Influence of humeral liner constraint in reverse total shoulder arthroplasty on simulated range of motion in patients with various posture types – a modeling study

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Background: The degree of constraint of the humeral liner is a key determinant of the stability of reverse total shoulder arthroplasty (rTSA). However, it remains largely unknown to what extent the degree of constraint affects range of motion (ROM).

Purpose: To analyze the influence of various liner types on simulated ROM following virtual rTSA implantation in patients with different posture types.

Methods: The CT scans of 48 consecutive patients scheduled for rTSA implantation were utilized to create patient-specific 3D bone models. For all cases, six shoulder surgeons independently virtually implanted a rTSA (lateralized 135° semi-inlay design) according to their respective preferences using an experimental surgical planning software. ROM was determined simulating posture type A (upright posture), B (intermediate), and C (kyphotic posture) utilizing a standard, constrained, and high mobility liner, resulting in a total of 2592 different rTSA configurations. Subgroup analyses were performed to determine the influence of the degree of constraint on simulated ROM across the three posture types.

Results: Total ROM decreased with increasing liner constraint from a median of 611° [interquartile range 522° to 666°] with high mobility liners to 512° [IQR 441-570°] with standard liners to 411° [IQR 322-470°] with constrained liners ($p < 0.01$). For all posture types, the use of a high mobility liner led to a significant increase in ROM in all planes except abduction, except for flexion in posture type A. Constrained liners significantly decreased ROM in all planes except abduction in posture type A. For posture type A, the greatest increase in ROM due to more mobile liners was observed in extension (+17°; $p < 0.01$) and internal rotation (+17°; $p < 0.01$), while the greatest decrease (due to more constrained liners) was also seen in extension (-34°; $p < 0.01$). In posture type B, the greatest increase in ROM occurred in adduction (+19°; $p < 0.01$), whereas the greatest decrease was in high internal rotation (-28°; $p < 0.01$). Similarly, for posture type C, the greatest increase in ROM was observed in adduction (+30°; $p < 0.01$), while the greatest decrease was in high internal rotation (-21°; $p < 0.01$).

Conclusion: While in posture types B and C, high mobility liners improved particularly adduction and constrained liners decreased high internal rotation, in posture type A extension and internal rotation could be improved most prominently while extension was most prominently decreased by a constrained liner.

What this study adds: This study shows that humeral liner constraint significantly impacts ROM in rTSA and that the effect varies by patient posture type. High mobility liners improve ROM, especially in extension and internal rotation, while constrained liners limit it.

How this study might affect research, practice or policy: These findings support posture-specific implant selection and encourage the use of virtual planning tools to optimize functional outcomes in rTSA.

Study Design: Computer-based modeling study (Simulation study)

Level of evidence: Level V

Keywords: Reverse Total Shoulder Arthroplasty; Humeral Liners; Prosthetic Joint Stability; Posture Types; Range of Motion

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Introduction

Continued advancements and innovations in reverse total shoulder arthroplasty (rTSA) have led to a significant increase in its use for treating various shoulder conditions, such as rotator cuff arthropathy, glenohumeral osteoarthritis, and proximal humerus fractures [1][2]. In addition to implant design and component position, the degree of constraint in humeral liners has been shown to play a crucial role in the overall stability following rTSA [3]. Constrained liners, which offer increased depth and a higher peripheral rim, are designed to enhance stability by providing greater contact area around the glenosphere. However, this increased stability may come at the cost of reduced impingement-free ROM [4]. Furthermore, constrained liners may introduce a higher risk of notching and increased polyethylene wear and longer term complications like aseptic loosening [5]. In contrast, a high mobility liner, offering a shallower depth and lower peripheral rim, could potentially maximize ROM by allowing more freedom of movement, although posing a higher risk of instability.

Recent studies have highlighted the impact of patient posture and scapulothoracic orientation on the range of motion (ROM) and functionality after rTSA [6][7][8][9]. Patients with a kyphotic posture (Type C) have been shown to exhibit inferior ROM compared to those with an upright posture (Type A) in adduction, abduction, extension, and external rotation due to more internally and downward rotated and anteriorly tilted scapulae [8]. However, it is still unknown how liner constraint affects patients with different posture types.

Therefore, the aim of this study was to analyze the influence of various liner types on simulated ROM following virtual rTSA implantation in patients with different posture types. The null hypothesis was that neither liner type nor posture influences simulated ROM.

Materials and Methods

Study Design and Patient Cohort

Computed tomography (CT) scans of 48 consecutive patients scheduled for rTSA were obtained to investigate the influence of the degree of constraint of the humeral liner on simulated ROM after virtual rTSA implantation in patients with various posture types. Detailed, patient-specific 3D bone models were created of the scapula and proximal humerus as described by Moroder et al. [8]. The Shoulder Statistical Shape Model (SSM) [6], which best matched the available 3D shapes of the humerus and scapula, was used to predict the distal humerus [10]. This prediction enables the computation of the missing epicondylar axis.

Virtual Implantation Procedure

Six experienced shoulder surgeons (P.S., P.R., P.J.D., B.C.W., J.G., P.M.) independently performed virtual rTSA implantations according to their respective clinical preferences on each of the 48 patients' 3D models using an experimental preoperative planning software that allows to virtually implant a rTSA (Univers Revers Augmented Modular Glenoid System, Arthrex, Naples, FL, USA). Each resulting implantation was then simulated with three different liner types (high mobility, standard, and constrained) and under three posture types (A, B, and C), resulting in a total of 2592 unique rTSA configurations (48 patients × 6 surgeons × 3 liners × 3 postures). In this software ROM simulation can be performed conventionally based on a scapular reference system or with adjustment to posture based on a global reference system. For the present study, posture-based simulation using the global reference system was utilized, allowing posture-specific scapulothoracic orientation to influence humeral movement. A lateralized 135° semi-inlay design prosthesis was utilized for all simulations. Three different liner types with differing degrees of constraint were used for each case—high mobility, standard, and constrained—reflecting the distinctions in constraint stability ratio as described by Moroder et al. [11]. The standard (194%) and constrained liners (300%) were selected to represent the corresponding designs from the Univers Reverse Humeral Prosthesis (Arthrex, USA) system, as detailed in the referenced study. In contrast, the high mobility liner was defined by the authors based on the lower end of the LSR spectrum (130%) reported across available systems, in order to simulate the minimal constraint configuration in a clinically relevant and reproducible way (**Figure 1**).

Determination of Simulated ROM

ROM was determined by simulating posture type A (upright posture), B (intermediate), and C (kyphotic posture) (**Figure 2**) utilizing a standard, constrained, and high mobility liner in all cases, resulting in a total of 2592 different rTSA configurations. The initial humerus position for computing ROM was set at 10° of abduction, with the transepicondylar axis of the elbow predicted from the shoulder SSM aligned perpendicular to the sagittal plane, and the ROM coordinate system was positioned so that the flexion and extension rotation planes were parallel to the sagittal plane [8]. ROM was simulated in each direction by rotating the humerus.

Statistical Analysis

To analyze the data, SPSS Statistics Version 29.0 (IBM) was utilized. All outcome variables were tested for normal distribution using the Kolmogorov-Smirnov test. ROM values for high mobility and constrained liners were statistically compared to those of the standard liner, which served as the reference condition. All ROM-related outcome variables were found to be not normally distributed. Therefore, results are displayed in terms of medians and interquartile ranges, and a Kruskal-Wallis test with a Bonferroni correction was used to compare groups. The level of statistical significance was set to an alpha of 0.05.

Ethical Considerations

All CT data used for this study was drawn from a multicenter shoulder arthroplasty registry approved by an institutional review board.

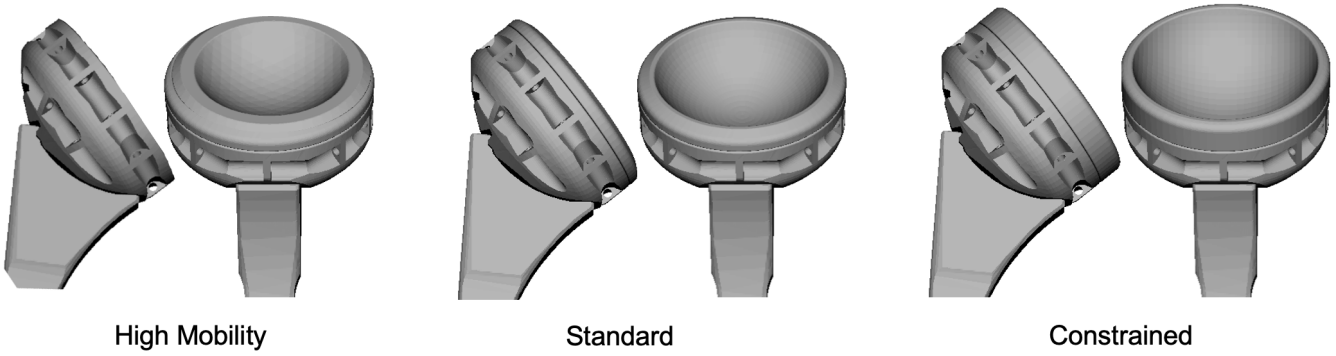


Figure 1: For each case, ROM was simulated with three types of liners: high mobility, standard, and constrained.

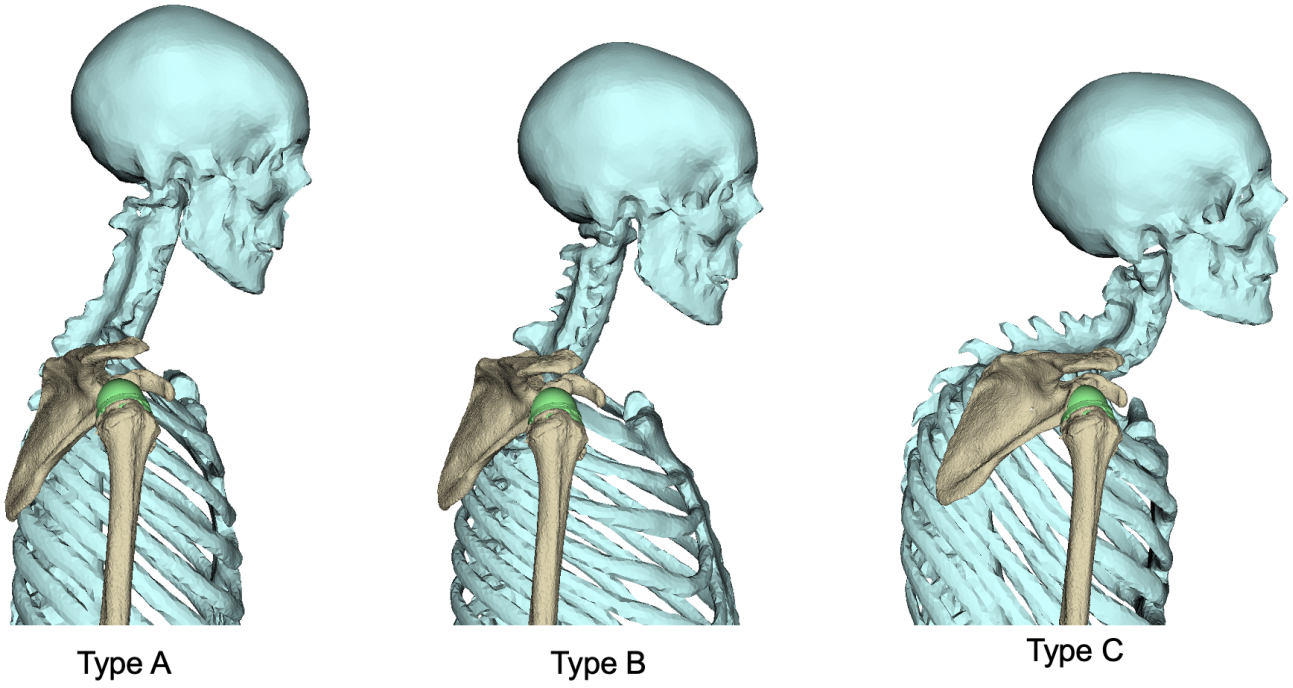


Figure 2: Range of motion (ROM) was determined for posture types A (upright posture), B (intermediate posture), and C (kyphotic posture).

Results

Influence of Liner Constraint on Simulated ROM

ROM increased significantly with the high-mobility liner compared to the standard liner in all movements except abduction and flexion. In contrast, the constrained liner demonstrated inferior simulated ROM compared to the standard liner in all tested movements (**Table 1**).

Effect of Liner Constraint in Different Posture Types

For all posture types, total ROM decreased with increasing liner constraint (**Table 2**).

The high-mobility liner significantly increased ROM in all movements except abduction and flexion across all posture types. The most pronounced increase was observed in extension (+17°; p <0.01) and internal rotation (+17°; p <0.01) for posture type A, and in adduction for posture types B (+19°; p <0.01) and C (+30°; p <0.01). In contrast, the constrained liner led to a significant decrease in ROM in all movements except abduction for posture type A, and in all movements for posture types B and C. The most pronounced reduction was observed in extension (-34°; p <0.01) for posture type A, and in high internal rotation for posture types B (-28°; p <0.01) and C (-21°; p <0.01) (**Figure 3**).

Table 1. Comparison of simulated range of motion across different liner types: high-mobility, standard, and constrained liners.

	High Mobility	Standard	Constrained
Total ROM	611° [IQR 522° to 666°]**	512° [IQR 441° to 570°]	411° [IQR 322° to 470°]**
Abduction	75° [IQR 67° to 82°]	75° [IQR 67° to 82°]	71° [IQR 62° to 78°]**
Adduction	32° [IQR 10° to 51°]**	15° [IQR -2° to 28°]	-2° [IQR -10° to 10°]**
Flexion	108° [IQR 93° to 117°]	106° [IQR 93° to 117°]	95° [IQR 80° to 108°]
Extension	33° [IQR 20° to 46°]**	20° [IQR 8° to 29°]	5° [IQR 0° to 16°]**
Internal Rotation	102° [IQR 72° to 121°]**	87° [IQR 59° to 106°]	68° [IQR 31° to 91°]**
External Rotation	37° [IQR 23° to 46°]**	22° [IQR 10° to 33°]	7° [IQR 0° to 20°]**
High Internal Rotation	136° [IQR 117° to 149°]**	123° [IQR 104° to 134°]	106° [IQR 76° to 121°]**
High External Rotation	63° [IQR 48° to 78°]**	50° [IQR 33° to 63°]	37° [IQR 20° to 50°]**

Data are presented as the median [interquartile range]. * and ** indicate significant differences from the standard liner. **p<0.01, *p<0.05

Table 2. Comparison of simulated total Range of Motion (ROM) for Different Liner Types in Patients with Posture Type A, B and C.

	High Mobility	Standard	Constrained
Posture Type A	628° [IQR 533° to 694°]**	524° [IQR 450° to 582°]	423° [IQR 344° to 480°]**
Posture Type B	621° [IQR 538° to 675°]**	526° [IQR 455° to 576°]	423° [IQR 361° to 482°]**
Posture Type C	591° [IQR 498° to 638°]**	492° [IQR 413° to 540°]	387° [IQR 202° to 443°]**

Data are presented as the median [interquartile range]. * and ** indicate significant differences from the standard liner. **p<0.01, *p<0.05

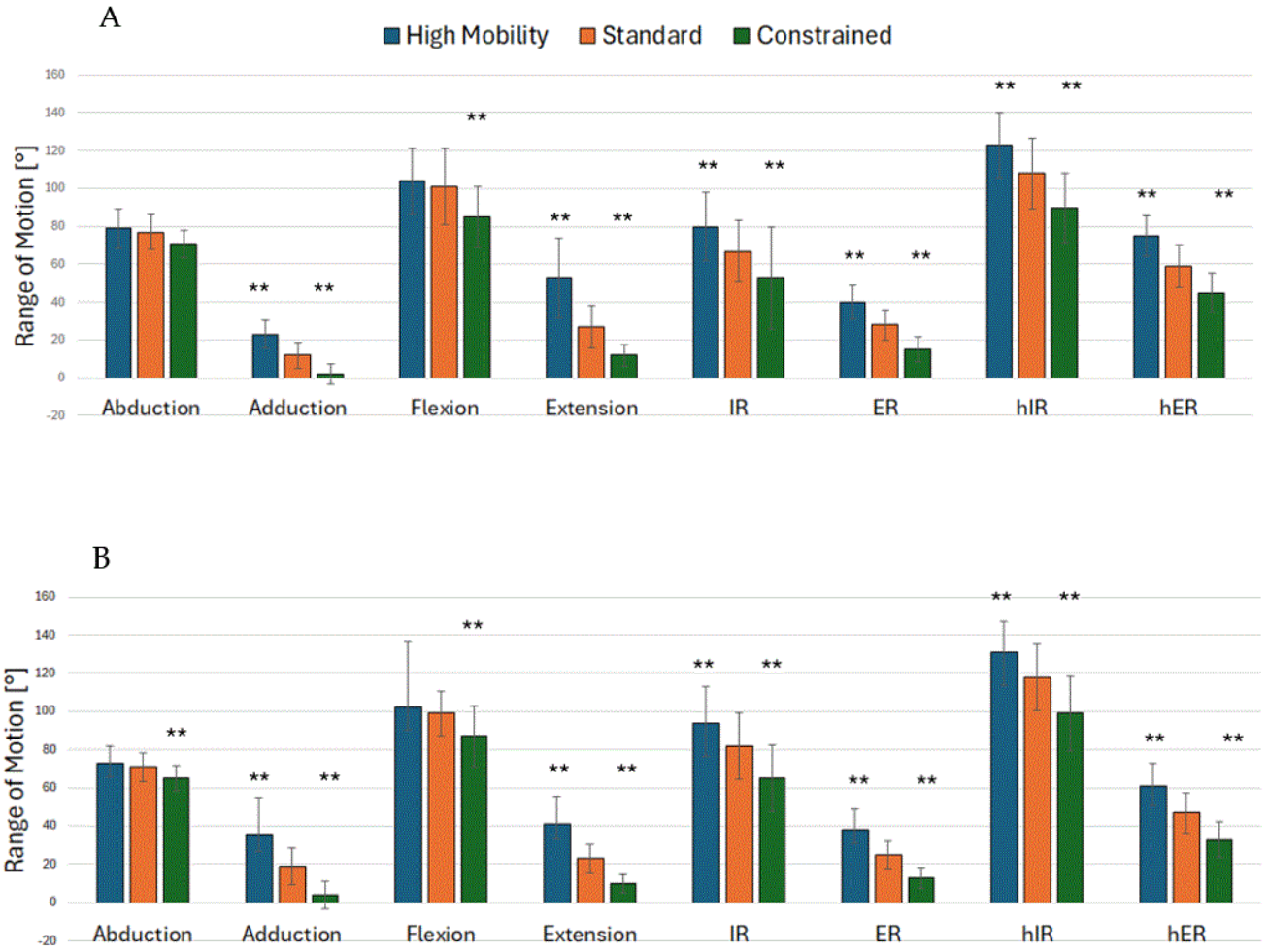
Discussion

The most important finding of the present study is that the degree of constraint in humeral liners significantly affects the simulated ROM in rTSA across all posture types. Specifically, the study revealed that constrained liners substantially decrease simulated total ROM, while high mobility liners enhance ROM across all posture types. These results highlight the potential role of liner type selection in optimizing functional outcomes for patients undergoing rTSA.

When indicated, the primary goal of rTSA is to restore function and alleviate pain. The choice of humeral liner plays a crucial role in achieving these objectives, as it directly affects the stability and ROM of the prosthetic joint [3][4][12]. However, it has recently been revealed that there are significant differences in jump height and degree of constraint of rTSA liners between various implant systems

[11]. Standard liners exhibit a stability ratio range from 126% to 214% and constrained liners from 151% to 479%. The angle of coverage also varies considerably, ranging from 103° to 130° for standard liners and 113° to 156° for constrained liners. These differences are of significant relevance considering the impact of liner constraint on stability and ROM, as demonstrated in the present study.

The results of this study revealed a clear relationship between the degree of liner constraint and the simulated ROM. Specifically, the use of constrained liners significantly decreased total ROM across all posture types. This finding aligns with previous studies, which reported that constrained liners, while improving stability, could limit the ROM due to their restrictive design [4][13]. Interestingly, Goodloe et al. [3] reported in contrast no significant differences in ROM or patient-reported outcome between constrained and standard liners in rTSA after 2 years. However, their comparatively small, though matched, patient cohort might have limited the power to detect differences in ROM. Furthermore, there is a high probability of confounders being present in clinical reality compared to a computer-simulated model. Conversely, scapulothoracic movement, which was not accounted for in our ROM simulation, might compensate for reduced ROM in clinical reality. More clinical studies are therefore needed to better understand the impact of humeral liner constraint in complex upper extremity movements. Furthermore, biomechanical data showed significantly greater volume loss and surface deviation of constrained liners [14]. It is possible that while more constrained liners may provide a reduced impingement-free ROM at time zero, the resulting notching could secondarily provide additional space for movement after the notch has been created. However, this might also lead to increased wear. Therefore, careful consideration in selecting the degree of liner constraint must be made.



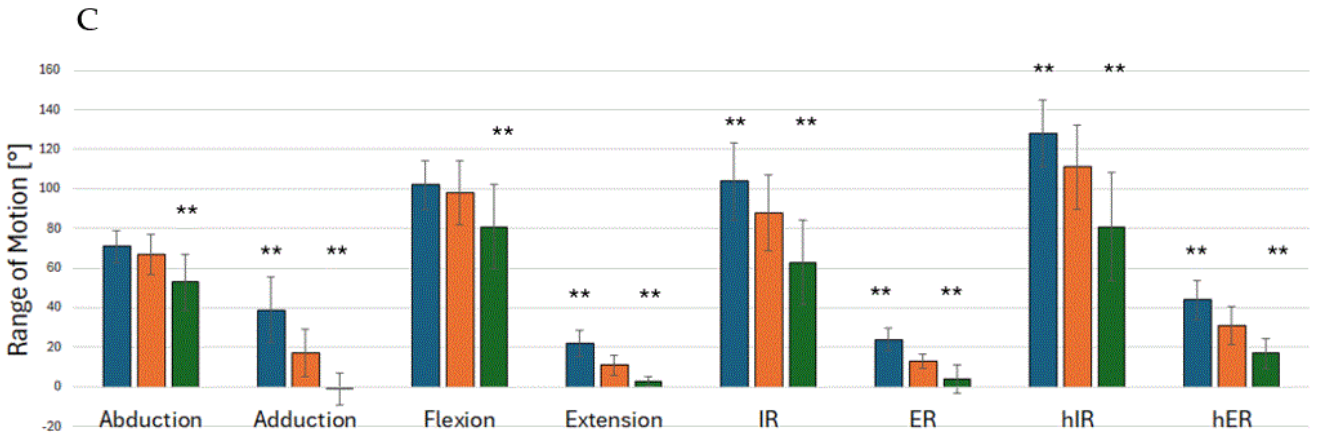


Figure 3. Comparison of the simulated range of motion (ROM) across different humeral liner types in reverse total shoulder arthroplasty (rTSA) for posture type A, B and C. The high mobility liner (blue) consistently shows the highest ROM in all measured planes. The standard liner (orange) provides moderate ROM, while the constrained liner (green) results in the lowest ROM across all planes. (**p<0.01, *p<0.05 ER-external rotation, IR-internal rotation, hER-high external rotation, hIR- high internal rotation)

In the present study, high mobility liners demonstrated a significant increase in ROM across all posture types. Yet, no improvements were observed in abduction and flexion. High mobility liners are characterized by a small jump height, defined as the vertical distance from the bottom of the liner concavity to the edge of the liner [11]. This leads to a lower stability ratio, indicating lesser resistance to dislocation. To mitigate the potential risk of instability associated with high mobility liners, careful patient selection and tailored rehabilitation are essential. Patients who present with reduced range of motion intraoperatively, but do not exhibit relevant risk factors for instability, may benefit from the use of a high mobility liner to maximize impingement-free motion. However, surgeons should be aware that flexion and abduction are not significantly improved by this design across all posture types. Conversely, when a constrained liner is selected to enhance joint stability in patients with an increased risk of dislocation, a significant reduction in range of motion must be expected across nearly all planes. This effect appears to be less pronounced in patients with an upright posture, as abduction is not significantly affected in posture type A. These liners may be most suitable for patients with good deltoid function, no history of shoulder instability, and lower neuromuscular risk. In such cases, the benefit of improved ROM may outweigh the reduced constraint. Postoperatively, controlled motion protocols with delayed external rotation and early strengthening of the deltoid and periscapular muscles may help compensate for lower implant stability and ensure a safe return to function. While the improvement in ROM highlights the potential benefits of high mobility liners in patients where preserving a wide range of motion is paramount, the risk of instability must be considered and further evaluated by future studies.

While total ROM was similarly affected by liner constraint across all posture types, there were notable differences in which movements showed the greatest increase or decrease. Constrained liners resulted in the most prominent decrease in extension and internal rotation in posture type A, as well as in high internal rotation in types B and C. Conversely, high mobility liners particularly enhanced extension and internal rotation in posture type A, while particularly increasing adduction in posture types B and C. Interestingly, internal rotation is the only motion that is reduced in posture type A compared to posture types B and C [8]. This was also observed in the present study. Hochreiter et al. demonstrated the importance of extension for internal rotation [15]. The authors highlighted that at least 40° of active extension is essential to achieve functional internal rotation, allowing placement of the hand behind the back to reach the lumbar spine and higher levels. One possible explanation is the impingement of the polyethylene liner on the scapular pillar [16].

The present study demonstrates for the first time how liner constraint influences impingement-free ROM to varying degrees for different posture types. Nonetheless, the present study has several limitations that should be considered. This includes the exclusion of certain complex factors that influence postoperative ROM, such as the role of soft tissues. The model used in the present study focused on impingement-free ROM, which means that soft tissue interactions were not accounted for in our simulations. This simplification may impact the accuracy of the findings, and further studies incorporating soft tissue dynamics are warranted. Notably, some simulated ROM values—particularly in high internal and external rotation—appear supraphysiologic, as no soft tissue resistance was modeled;

in reality, such extreme values are unlikely to be achieved postoperatively. Additionally, the exclusion of scapulothoracic kinematics may have affected the simulated orientation and path of the humerus, particularly in posture types with increased scapular tilt or rotation. This may further limit the physiological accuracy of the results in postures that deviate from the upright norm. Furthermore, the kinematics of the scapula were not considered. However, unlike comparable studies, the present study accounted for posture types in the simulated ROM. Additionally, the study was constrained by the limitations of the surgical planning software used. The use of virtual simulations rather than actual clinical outcomes poses limitations on the robustness and applicability of these findings. Although the virtual implantations were performed by experienced surgeons using advanced software, clinical studies are necessary to validate the impact of different humeral liner constraints on ROM in patients with varying posture types.

Conclusions

This study demonstrates that the degree of constraint in humeral liners significantly impacts simulated ROM in rTSA, varying across different posture types. High mobility liners consistently provided the highest ROM, while constrained liners reduced ROM across all posture types. While constrained liners had a negative effect in high internal rotation across all posture types to a similar degree, high mobility liners improved extension and internal rotation in posture type A, while particularly increasing adduction in posture types B and C. These results emphasize the necessity of tailored liner selection to optimize postoperative outcomes, balancing stability and mobility based on individual patient posture. Future clinical studies are needed to corroborate these findings and to evaluate the long-term effects of different liner constraints on joint function and implant longevity.

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Conflict of Interest

Dr. Lappen, Dr. Siegert and Ms Eva Herbst have no conflicts of interest to declare. Dr. Raiss is a paid consultant for Arthrex Inc. and a shareholder for Zurimed AG. Dr. Denard is a consultant for LifeNet and Arthrex, and receives royalties and research support from Arthrex. Dr. Werner is a consultant for Arthrex and receives research support from Biomet and Flexion Therapeutics. Dr. Griffin serves as a consultant and paid speaker and receives royalties from Arthrex Inc. He also serves on committees or boards for ASES and receives royalties from Springer. Dr. Shah is a consultant for Arthrex, receives research support from Arthrex, and royalties from Medacta. Sergii Poltaretskyi and Nick Metcalfe are employees of Arthrex. Dr. Moroder is a consultant for Arthrex and receives royalties and research support from Arthrex.

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