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Factors contributing to glenoid baseplate micromotion in reverse shoulder arthroplasty: a biomechanical study

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Background: Reverse shoulder arthroplasty (RSA) is typically performed in patients with cuff tear arthropathy. A common type of RSA baseplate has a central peg and 4 peripheral screws inserting into the glenoid surface. Baseplate failure is a significant postoperative complication that reduces prosthetic longevity and usually requires revision surgery. This study evaluated the contribution of mechanical factors on initial baseplate fixation.
Materials and methods: This study simulated glenoid baseplate loading in a RSA. A half-fractional factorial design was used to test 5 factors: bone density (160 or 400 kg/m^3), screw length (18 or 36 mm), number of screws (2 or 4), screw angle (neutral or diverging), and central peg length (13.5 or 23.5 mm). Trials were cyclically loaded at a 60° angle with 500 N for 1000 cycles. Micromotion at 4 peripheral screw positions was analyzed using a multifactorial analysis of variance ($P < .05$).
Results: We found an increase in micromotion with 3 scenarios: (1) lower bone density at all screw positions; (2) shorter central peg length at the inferior, superior and anterior screws; and (3) shorter screw length at the inferior and anterior screws. There were interactions between bone density and screw length at the inferior and anterior screws and between bone density and central peg length at the inferior, superior, and anterior screws.
Discussion: Greater bone density, a longer central peg, and longer screws provide improved initial glenoid fixation in an RSA, whereas the number of screws, and the angle of screw insertion do not. These findings may help minimize baseplate failure and revision operations.
Level of evidence: Basic Science Study; Biomechanics

Keywords: Reverse shoulder arthroplasty; reverse shoulder prosthesis; micromotion; baseplate fixation; baseplate failure; biomechanical testing

Reverse shoulder arthroplasty (RSA) is frequently used to treat patients with a variety of disorders, most commonly, advanced glenohumeral arthritis with rotator cuff deficiency, painful debilitating rotator cuff tears, and complex proximal humeral fractures.[17] The RSA design consists of a humeral

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socket and a glenosphere that is secured to the glenoid bone by a baseplate.[6] The baseplate has a central peg (post) or a central screw that goes into the glenoid surface and is then secured by peripheral screws. This design has proven to be very effective in improving patients' pain, function, and quality of life postoperatively.[1,13,19]

One of the most common complications with first-generation implants is glenoid baseplate loosening and failure.[2,21,24] Although this is thought to be less important in later-generation implants, no long-term outcomes are available. As well, several factors may lead to this becoming a concern in the future, including the increased life expectancy and higher activity levels of older patients, and that RSA is being expanded into younger patients. Glenoid loosening rates vary in the literature and are reported as high as 12%.[20,24]

Baseplate failure is a serious complication because it reduces prosthetic longevity and may require revision surgery.[4] Implant-related factors that may contribute to glenoid loosening include bone quality, number of peripheral screws, screw angle, screw length, and central peg length. The literature has consistently shown that implantation of a baseplate onto higher density bone is advantageous for fixation,[5,21] but the interaction of bone density with these other implant factors is not known.

A literature review revealed inconsistent results when the number of screws and screw arrangement on baseplate fixation were tested.[5,8,11] Some studies showed a significant reduction in micromotion with the use of more screws and diverging arrangement of screws, but this has not been reliably reproduced. Furthermore, a limited number of investigations have focused on the effect of screw length and central peg length on baseplate fixation.[9,14]

The objective of this study was to simulate physiologic loads in a reverse shoulder prosthesis to mechanically evaluate the contribution of bone density, screw length, number of peripheral nonlocking screws, screw angle, and central peg length on the initial fixation of a glenoid baseplate. We hypothesized that improved initial fixation, as measured by reduced micromotion, would be observed in higher-density bone, with longer screws, a larger number of screws, diverging screws, and a longer central peg.

Materials and methods

Experimental design

This basic science study measured micromotion of the baseplate under a range of physiologic loading conditions. We modeled the glenoid surface using polyurethane blocks of 2 different densities (Sawbone Model #1522-660, rigid solid foam; Pacific Research Laboratories, Vashon Island, WA, USA). Baseplates from the Delta Xtend RTSA (DePuy Synthes, Warsaw, IN, USA) were implanted onto a polyurethane block. Three linear variable differential transformers (LVDTs; Orbit 3, Solartron Metrology, West Sussex, United Kingdom) measured the amount of micromotion from a metal ring interface soldered around the glenosphere (Fig. 1). The LVDTs have an accuracy

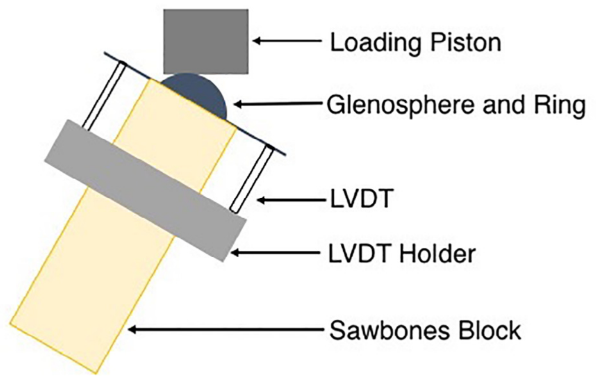

Figure 1 Materials and set up used for each trial. *LVDT*, linear variable differential transformer.

of 3 μm and a measuring capacity of 2 mm. The LVDTs were secured 120° apart onto a plastic ring. This plastic ring was secured onto the polyurethane block with Steinmann pins approximately 1 inch below the metal ring. This buffering distance of 2.5 cm would prevent any interference of the plastic ring with the metal ring.

We cyclically loaded a baseplate in an inferior-to-superior direction at 500 N to simulate the peak loads that a shoulder would endure when performing certain activities of daily living involving shoulder abduction (ie, holding a 2-kg shopping bag).[16] A materials testing system (Bionix Servohydraulic Test System; MTS Systems, Eden Prairie, MN, USA) loaded the apparatus under force control. The polyurethane block was mounted to 60° of glenohumeral abduction, which corresponds to 90° arm abduction and the largest joint reaction forces across the glenoid surface.[3,15] We loaded the baseplate to 20 N for 15 seconds to calibrate the materials testing system machine, then for 1000 cycles at 1 Hz. We chose 1000 cycles to simulate loading within the first 3 postoperative months, which are most important for initial fixation and osseous integration of the baseplate into bone.[15] According to Harman et al,[7] loading past 1000 cycles does not give additional information. The outcome measure was the amount of micromotion between the baseplate and the polyurethane block at the 4 peripheral screw positions. The secondary outcome was failure at the baseplate-block interface.

Because the LVDTs measure the motion of the metal ring, the measured motion at the ring was mapped to the motion at the baseplate-to-bone interface at the 4 peripheral screw positions (superior, inferior, anterior, and posterior). We defined failure at the baseplate-block interface as micromotion greater than 2000 μm because this exceeds the LVDT measuring range.

Factors investigated

Baseplates were implanted onto 1 of 2 different density polyurethane blocks (10 pounds per cubic foot [pcf] and 24 pcf) with peripheral nonlocking screws. A screening half-fraction factorial design with a level V resolution[18] tested 5 factors at 2 levels each: bone density (10 pcf and 24 pcf), number of screws (2 screws at superior and inferior positions, 4 screws at all positions), angle of screw insertion (neutral 0° and diverging 27°), screw length (18 and 36 mm), and central peg length (13.5 and 23.5 mm). Briefly, this design creates unique trials where different combinations of factors are tested such that fewer trials need to be compared to find a significant difference. Our design created 16 unique conditions with different combinations of factors. Each condition was repeated 3 times for a total of 48 trials that were executed in a randomized order.

Statistical analysis

We captured micromotion of the baseplate relative to the polyurethane block from the last 10 loading cycles and accounted for any deformation of the block throughout the trial. Average displacements at the baseplate-block interface were analyzed using a repeated-measures analysis of variance and a Tukey honestly significant difference post hoc test. Alpha values of $P < .05$ were considered significant.

Results

Lower bone density generated more micromotion at the baseplate-bone interface at all 4 screw positions compared with the higher bone density ($P < .001$; Table I). Applying a shorter screw created significantly more micromotion than a longer screw at the inferior ($P = .021$) and anterior ($P = .049$) screw positions. The longer central peg resulted in significantly lower micromotion values at the inferior ($P = .046$), superior ($P = .018$), and anterior ($P = .007$) screw positions. There was no significant difference in micromotion when using 2 screws placed at the inferior and superior position vs. 4 screws placed at all peripheral positions. There was also no significant difference between inserting the screws at a neutral or diverging angle at any screw position (Fig. 2). There was a significant interaction between bone density and screw length at the inferior ($P = .007$) and anterior screw positions ($P = .021$).

Finally, there was a significant interaction between bone density and central peg length at the inferior ($P = .032$), superior ($P = .023$), and anterior ($P = .004$) screw positions (Fig. 3). Two of the 3 trials tested for the condition with 10 pcf polyurethane block, 2 short screws, diverging angle, and short central peg failed. These data were omitted from the analysis because the micromotion experienced by the LVDTs exceeded their measuring capacity.

Discussion

Our results confirm that higher bone density significantly improves fixation of the baseplate onto the bone, as shown by significantly reduced micromotion at all screw positions when loading higher-density polyurethane. Increasing screw length and central peg length also seem to improve baseplate fixation. There is no difference in micromotion when changing the number of screws or the angle of screw insertion under the conditions in this study. This study's strength is that it directly compares different factors related to the baseplate in a reverse shoulder prosthesis through measuring baseplate-bone micromotion during simulated physiologic loading. This direct comparison can help inform surgeons' decisions when performing an RSA. Furthermore, our study dissociated the effect of increasing screw length with more diverging screw arrangements, whereas many studies in the literature use the capacity to insert longer screws as an indicator for improved baseplate fixation.

The interactions among factors in this study reinforce the importance of the screw and central peg length. These results suggest that especially in low-density bone, achieving greater peripheral screw and central peg purchase is conducive to reducing micromotion during loading. This was further reinforced by the 2 trials that failed when a low-density block, 2 short, diverging screws, and a short peg was used. We can infer that the cause of this failure was a lack of screw and peg purchase into the low-density block. This occurred despite the diverging arrangement of screws, further reinforcing that

Table I Average micromotion for all factors

Factor	Inferior			Superior			Anterior			Posterior		
	Mean (μm)	SE	*P*	Mean (μm)	SE	*P*	Mean (μm)	SE	*P*	Mean (μm)	SE	*P*
Bone density			<.001*			<.001*			<.001*			<.001*
10 pcf	384	23		197	18		286	17		296	23	
25 pcf	56	22		32	17		46	16		41	22	
Screw length			.021*			.967			.049*			.373
18 mm	258	23		114	18		190	17		182	23	
36 mm	182	22		115	17		143	16		154	22	
Screws, No.			.355			.228			.353			.228
2	235	23		130	18		177	17		187	23	
4	205	22		99	17		155	16		149	22	
Screw angle			.098			.581			.245			.206
Neutral	247	22		121	17		180	16		188	22	
Diverging	193	23		108	18		153	17		148	23	
Central peg			.046*			.018*			.007*			.057
13.5 mm	252	23		145	18		198	17		199	23	
23.5 mm	187	22		84	17		134	16		138	22	

* Statistically significant ($P < .05$).

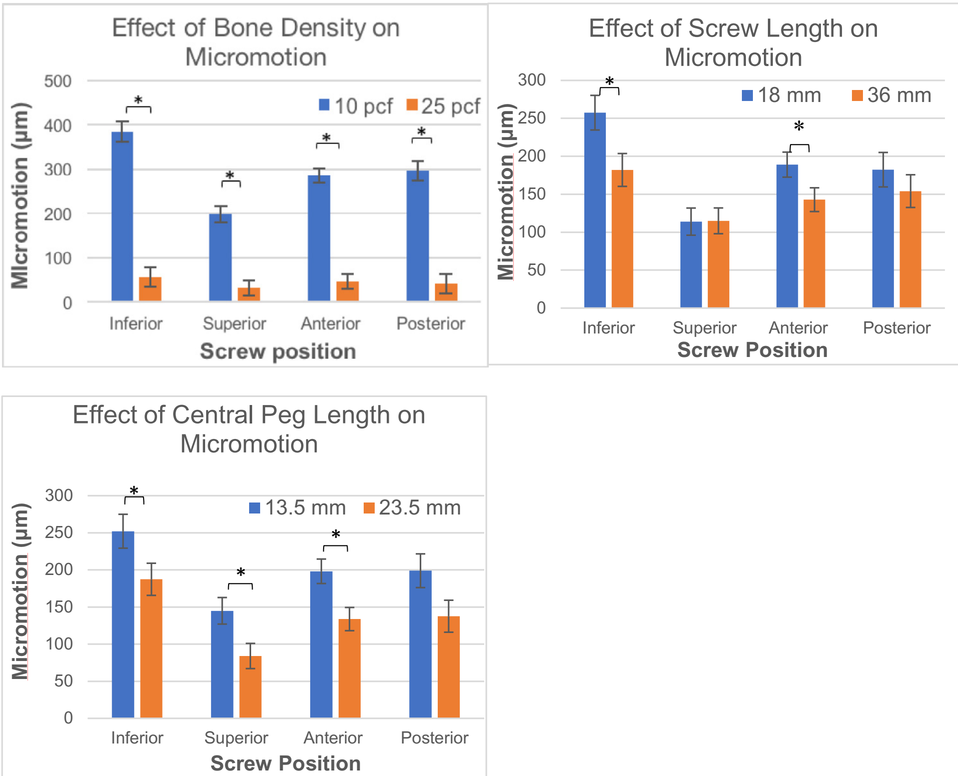

Figure 2 Main effects of bone density (*pcf*, pounds per cubic foot), screw length, and central peg length on micromotion. Data are presented as the mean and standard error (*range bar*). *Significant difference ($P < .05$).

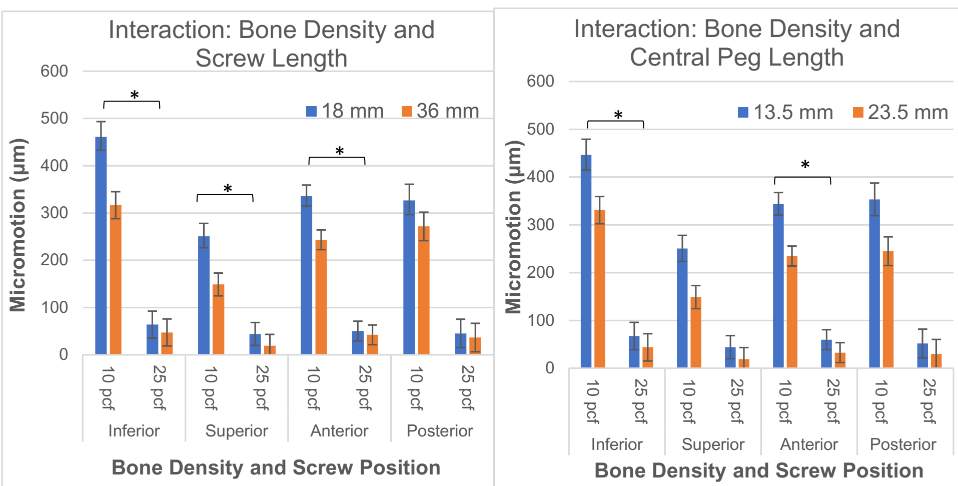

Figure 3 Significant interactions between bone density (*pcf*, pounds per cubic foot) and screw length, and bone density and central peg length. Data are presented as the mean and standard error (*range bar*). *Significant difference ($P < .05$).

a diverging arrangement is not useful for initial baseplate fixation.

Our finding that increasing bone density improves baseplate fixation is consistent with results in the literature. Chebli et al[5] found that loading lower-density Sawbones blocks requires a smaller load to failure. Similarly, Stroud et al[21] found more displacement of the baseplate when fixated on lower-density Sawbone blocks. Bone density is fixed in patients, and therefore, this finding reinforces the importance of good patient selection when considering a RSA and the risks with performing this procedure in patients with lower bone density.

In our study, increasing the number of screws did not influence initial baseplate fixation. This finding contrasts with Chebli et al,[5] who found that the load to failure (screw pullout) was reduced by 16% to 35% when 1 screw was omitted. Likewise, Hoenig et al[8] looked at the contribution of the posterior screw and found that the rate of glenoid loosening was 3 times faster without the posterior screw compared with when it was present.

However, the positive effect on baseplate fixation from increasing the number of screws has not been consistently reported. Irlenbusch and Kohut[11] compared 2 baseplate designs: a baseplate with 1 peg and 4 screws and a baseplate with 2 pegs and 3 screws and found no differences in micromotion. James et al[12] compared the use of 2 (superior and inferior) and 4 screws on micromotion and displacement and found no significant differences between testing conditions. The present study also used the inferior and superior screws when testing any trial requiring 2 screws and found no difference between using 2 or 4 screws. This suggests that the inferior and superior screw positions are most important for resisting micromotion during shoulder abduction. Although all these studies used mechanical testing methods, the heterogeneity in the literature may be attributable to the specific testing protocols or the different outcome measures.

Various studies have used the potential to insert longer screws as a measure of stability, inferring that longer screws are more stable. Hopkins and Hansen[9] used finite element analysis to test this hypothesis and found that using longer and thicker screws offered more resistant to micromotion. The current study reinforces this finding at the inferior and anterior screw positions. We can surmise that using a longer screw in the inferior position is more important than in the superior position based on the direction of physiologic inferior-to-superior loading on the glenosphere during abduction.[15] Furthermore, because of the 60° loading angle used, the inferior screw was closest to the point of loading. This outcome is similar to results from Chebli et al,[5] who found that the screw closest to the point of load had the largest contribution to load bearing.

Increasing the central peg length reduced micromotion at the inferior, superior, and anterior screw positions. Although not significant, there was a trend toward reducing micromotion with a longer central peg in the posterior position. Königshausen et al[14] showed that when a more central peg is fixed to the bone, the loading capacity of the entire baseplate is improved. In clinical practice, however, the central peg length may be limited by the patient's bone stock. Therefore, consideration should be made to fit the longest central peg possible to improve initial baseplate fixation.

Finite element studies support the role of diverging screw configurations in promoting baseplate stability.[9,23] Furthermore, a diverging arrangement of screws allows for greater screw purchase, which studies have used as a measure of fixation.[10,22] Because our study treated screw length and diverging screw arrangement as separate factors, we can infer that the screw angle is not as important in initial fixation of the baseplate as the length of the screw.

When interpreting our findings, it is important to consider the following limitations. Sawbone polyurethane blocks have a uniform density and do not account for cortical bone fixation or regional differences in scapular bone density. More research is needed to examine these factors more closely in cadaveric scapula or fourth-generation Sawbones to account for the varying scapular densities.

Our study evaluated the contribution of mechanical factors on baseplate fixation by loading the baseplate in an inferior-to-superior direction to simulate shoulder abduction. However, this model does not account for shoulder motions in other planes (eg, forward flexion and extension). Furthermore, the half-fractional factorial design used in this study confounds 2-factor interactions with 3-factor interactions. Because 3-factor interactions are unlikely to be clinically significant, this was an accepted risk of the design.

Conclusions

Our findings corroborate the importance of higher bone densities, longer central peg length, and greater peripheral screw length in improving baseplate fixation in a RSA. Central peg and peripheral screw purchase is especially crucial in lower bone densities and should be maximized if possible. Furthermore, neither a diverging screw arrangement nor increasing the number of screws from 2 to 4 significantly contributes to initial baseplate fixation in uniform bone density. Lastly, the peripheral screw at the inferior position may be the most important in withstanding micromotion during shoulder abduction. A logical next step in this research would include mechanically loading in vitro cadaveric models to verify these results. Future findings may help inform surgical decision making in RSA to minimize baseplate failure and the need for revision surgery.

Disclaimer

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