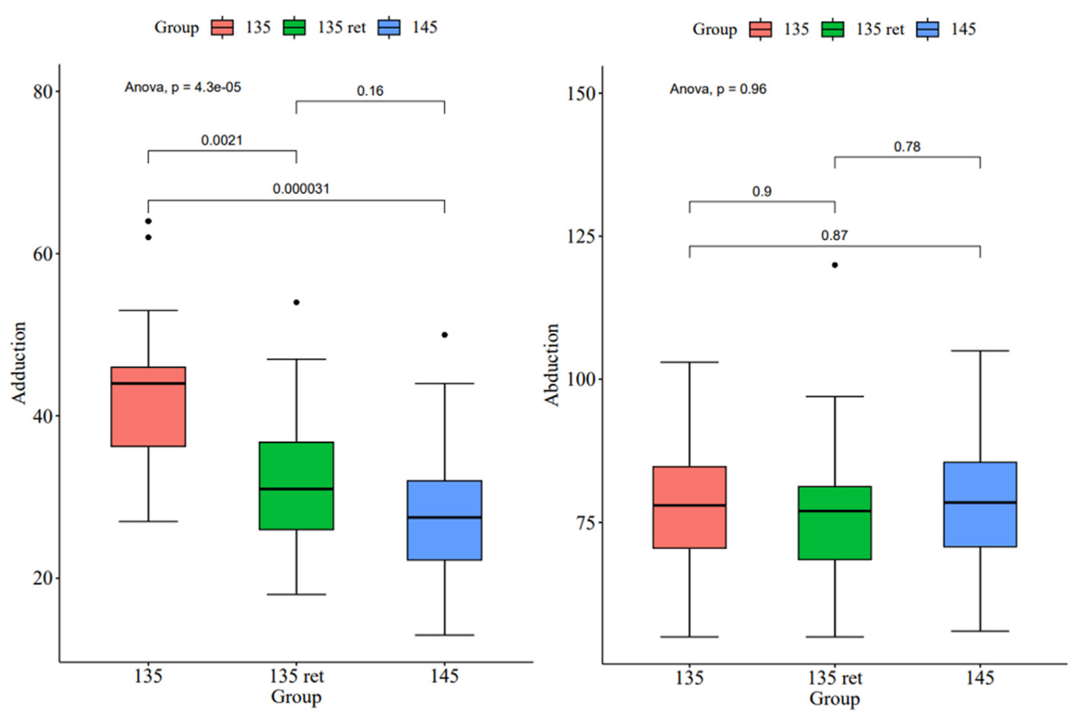

Figure 4 Box-plot comparison of adduction (ADD) and abduction (ABD) between the 3 groups.

for stability which may cause problems with overstuffing and difficulty repairing subscapularis.

As expected, the stem with a standard 135° insert showed significantly better ROM overall for ADD, EXT, ER, and IR when compared to a standard 145° and 135° retentive insert. ABD and FLE have only minimally been influenced by the change in NSA without statistical significance. A computer simulation study by Arenas-Miquelez et al have shown that increasing NSA increases the ABD at the detriment of ADD, and concluded that the 145° stem gives the best overall ROM. The loss of ABD with the 135° stem and onlay insert was explained by the excessive proximalization and lateralization, causing impingement between the greater tuberosity and

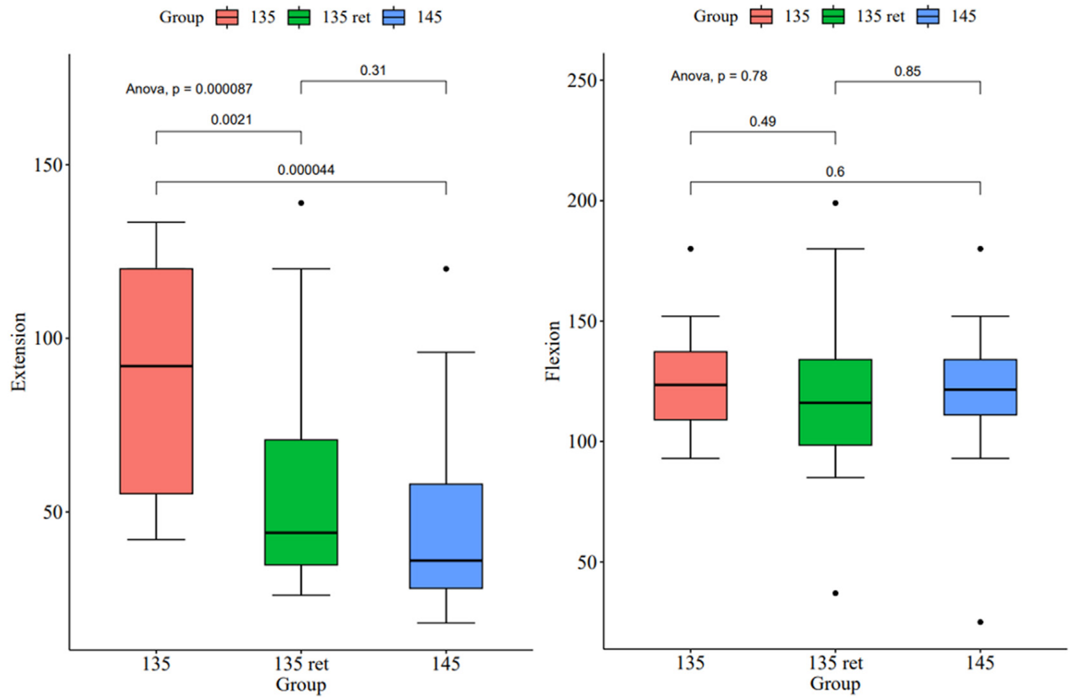

Figure 5 Box-plot comparison of extension (EXT) and flexion (FLE) between the 3 groups.

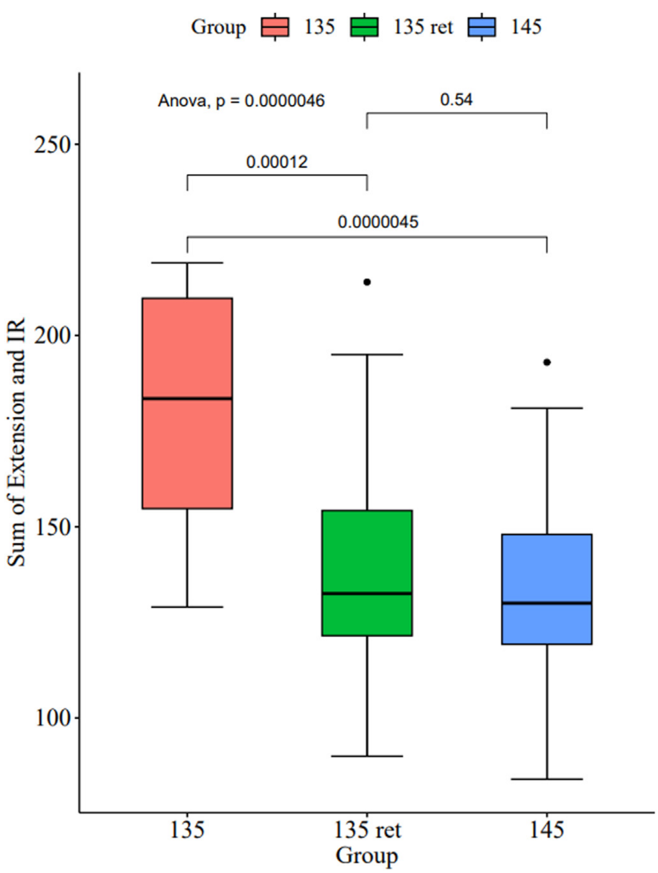

Figure 6 Box-plot comparison of combined internal rotation (EXT + IR) between the 3 groups. *EXT*, extension; *IR*, internal rotation.

the acromion.[2] However, in a clinical scenario, the small differences in FLE and ABD between different NSA can be expected to be compensated by scapula motion.[4-6]

When comparing the 135° standard insert to the 135° retentive insert, there was a statistically significant difference in favor of the 135° standard insert. However, a clinical study by Abdulla et al with a different implant concluded that a constrained insert does not alter the resultant joint load and the deltoid forces, nor changes the active ROM in ABD, IR, or ER, although a statistically significant difference was observed in passive ER between the high constraint group and the low constraint group.[1] This study was, however, performed with a different NSA of 155°, which has a major influence on the effect of a retentive liner in combination with a GS without lateralization. It is also important to point out that there are a range of different constrained liners on the market with different constraint ratios, and therefore, the label “retentive insert” has only a comparative meaning for liners of the same manufacturer and specific type of implant.[17,19]

Instability after RSA remains an important complication. Using a retentive insert, increasing the NSA, and building up insert thickness leading to increased joint reaction forces have all been shown to increase stability and are the 3 readily available options after intraoperative testing once the glenoid-sided implants are already in place.[15,23] When deciding between a retentive insert and an angled insert which increases the NSA, the specific ROM must be considered to provide optimized ROM.

Work by Gerber’s group has shown that functional IR requires at least 40° of active EXT for daily tasks such as tucking shirts or unbuttoning bras.[25] Lädermann et al have pointed out that the implantation of RSA results almost always in a diminution of EXT compared to the contralateral side.[29] Therefore, we also looked at combined computer-simulated motion for IR (CIR = IR + EXT), which showed no statistical difference in IR + EXT with the retentive 135° insert compared to a standard 145° insert.

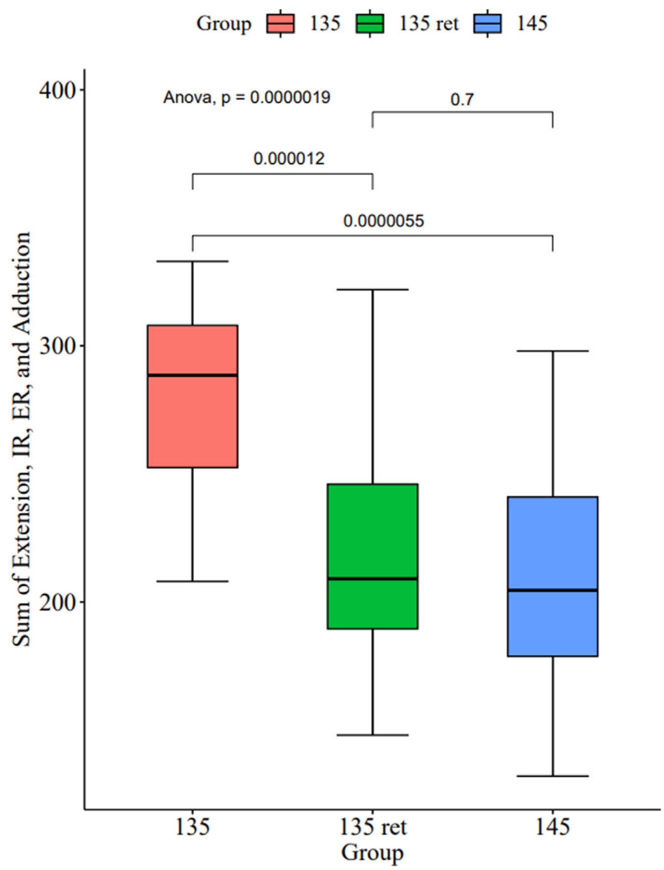

Figure 7 Box-plot comparison of combined notching relevant range of motion (ADD + IR + ER + EXT) between the 3 groups. *ADD*; adduction; *IR*, internal rotation; *ER*, external rotation; *EXT*, extension.

Scapular notching has been associated with worse clinical outcomes after RSA.[36] Mechanical impingement in IR and ER causes limited passive ROM and glenoid loosing.[37] Although changing the NSA from 145° to 135° does not significantly lateralize the humeral implant, the lower NSA does decrease the risk of notching by tilting the polyethylene away from the scapular pillar.[7,39] Several studies have pointed out that decreasing NSA improves ADD and avoids notching, but emphasized that increasing GS lateral offset and inferior eccentricity have a positive effect on ER, hence decreasing scapular notching as well.[2,4-6] Neyton compared a 135° stem to a 145° stem at 2 years and found 135° reduced the phenomenon of notching from 53.4% to 30% but failed to notice any clinical differences.[33] In a meta-analysis, Holster has shown decreasing the NSA improves ER at the expense of ABD and decreases the rate of notching and, ultimately, dislocation (1.4% for 135° compared to 4.6% for 145°).[26] According to a review by Bauer et al,[6] the notching phenomenon is influenced by 5 factors:

(1) Location of the COR of the GS relative to the glenoid center,
(2) Humeral NSA,
(3) Shape of the scapular pillar,
(4) Shape of the scapular neck (which can be elongated by glenoid lateralization), and
(5) Distance of the scapular pillar in relation to the posteroinferior extent of GS.[3]

In the present study, a standard 135° insert has significantly greater overall ROM and, therefore, potentially reduces the risk of notching. The effect of retentive inserts on scapular notching is not clearly understood and is difficult to compare because of the heterogenicity of constraint ratios of different manufacturers.[19] Kowalsky et al. retrospectively examined 88 patients and found that the retentive insert Zimmer Trabecular Metal Reverse Shoulder System (Zimmer Biomet, Warsaw, IN, USA) has a high rate of notching compared to the nonretentive insert (71% vs. 58%). However, the stem used in the study had a 150° NSA, so the results should be interpreted with caution.[27]

Table I
Summary of all measured range of motion.

	135 standard insert Mean (min-max)	135 retentive insert Mean (min-max)	145 standard insert Mean (min-max)
Adduction (ADD)	41 (29-61)	29 (12-44)	26 (15-41)
Abduction (ABD)	77 (58-98)	75 (58-93)	78 (58-99)
Internal rotation (IR)	96 (83-106)	87 (71-98)	92 (76-104)
External rotation (ER)	55 (32-69)	43 (20-58)	42 (23-56)
Extension (EXT)	87 (32-120)	48 (12-100)	40 (16-96)
Flexion (FLE)	124 (98-153)	122 (85-199)	121 (97-153)
IR + EXT	183 (136-223)	135 (95-191)	132 (105-193)
IR + EXT + ADD + ER	279 (211-333)	207 (127-285)	200 (156-280)

The measurements are expressed in degree.

Anatomical considerations such as lateralization and especially distalization may also play an important role in favor of a more "anatomical" RSA and subscapularis length and orientation if repairable. A more lateralized humeral stem has been shown to restore the anatomical position of the lesser and greater tuberosities, improving the length/tension curve of the remaining cuff.[21] A more lateral greater tuberosity increases the ABD angle and improves deltoid wrapping, which ultimately leads to a greater compressive force across the joint surface.[18] On the other hand, Levin et al have shown that a lateral glenoid-medial humerus combination with a 135° NSA provides the most anatomical fiber-length relationship for optimized muscle contractility according to the Blix curve.[31] If instability is encountered with such an optimized "anatomical" RSA with a 135° NSA, solving the problem with a thicker insert could be detrimental to the repair of subscapularis by adding more humeral lateralization and distalization, with fiber overlengthening and possibly reduced contractility,[31] failure of the repair, or even inability to repair the tendon. Furthermore, some patients with hyperlaxity and instability of the RSA may be vulnerable to nerve stretching when the insert thickness is increased as pointed out by Marion et al.[32] They recommended avoiding building up the humerus by increasing implant thickness while simultaneously distalizing it since they demonstrated axillary nerve stretching if the summit of the greater tubercle of the humerus was distalized below the equatorial mid-glenoid line. They conclude that alternative options to increase stability should be considered. Given the findings that a retentive 135° inlay is "as good" for ROM as a standard 145° inlay, the threshold to use a retentive 135° instead of an increased thickness 135° inlay should be lowered in the future. Retentive inlays may have had a negative connotation in the past with a 155° NSA being associated as a salvage option with reduced ROM, notching, and decreased implant longevity.

Our study has several strengths. These include a controlled design of both the humeral-sided and glenoid-sided implant guided by a neutral RSA position in the scapular plane computed by the software; the standardized measurement of ROM for IR, ER, EXT, and ADD pertinent for scapular notching; and an even distribution of male and female patients in the study cohort.

Limitations of this study are those inherent to computer modeling studies with RBM of the glenohumeral joint. First, it does not take scapulothoracic motion into account, which delivers a large contribution to FLE and ABD, a lesser degree to EXT, and little contribution to ER and ADD with the "arm at side." Second, the influence of the soft tissues and muscle forces cannot be accounted for with these. In addition, EXT beyond 60° is not physiological and could be of little clinical relevance. Third, our RBM results are representative for only 1 implant configuration, which cannot reflect the design of all humeral stems with a NSA of 135° and different retentive liners with different "constraint ratios" in the market. Implantation strategies to increase impingement-free ROM, such as anteriorization, posteriorization, change of version, and dialing GS eccentricity more posteriorly, and glenoid strategies to increase stability, such as increasing the GS size and eccentricity, were not explored in this study. Computer model studies assessing RBM are not able to assess the stability of different inserts and this was not the purpose of this study. However, it is mechanically evident that a retentive insert with a higher lip is more stable compared to the same nonretentive insert with a lower lip. Finally, instability in RSA is often multifactorial, and specific etiological factors require a precise diagnosis and specific treatment prior to the use of a constrained liner.

Conclusion

In silico, a 135° retentive liner of the tested implant system offers CIR and CNR ROM, which is at least equivalent to a standard 145° liner. It has the advantages of a less distalized and more "anatomic" RSA, especially if insert thickness is not increased simultaneously.

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