Association of the Stability Ratio With Postoperative Clinical Function and Recurrence of Instability in Patients With Anterior Shoulder Instability

A Retrospective Cohort Study

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Background: The stability ratio (SR) is used to assess the stability of the glenoid in anterior shoulder instability (ASI). However, the association between the SR and postoperative clinical function and instability recurrence after arthroscopic Bankart repair is unknown.

Hypothesis: Patients with a higher SR would have better postoperative clinical scores and a lower incidence of recurrent instability than patients with a lower SR after arthroscopic Bankart repair.

Study Design: Cohort study; Level of evidence, 3.

Methods: A total of 62 patients who underwent arthroscopic Bankart repair for ASI between 2013 and 2019 were enrolled. All patients had at least 2 years of follow-up data. The preoperative SR was calculated via biomechanical testing based on patient-specific 3-dimensional glenoid models, and patients were evenly divided into 2 groups: high SR ($\geq$16.13%) and low SR ($<$16.13%). Baseline information (patient characteristics, clinical history, bone defect area [BDA], and SR), clinical scores at the final follow-up (Single Assessment Numerical Evaluation, Western Ontario Shoulder Index, and American Shoulder and Elbow Surgeons), and instability recurrence were compared between the 2 groups.

Results: No significant differences were found in the baseline information between the high- and low-SR groups, except for the BDA (8.5% [high-SR group] vs 11.9% [low-SR group]; $P = .01$). No patients in the high-SR group had recurrent instability, while 6 patients (19.4%) had recurrent instability in the low-SR group ($P = .02$). Patients in the high-SR group had superior clinical outcomes compared with those in the low-SR group in terms of postoperative Western Ontario Shoulder Index scores (median, 205 vs 410, respectively; $P = .006$) and American Shoulder and Elbow Surgeons scores (median, 98.3 vs 95, respectively; $P = .02$).

Conclusion: In the present study, the SR was significantly associated with postoperative clinical function and recurrence of instability after arthroscopic Bankart repair in patients with ASI.

Keywords: anterior shoulder instability; bone defect area; concavity compression; stability ratio

The stability ratio (SR) is a biomechanical parameter for evaluating the concavity-compression effect—a vital mechanism for maintaining shoulder stability in midrange motion.[8,12] By definition, the SR is the ratio between 2 forces—one required to displace the humeral head and the other the joint compressive load during dislocation.[10] The SR provides biomechanical information regarding glenoid stability, and it is an important indicator of supplementary morphological information, including the bone defect area (BDA).[16-18] However, the traditional method of SR calculation[18,22] has overlooked the determination of

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the glenoid center line, thus limiting its clinical application, especially among glenoids with remarkable bone defects. It remains unknown whether the SR can predict postoperative clinical function and instability recurrence after arthroscopic Bankart repair in patients with anterior shoulder instability (ASI).

Based on a study by Moroder et al,[17,18] we conducted a previous study[6] in which we proposed and verified a new computed tomography (CT)-based method to estimate the SR that overcame the shortcomings of traditional SR calculation methods. This study aimed to evaluate whether the SR is associated with postoperative clinical function and recurrence of instability after arthroscopic Bankart repair in patients with ASI. We hypothesized that patients with a higher SR would have better postoperative clinical assessment scores and a lower incidence of recurrent instability than patients with a lower SR.

METHODS

Patient Selection

This retrospective cohort study received institutional review board approval, and all included patients provided written informed consent. The study inclusion criteria were as follows: (1) age between 18 and 40 years; (2) diagnosis of traumatic ASI regardless of bone defects in the anterior or anteroinferior quadrant of the glenoid rim; (3) positive apprehension test on physical examination; (4) confirmation of a Bankart lesion through preoperative magnetic resonance imaging; (5) treatment with index arthroscopic Bankart repair only without bony augmentation procedure at our institution between 2013 and 2019; and (6) a minimum of 2 years of evaluation.

The exclusion criteria were as follows: (1) diagnosis of bony Bankart lesions, neurologic abnormalities, rotator cuff tears, superior labrum anterior to posterior lesions, greater tuberosity fractures, or other types of instability—such as posterior instability and multidirectional instability; (2) concomitant surgical treatment—including remplissage procedure for an engaging Hill-Sachs lesion and bony augmentation procedures—including iliac crest bone graft augmentation, allograft augmentation, Latarjet, Bristow, or anterior inferior glenohumeral ligament reconstruction procedures—including long head of biceps tendon transfer; (3) previous surgeries on the affected shoulder; (4) unavailability of preoperative CT data; and (5) refusal of follow-up. If the instability severity index score is >6 and there is a significant bone defect, we typically perform a Latarjet procedure. If a Hill-Sachs lesion is present and engagement still occurs after completing the labral repair, a remplissage procedure is performed.

A total of 725 patients were diagnosed with ASI between 2013 and 2019, of whom 476 patients met the inclusion criteria and were assessed for eligibility. However, 414 patients were excluded from the study because of the following reasons: 32 for the diagnosis, 297 for the treatment, 40 for the medical data, and 45 for the follow-up. Ultimately, 62 patients were enrolled in this study, comprising 49 men and 13 women, with a mean age of 27 ± 6.1 years (range, 18-40 years) at the time of surgery. The included patients were evenly divided into 2 groups according to the SR: high SR ($\geq$16.13%; n = 31) and low SR (<16.13%; n = 31) (Figure 1).

Baseline Information

Baseline data—including patient characteristics, time from first dislocation to surgery, dominant arm, number of episodes of instability before surgery, glenoid BDA, SR, number of suture anchors, and time from surgery to the final follow-up—were recorded.

Bone Defect Measurement

The en face view on preoperative 3-dimensional (3D) CT was used to determine the percentage of anterior glenoid bone defects. This was done by calculating the ratio of the glenoid loss width to the longest anteroposterior glenoid width, which corresponds to the diameter of the outer-fitting circle based on the inferior part of the glenoid contour.[1,11,23] A circle was drawn based on the 6- to 9-o'clock position of the glenoid contour, as most glenoid bone defects occur in the anterior or anteroinferior quadrant of the glenoid rim. Two sports medicine surgeons (Q.H., D.W.) measured the CT images independently. After 4 weeks, 1 of the surgeons (Q.H.) repeated the measurements to assess intraobserver reliability.

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Ethical approval for this study was obtained from Shanghai Jiao Tong University Affiliated Sixth People's Hospital (ref No. 2021-KY-62[K]).

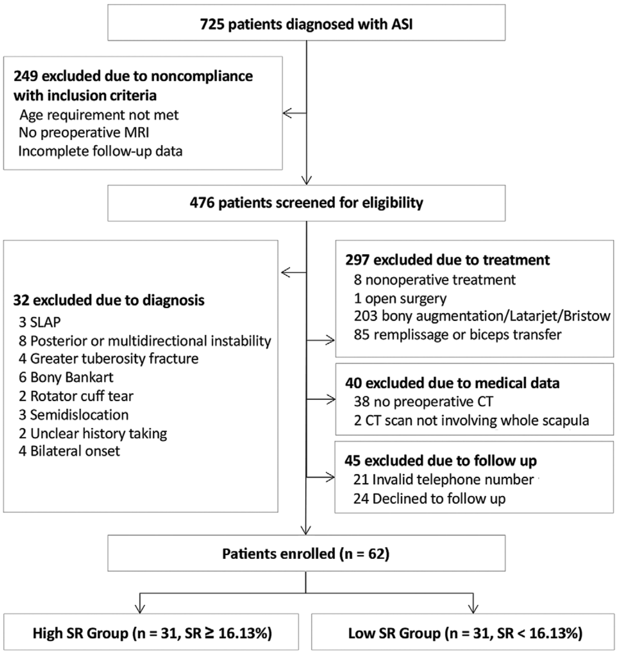

Figure 1. A flowchart showing patient inclusion and final study cohorts. ASI, anterior shoulder instability; CT, computed tomography; MRI, magnetic resonance imaging; SLAP, superior labrum anterior to posterior; SR, stability ratio.

SR Measurement

The SR was calculated via a biomechanical test of the 3D glenoid model of corresponding patients on the customized inclination platform based on our previous study.[6] In brief, patient-specific 3D glenoid models were designed and produced. A customized biomechanical testing platform was constructed in which the inclination angle of the platform could be manually altered. When testing, the 3D glenoid model was mounted on the connecting board to test in the 3-o'clock position (right shoulder), and a 40-mm diameter humeral steel ball was placed on the glenoid to represent the humeral head.[15,24] Then, the inclination angle was gradually increased until the point at which the steel ball rolled off the glenoid (Figure 2A). At the last moment of the quasi-equilibrium state, according to the force analysis, the gravity of the steel ball is able to be decomposed into the compressive force perpendicular to the board (or the glenoid) and the dislocating force along the board (Figure 2B). Based on geometric properties, the tangent value of the balance stability angle (BSA) is equivalent to the SR.[10] The BSA represents the maximum angle formed by the net force on the humeral head and the glenoid centerline before dislocation occurs.[10] Therefore, the tangent value of the inclination angle (BSA) is the ratio between the dislocating force and the compressive force (Figure 2B), which is the SR. In addition to this biomechanical test, the SR can also be calculated based on CT scans (for details, see the Supplemental Material, available separately).

Index Surgical Procedure and Physical Rehabilitation

All patients underwent arthroscopic Bankart repair at our medical center. Patients were positioned in the lateral decubitus position with the arm at 30° of abduction and slight forward flexion using a lateral traction device under general anesthesia and interscalene nerve block. The surgeon utilized a standard posterior portal for initial visualization and an anterior portal for anchor insertion in the rotator interval close to the upper margin of the subscapularis tendon. An anterosuperior viewing portal was created through the musculotendinous junction of the rotator cuff posterior to the biceps tendon. Diagnostic arthroscopy was performed through the posterior portal to assess any associated intra-articular lesions, and all pathologic findings were recorded. The surgeon then moved the arthroscope to the anterosuperior portal to identify the Bankart lesion. The anterior capsulolabral complex was dissected and mobilized from the anteroinferior glenoid neck using an arthroscopic radiofrequency probe. A motorized shaver was utilized to remove frayed tissue and decorticate the glenoid rim to promote healing of the tissue to the glenoid. One double-loaded suture anchor was used in the most inferior part of the Bankart lesion for all patients. In contrast, additional double-loaded suture anchors were inserted between the 5-o'clock and 3-o'clock positions based on the extent and quality of the detached capsulolabral structure and the positions of the glenoid. The suture was tied through the anterior portal using sliding knots to pull the capsulolabral tissue to form a "bumper" on the glenoid.

After the index surgery, immobilization with an abduction brace was maintained for 4 weeks. Once immobilization was discontinued, patients began passive- and active-assisted exercises in all directions. Shoulder muscle strengthening exercises were initiated 8 to 12 weeks postoperatively. Patients were allowed to return to sports activities 12 months after surgery.

Recurrent Instability and Clinical Function

Any episodes of recurrent instability were recorded at the final follow-up evaluation. Recurrent instability was defined as a redislocation or subluxation event after the initial arthroscopic surgery.[7]

The clinical outcomes of the patients were evaluated using the Single Assessment Numerical Evaluation (SANE), Western Ontario Shoulder Index (WOSI), and American Shoulder and Elbow Surgeons (ASES) scores. Patients were evaluated at 3, 6, 12, and 24 months postoperatively then every 6 months after that. The preoperative clinical scores—except for the SANE, assessed postoperatively—were obtained via the medical history. The clinical scores at the final follow-up were obtained via telephone or outpatient visits.

Statistical Analysis

To examine normality, statistical analysis was performed using the Shapiro-Wilk test. Continuous variables were

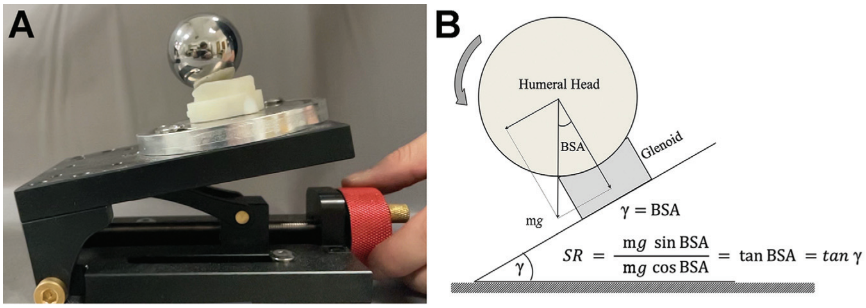

Figure 2. The biomechanical test and its principle. (A) The SR in the 3-o'clock position was measured by an inclination board. The inclination angle was enlarged until the steel ball rolled off. The inclination angle and the tangent value of the inclination angle are the SR. (B) The principle of the biomechanical test. BSA, balance stability angle; m*g*, gravitational acceleration of the steel ball; SR, stability ratio; γ, inclination angle.

reported as means and standard deviations with 95% CIs or ranges when normally distributed or as medians, interquartile ranges (IQRs), and ranges when nonnormally distributed. Categorical variables were reported as frequencies and proportions. Categorical variables were examined using the Fisher exact test. For continuous variables, differences between groups were analyzed using the Student *t* test or the Mann-Whitney *U* test, depending on the data distribution. Baseline information, instability recurrence, and preoperative and final follow-up clinical scores were compared between the high-SR and low-SR groups. The significance level for all comparisons was set at $P < .05$.

We also calculated the percentage of patients in the study groups who exceeded the minimum clinically important difference (MCID) threshold for the WOSI and the ASES. According to a previous study,[4] the MCID is 220 for the WOSI and 6.4 for the ASES.

The interobserver and intraobserver reliability of the bone defect measurements was assessed by the intraclass correlation coefficient (ICC) using a 2-way random-effects model, assuming a single measurement and absolute agreement. An ICC value of >0.7 was deemed to be good reliability. All statistical analyses and tests were conducted using SPSS Version 18.0 statistical software (SPSS Inc) and GraphPad Prism 9.0.

RESULTS

The median time from the first dislocation episode to surgery was 42.1 months (IQR, 17.6-106.5 months [range, 1-310.4 months]). The primary arthroscopic surgery involved a mean of 3.1 ± 0.5 suture anchors (range, 2-4 anchors). Among the 62 study patients, shoulder dislocation before surgery occurred >10 times in 5 patients (8.1%), 5 to 10 times in 27 patients (43.5%), and <5 times in 30 patients (48.4%).

BDA and SR

The patients had a mean glenoid BDA of 10.2% ± 5.2% (range, 0% to 23%). There were only 2 patients (3.2%) without glenoid bone defects. The ICC for interobserver reliability was 0.893 (95% CI, 0.829 to 0.934), and the ICC for intraobserver reliability was 0.800 (95% CI, 0.688 to 0.874), passing the threshold for good reliability in both cases. The mean SR was 14.9% ± 9.3% (range, –5.4% to 32%). There were 20 patients (32.3%) with an SR <10%, 23 patients (37.1%) with an SR between 10% and 20%, 16 patients (25.8%) with an SR between 20% and 30%, and 3 patients (4.8%) with an SR >30%.

Baseline Information Between the High- and Low-SR Groups

The baseline information for the high- and low-SR groups is summarized in Table 1. No significant differences were found between the 2 groups, except for the BDA ($P = .01$) and the SR ($P < .001$).

Recurrent Instability and Clinical Function

The number of patients with recurrent instability at the final follow-up was significantly smaller in the high-SR group than in the low-SR group (0 vs 6 patients, respectively [$P = .02$]) (Table 2). There were 4 redislocations due to low-energy traumatic episodes and 2 subluxations without trauma. None of the patients underwent revision surgery. The BDA and SR of the 6 patients with recurrent instability are available in Supplemental Table S1, available separately.

In both high- and low-SR groups, WOSI and ASES scores improved from the preoperative assessment to the final follow-up (high-SR group: $P < .001$ for WOSI, $P = .01$ for ASES; low-SR group: $P = .001$ for WOSI, $P < .0001$ for ASES). There were no differences in the preoperative scores between the 2 groups, except for the ASES score, which was significantly higher in the high-SR group ($P = .006$) (Table 2). However, postoperative scores for the WOSI and ASES were significantly worse in the low-SR versus the high-SR group ($P = .006$ for WOSI, $P = .02$ for ASES) (Table 2). The scores on WOSI items that were significantly different between the 2 groups at the final

TABLE 1
Comparison of Baseline Information Between the Study Groups[a]

	High-SR Group (SR ≥16.13%; n = 31 Shoulders)	Low-SR Group (SR <16.13%; n = 31 Shoulders)	*P*
Age at operation, y, mean (95% CI)	28.1 (25.8-30.4)	26 (23.8-28.1)	.18
Sex, n (%)			.53
Female	5 (16.1)	8 (25.8)	
Male	26 (83.9)	23 (74.2)	
Follow-up, mo, mean (95% CI)	68.2 (60.9-75.4)	71.2 (63.3-79.1)	.57
Dominant arm, n (%)	21 (67.7)	26 (83.9)	.23
Episodes of instability, mean (IQR) [range]	3 (3-7) [1-20]	6 (3-10) [1-50]	.18
Time from first dislocation to surgery, mo, mean (IQR) [range]	45.2 (12.4-105.7) [1-310.4]	42 (23.7-109) [2.0-221.6]	.57
BDA, %, mean (95% CI)	8.5 (6.9-10.1)	11.9 (9.9-13.9)	**.01**
SR, %, mean (95% CI)	22.6 (20.9-24.4)	7.2 (5.2-9.1)	**<.001**
Anchors, n, mean (95% CI)	3.1 (2.9-3.3)	3.2 (3.1-3.4)	.18

[a] Bold *P* values indicate statistically significant differences between groups ($P < .05$). BDA, bone defect area; IQR, interquartile range; SR, stability ratio.

TABLE 2
Comparison of Recurrent Instability and Clinical Function Between the Study Groups[a]

	High-SR Group	Low-SR Group	*P*
Recurrent instability	0 (0)	6 (19.4)	**.02**
SANE score			
Final follow-up	81 (70-90) [21-100]	80 (70-90) [30-100]	.52
WOSI score			
Preop	824 (387-1087) [0-1980]	1034 (640-1422) [0-1791]	.23
Final follow-up	205 (120-341) [0-906]	410 (202-752) [20-1235]	**.006**
ASES score			
Preop	91.7 (78.3-100) [0-100]	74 (53.7-88) [33.2-100]	**.006**
Final follow-up	98.3 (93.3-100) [80.3-100]	95 (85-98.3) [76.7-100]	**.02**

[a] Data are reported as n (%) or median (IQR) [range]. Bold *P* values indicate statistically significant differences between groups ($P < .05$). ASES, American Shoulder and Elbow Surgeons; IQR, interquartile range; Preop, preoperative; SANE, Single Assessment Numerical Evaluation; SR, stability ratio; WOSI, Western Ontario Shoulder Index.

follow-up are presented in Table 3. Regarding the MCID achievement, 71% (22/31) of patients in both groups achieved the MCID for the WOSI. The MCID for the ASES was achieved in 80.6% (25/31) of patients in the low-SR group but only in 58.1% (18/31) of the patients in the high-SR group.

There was a significant difference in the BDA between the high- and low-SR groups (8.5% vs 11.9%; $P = .01$); thus, it is reasonable to suspect that the BDA influenced the postoperative clinical scores. To investigate, we divided the study patients evenly into 2 groups based on the BDA: a low BDA (<10.5%; n = 31) and a high BDA (>10.5%; n = 31). Results demonstrated no group differences regarding SR, recurrent instability, or clinical scores except for the preoperative WOSI ($P = .04$) (Supplemental Tables S2 and S3). Thus, the clinical differences between the high- and low-SR groups were not attributed to the difference in the BDA.

DISCUSSION

The most significant finding of this study was that a higher SR is significantly associated with better clinical function and a lower incidence of recurrent instability after arthroscopic Bankart repair in patients with ASI. Patients in the high-SR group had superior clinical outcomes compared with those in the low-SR group in terms of postoperative WOSI scores (median, 205 vs 410, respectively; $P = .006$) and ASES scores (median, 98.3 vs 95, respectively; $P = .02$).

The preoperative ASES scores were significantly higher in the high-SR group than in the low-SR group (91.7 vs 74, respectively; $P = .006$). We believe that 2 factors may explain these findings. First, each scoring system has its focus. The ASES score primarily focuses on evaluating patients' pain and function. For patients with milder instability, the level of pain and the impact of the instability on their daily life may not be significant. On the other hand,

TABLE 3
Comparison of Significantly Different WOSI Items Between the Study Groups[a]

	High-SR Group	Low-SR Group	*P*
Physical symptoms			
Aching or throbbing in the shoulder	0 (0-3) [0-36]	5 (0-15) [0-40]	.0042
Weakness or lack of strength	0 (0-20) [0-47]	17 (6-37) [0-84]	.0092
Fatigue or lack of stamina	0 (0-20) [0-41]	20 (10-52) [0-85]	.0025
Discomfort in the neck muscle as a result of shoulder	0 (0-10) [0-86]	10 (0-25) [0-91]	.0073
Instability or looseness	1 (0-20) [0-65]	19 (7-41) [0-63]	.0055
Lifestyle			
Fear falling on the shoulder	20 (0-23) [0-100]	44 (15-80) [0-100]	.0049
Difficult to maintain the desired level of fitness	10 (0-20) [0-60]	21 (10-61) [0-80]	.0127
Difficult to horse around with friends	0 (0-10) [0-81]	6 (0-42) [0-93]	.0398
Emotions			
Conscious of the shoulder	0 (0-14) [0-50]	23 (10-52) [0-100]	<.0001
Frustrated because of the shoulder	0 (0-20) [0-80]	15 (0-45) [0-81]	.0103

[a] Data are reported as median (IQR) [range]. Presented are 10 of the 21 WOSI items that showed significant group differences. IQR, interquartile range; SR, stability ratio; WOSI, Western Ontario Shoulder Index.

the WOSI score primarily evaluates shoulder joint stability, which explains why lower preoperative WOSI scores were reported in the high-SR group than in the low-SR group (824 vs 1034, respectively; $P = .23$), although this difference did not reach statistical significance. Second, the SR may be able to distinguish the severity of patients' preoperative conditions. Since the SR is an indicator of shoulder joint stability, it is reasonable that it can assess the severity of patients' conditions.

The comparison of postoperative WOSI subscores between the high- and low-SR groups indicated group differences on 10 of the 21 items, primarily those involving physical symptoms, lifestyle, and emotions (see Table 3). Notably, patients in the low-SR group experienced more feelings of instability or looseness postoperatively, indicating that the biomechanical indicator agrees with actual clinical manifestation. In addition, patients in the low-SR group were more prone to experiences with discomfort such as fatigue, weakness, and aching in the shoulder, fear of falling on the shoulder, and conscious of the shoulder.

Although the SR exhibits the potential to predict postoperative clinical function and recurrent instability, this does not mean that the SR can replace the BDA; nonetheless, it serves as a supplementary indicator for evaluating glenoid bone defects from a biomechanical perspective. Recent studies[2,3,19,21,26] regarding the cutoff value of glenoid bone defects have implied that the BDA alone is insufficient to predict prognosis in patients with ASI. Therefore, an evaluation combining morphology and biomechanics is necessary. We believe that the SR is a potential indicator, as it is of advantage when the bone defects are noncritical. This is mainly because the SR is more sensitive than the BDA when the bone defects only involve a small portion of the glenoid rim area.[17] In addition, as the measurement of SR requires determining the glenoid centerline (this step implies a positional relationship between the glenoid and the scapular body), it allows for evaluating the glenoid version on shoulder stability. However, BDA only represents changes in the glenoid area and does not consider the influence of glenoid anteversion on stability. It is well known that glenoid anteversion is a risk factor for anterior glenoid instability.[5,13,20] Even identical bone defects can result in different SR values if the glenoid anteversion is altered. Therefore, it is recommended to evaluate shoulder stability via the BDA and the SR.

Limitations

There are some limitations in this study. First, the present study determined the SR utilizing 3D-printed glenoids that were reconstructed solely from CT data, thereby representing only the bony anatomy of the glenoid while excluding information regarding the surrounding soft tissues such as labrum, ligaments, cartilage, and other anatomic structures. Consequently, the determined SR reflects exclusively the bony stability of the glenoid. However, previous studies have demonstrated that the soft tissue structures are lax during the mid-range of motion. Hence, the stability of the shoulder joint mainly depends on the bony structures.[14,17,18,25] Second, the methodology employed 40-mm steel balls to simulate the humeral head without considering Hill-Sachs lesions—a defect associated with the off-track mechanism at the end-range of movement.[8] However, we investigated shoulder stability during the mid-range of motion, where the concavity-compressive effect is the primary factor rather than the off-track mechanism.[9,12] Third, our sample size was relatively small, and we could not investigate a specific cutoff value for the SR. In future research, it may be possible to identify a critical value that distinguishes a stable from an unstable glenoid. Fourth, we only assessed the effect of SR on patients with relatively mild glenoid bone loss, which may limit its predictive capability for cases involving more significant bone loss. Fifth, calculating the SR using the biomechanical test is complex and inconvenient for clinical application. However, our previous study[6] demonstrated a strong correlation ($r = 0.97$) between the SR calculated using the biomechanical method and that obtained using the more straightforward CT-based method. Sixth, there were no data on pre- and postoperative sporting activities among the study patients.

CONCLUSION

The present study has demonstrated an association between SR and postoperative clinical function and instability recurrence among patients with ASI. The SR appears to reflect the stability of the glenohumeral joint, suggesting its potential utility in predicting patient prognosis. We plan to expand the sample size to explore the cutoff value for the SR in future investigations. In addition, we aimed to simplify the SR measurement process, thereby reducing the measurement costs for clinicians and facilitating its clinical applicability. The SR may serve as a factor in formulating a surgical plan for patients with ASI who have subcritical bone loss.

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