



■ SHOULDER AND ELBOW

Biomechanical analysis of the effect of congruence, depth and radius on the stability ratio of a simplistic 'ball-and-socket' joint model

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Objectives

The bony shoulder stability ratio (BSSR) allows for quantification of the bony stabilisers *in vivo*. We aimed to biomechanically validate the BSSR, determine whether joint incongruence affects the stability ratio (SR) of a shoulder model, and determine the correct parameters (glenoid concavity *versus* humeral head radius) for calculation of the BSSR *in vivo*.

Methods

Four polyethylene balls (radii: 19.1 mm to 38.1 mm) were used to mould four fitting sockets in four different depths (3.2 mm to 19.1 mm). The SR was measured in biomechanical congruent and incongruent experimental series. The experimental SR of a congruent system was compared with the calculated SR based on the BSSR approach. Differences in SR between congruent and incongruent experimental conditions were quantified. Finally, the experimental SR was compared with either calculated SR based on the socket concavity or plastic ball radius.

Results

The experimental SR is comparable with the calculated SR (mean difference 10%, SD 8%; relative values). The experimental incongruence study observed almost no differences (2%, SD 2%). The calculated SR on the basis of the socket concavity radius is superior in predicting the experimental SR (mean difference 10%, SD 9%) compared with the calculated SR based on the plastic ball radius (mean difference 42%, SD 55%).

Conclusion

The present biomechanical investigation confirmed the validity of the BSSR. Incongruence has no significant effect on the SR of a shoulder model. In the event of an incongruent system, the calculation of the BSSR on the basis of the glenoid concavity radius is recommended.

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Article focus

- Is the bony shoulder stability ratio (BSSR) valid?
- Does incongruence affect the stability ratio (SR) of a shoulder model?
- Is it valid to use the radius of the glenoid concavity of an incongruent shoulder joint in order to calculate the BSSR *in vivo*?

Key messages

- The BSSR was proved valid for congruent and incongruent systems.
- For the calculation of the BSSR *in vivo*, the use of the radius of the glenoid concavity

is recommended over the use of the humeral head radius.

- Our study findings support the use of the BSSR for *in vivo* CT-based determination of bony shoulder stability.

Strengths and limitations

- First biomechanical study analysing the effect of joint incongruence on the SR.
- This study determines the correct parameters (glenoid concavity radius *versus* humeral head radius) for calculation of the BSSR *in vivo*.
- Material properties and friction coefficients are limitations of the present study.

Introduction

In shoulder instability research, the ratio of the peak translational force causing dislocation to the compressive load that provides stability is called the stability ratio (SR).^{1,2} The ratio is determined by the morphology of the articulating surfaces,^{1,3} and in clinical practice largely depends on the integrity and geometry of the glenoid. It is known that patients with a glenoid defect are at high risk of recurrent instability,^{4,5} which necessitates glenoid reconstruction surgery by means of coracoid transfers, iliac crest bone graft transfers, or allografting.⁶⁻¹¹ On the other side, atraumatic and traumatic shoulder instability, without any sign of glenoid bone loss, is associated with an inherent flattening of the bony glenoid concavity.¹²

Thus far, glenohumeral stability in experimental studies has been described either by the SR^{1,3,5,13} or by displacement after applying a predetermined translational force.¹⁴⁻¹⁸ Oosterom et al¹⁹ aimed to predict stability by means of the “translational stiffness” of the shoulder after joint replacement. Based on their mathematical model for circular shapes, translational force over the “distance to dislocation” can be calculated. Most recently, Willemot et al²⁰ derived a mathematical model based on machine design principles. The humeral head as a follower translates over the cam-like glenoid surface, an applicable concept for non-circular shapes like the native glenohumeral anatomy. However, none of the reported studies described a method allowing for calculation of glenohumeral stability in daily clinical practice.

Lazarus et al¹ aimed to approximate the SR based on mathematical considerations. The relationship between the effective glenoid concavity depth and the SR was described by an empirical equation. This equation was based on a linear relationship between the two factors. Moroder et al¹² have presented a theoretical model to calculate the bony shoulder stability ratio (BSSR). In this CT-based study, the BSSR was calculated based on the patients' glenoid morphology, allowing for quantification of the passive bony stabilisers of a human shoulder. It was shown that the relationship between the glenoid concavity depth and the SR is non-linear.

The BSSR is based on a theoretical congruent joint, the humeral head and the glenoid concavity having the same radius of curvature. Calculations of the BSSR *in vivo* were therefore conducted with both glenoid and humeral head radii.¹² However, several studies have shown that the bony structures of the glenohumeral joint are incongruent, with the glenoid concavity having a larger radius than the humeral head.²¹⁻²⁴ Yet it is not clear which of the radii can be used for valid *in vivo* calculations of the bony shoulder stability.

The first aim of the present study was to validate the BSSR with a biomechanically relevant model. Secondly, we aimed to analyse the effect of joint incongruence on a shoulder model and subsequently on a mathematical

equation based on a theoretical congruent joint. Finally, we aimed to analyse which of the radii, glenoid concavity or humeral head, should be used for valid calculations of the BSSR *in vivo*. We hypothesised that the congruent experimental SR would not be significantly different from the calculated SR based on the BSSR approach, that incongruence has no effect on the SR of a simplistic ball-and-socket joint, and that the radius of the glenoid concavity, rather than of the humeral head, should be used for calculation of the BSSR *in vivo*.

Materials and Methods

Model preparation. A total of four high density polyethylene (HDPE) plastic balls with four different radii of curvature were used in the present study. Based on morphological analyses,^{21,25} radii were selected to be 19.1 mm (B_a), 25.4 mm (B_b), 31.8 mm (B_c) and 38.1 mm (B_d). Plastic balls were mounted on an aluminium rod, forming an analogue to a human proximal humerus. Similar plastic balls were used as a pattern to mould four fitting sockets from resin (Smooth-Cast 65D, Smooth-On, Macungie, Pennsylvania) with matching radius of curvature (S_a , S_b , S_c , S_d). Furthermore, each socket was moulded in four different concavity depths: 3.2 mm (I), 6.4 mm (II), 12.7 mm (III) and 19.1 mm (IV). In total, 16 different sockets were created for the experiment. In order to minimise friction, the surfaces of all moulded sockets were smoothed with 240-grit sandpaper.

Testing apparatus. Components were evaluated using a custom multi-axis electromechanical testing machine described in previous studies of shoulder stability.^{13,26} Briefly, the system consists of a six-axis load cell (model 45E15A-E24ES-A; JR3, Inc., Woodland, California) fitted on a motorised XY table (DCI Design Components, Franklin, Massachusetts), the movement of which simulates anterior-posterior or superior-inferior motion. Sockets were mounted to the XY table (Fig. 1). The z-axis is pneumatically controlled and compressive (medial-lateral) load is applied to the humerus analogue with motion measured with a linear potentiometer (TR-50; Novotechnik, Stuttgart, Germany). According to the manufacturer, the capacity and resolution of the load cell are 100 N and 1.3 N, respectively (Fig. 1). Following previous studies, measuring the point where the ball was seated at the deepest part of the socket concavity identified the neutral position.^{13,26} A 50-N concavity compression force, selected based on previous studies,^{1,13,27} was applied to the plastic ball by the pneumatic cylinder. All analyses were based on a normalised displacement, where each head size was displaced one diametrical distance anteriorly at 2 mm/s. The translational force was defined as the maximum force observed as the ball translated across its normalised distance.

Test conditions. Each experiment and condition was repeated three times to evaluate repeatability of the results.

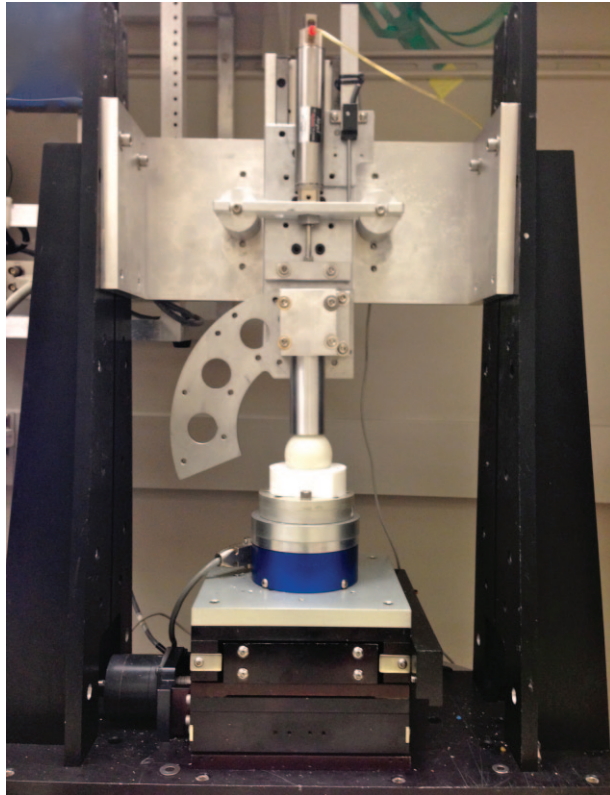


Fig. 1

A photograph of the custom testing machine and the experimental setup. The high density polyethylene plastic ball is mounted on an aluminium rod, whereas the moulded socket is mounted on an aluminium plate attached to the load cell (blue).

The peak translational force was measured in two different ways: with congruent radii of curvature between the ball and socket (Fig. 2a) and with a series of incongruent radii of curvature between the ball and socket (Fig. 2b).

In the validation series, each ball (B_a to B_d) was translated against a mating socket (S_a to S_d) of each of the different concavity depths (I to IV) (Table I). The ratio of the peak translational force causing dislocation and the constant concavity compression force was defined as the SR for each condition.^{1,3}

The second testing series evaluated incongruent radii of curvature. As previously reported, mismatch was defined as the ratio of the ball radius to the radius of curvature of the socket.^{19,21} Our mismatched conditions had a ratio of 0.75, 0.80 and 0.83. In other words, we articulated the 19.1 mm ball (B_a) with the 25.4 mm socket (S_b) (ratio = 0.75), the 25.4 mm ball (B_b) with the 31.8 mm socket (S_c) (ratio = 0.80) and the 31.8 mm ball (B_c) with the 38.1 mm socket (S_d) (ratio = 0.83). Each ball was translated against the incongruent sockets of four different depths (I to IV) (Table I).

Statistical analysis. The BSSR (i.e. calculated SR) for each ball-and-socket configuration was calculated as described by Moroder et al.¹² The ratio between translational force (T) and compressive force (C) (Equation 1) was expressed in terms of the radius of curvature (r) and concavity depth (d) based on Pythagorean trigonometric identities (Equation 2). The full derivation of Equations 1 and 2 are given in the supplementary material.

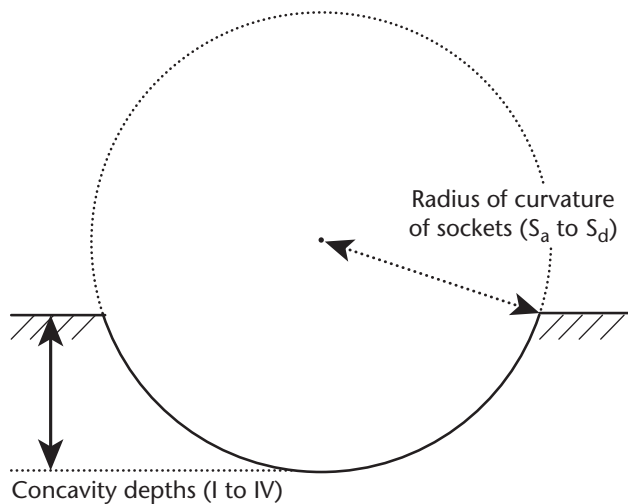


Fig. 2a

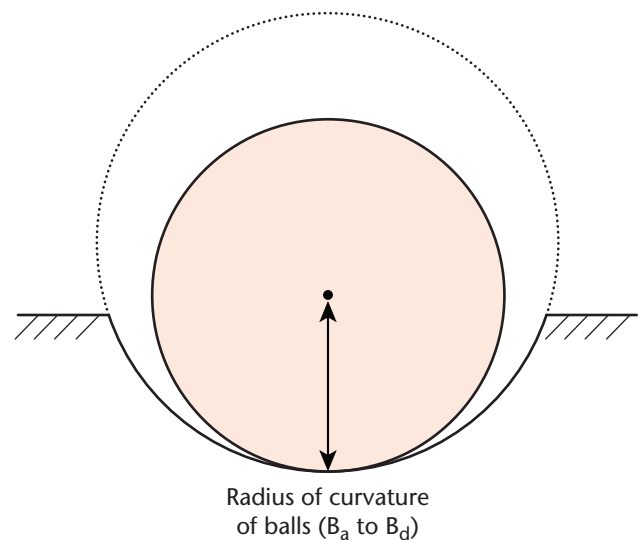


Fig. 2b

The radii of curvature of the ball (B_a to B_d) and socket (S_a to S_d), and its concavity depths (I to IV) are shown; a) the radius of the socket (dashed arrow) is the circumference, depicted by the socket and the dashed circle arc, starting from the socket's rim. The radius of the ball matches the circumference; b) in an incongruent system, the radius of the ball (continuous arrow and circumference) does not match the socket's circumference depicted by the socket and dashed circle arc.

Table I. All applied testing conditions

Test conditions			
Congruent System			
$B_a : S_a$ (I)	$B_b : S_b$ (I)	$B_c : S_c$ (I)	$B_d : S_d$ (I)
$B_a : S_a$ (II)	$B_b : S_b$ (II)	$B_c : S_c$ (II)	$B_d : S_d$ (II)
$B_a : S_a$ (III)	$B_b : S_b$ (III)	$B_c : S_c$ (III)	$B_d : S_d$ (III)
$B_a : S_a$ (IV)	$B_b : S_b$ (IV)	$B_c : S_c$ (IV)	$B_d : S_d$ (IV)
Incongruent System			
.75	.80	.83	
$B_a : S_b$ (I)	$B_b : S_c$ (I)	$B_c : S_d$ (I)	
$B_a : S_b$ (II)	$B_b : S_c$ (II)	$B_c : S_d$ (II)	
$B_a : S_b$ (III)	$B_b : S_c$ (III)	$B_c : S_d$ (III)	
$B_a : S_b$ (IV)	$B_b : S_c$ (IV)	$B_c : S_d$ (IV)	

0.75, 0.80 and 0.83 indicate the ratio of the mismatched radii B_a to B_d , radii of curvature of the balls; S_a to S_d , radii of curvature of the sockets; I to IV, concavity depths of the sockets

$$BSSR = \frac{T}{C} \quad (\text{Equation 1})$$

$$BSSR = \frac{\sqrt{1 - \left(\frac{r-d}{r}\right)^2}}{\frac{r-d}{r}} \quad (\text{Equation 2})$$

BSSRs calculated from this approach were validated against SRs derived from experimental data of a congruent system. To analyse the influence of incongruence, experiment-derived SRs of congruent conditions were compared with their incongruent counterparts. In order to determine the correct parameters (glenoid concavity radius *versus* humeral head radius) for calculation of the BSSR *in vivo*, the experimental SR was compared with the calculated SR based on the socket concavity or plastic ball radius.

In the validation study, data were analysed by comparing SRs with the same radii of curvature of the ball and socket but different depths (e.g. experimental $B_a : S_a$ (I to IV) *versus* calculated $B_a : S_a$ (I to IV)) and with same depth but different radii of curvature (e.g. experimental $B_{a-d} : S_{a-d}$ (I) *versus* calculated $B_{a-d} : S_{a-d}$ (I)).

In order to prove the influence of incongruence on the SR of a simplistic ball-and-socket joint, data were analysed by comparing only experimental SRs with the same radii of curvature (same mismatched radii) of the ball and socket, but different depths (e.g. 0.75 mismatch; $B_b : S_b$ (I to IV) *versus* $B_a : S_b$ (I to IV)).

Finally, the experimental SR was compared with the calculated SR based on the radius of the socket concavity and the calculated SR based on the radius of the plastic ball. Data were analysed by comparing the experimental SRs with each of the corresponding calculated SR based on the socket concavity or plastic ball radius (e.g. experimental $B_a : S_b$ (I to IV) *versus* calculated S_b (I to IV); experimental $B_a : S_b$ (I to IV) *versus* calculated B_a (I to IV)).

Paired sample *t*-tests or Wilcoxon signed-rank tests were applied using SPSS Statistics (Version 22, IBM

Corporation, Chicago, Illinois). In addition, differences between experimental *versus* calculated SR and congruent *versus* incongruent SR were plotted on a graph. In order to evaluate repeatability of the results, test-retest reliability was proved. A *p*-value less than 0.05 indicated statistical significance.

Results

Experimental *versus* calculated SR. In the test condition B_a (IV) : S_a (IV), the measured translational force exceeded the load cell capacity. These results were excluded.

The mean difference in this series was 10% (SD 8%) (relative value) (Fig. 3). Comparing the SRs of the simplistic ball-and-socket joints, no significant differences were observed, except in the comparisons $B_b : S_b$ (I to IV) ($p = 0.010$;) and $B_d : S_d$ (I to IV) ($p = 0.049$), as well as in $B_{a-d} : S_{a-d}$ (I) ($p = 0.029$) and $B_{a-d} : S_{a-d}$ (III) ($p = 0.026$). Of these significant comparisons, the mean difference in $B_b : S_b$ (I to IV) was 11% (SD 5%) and in $B_d : S_d$ (I to IV) 3% (SD 3%) (relative value). On the other side, the mean difference in $B_{a-d} : S_{a-d}$ (I) was 8% (SD 5%) and in $B_{a-d} : S_{a-d}$ (III) 12% (SD 8%) (relative value).

The test-retest reliability of the congruent experimental SRs was proved excellent ($R = 0.995$).

Congruent *versus* incongruent SR. In this experimental study, the mean difference was 2% (SD 2%) (relative value) (Fig. 4). SRs of congruent compared with incongruent simplistic joints revealed no significant differences, except for the comparison $B_d : S_d$ (I to IV) *versus* $B_c : S_d$ (I to IV) (0.83 mismatch). In this significant comparison, the mean difference gave a result of 1% (SD 1%) (relative value).

Repeatability of the incongruent experimental SRs observed an excellent test-retest reliability ($R = 0.995$).

Experimental *versus* calculated SR based on socket concavity radius and experimental *versus* calculated SR based on plastic ball radius. Comparing the experimental SR of an incongruent system with the corresponding calculated SR based on the radius of the socket concavity, a mean difference of 10% (SD 9%) (relative value) was observed. When comparing the experimental SR with the corresponding calculated SR based on the radius of the plastic ball, a mean difference of 42% (SD 55%) (relative value) was proved.

Discussion

The biomechanical relationship between the SR and the glenoid concavity was explained in previous studies.^{1,3,13,28} Lippitt et al³ showed that the greater the glenoid concavity, the greater the SR. Yamamoto et al^{5,28} observed that loss of glenoid concavity due to glenoid bone loss results in a significant decrease of SR of the shoulder,⁵ which cannot be overcome by mere capsulolabral repair but necessitates glenoid reconstruction surgery.²⁸ The measurement of the SR is, however, only possible by means of *in vitro* biomechanical testing. Until recently, there was no

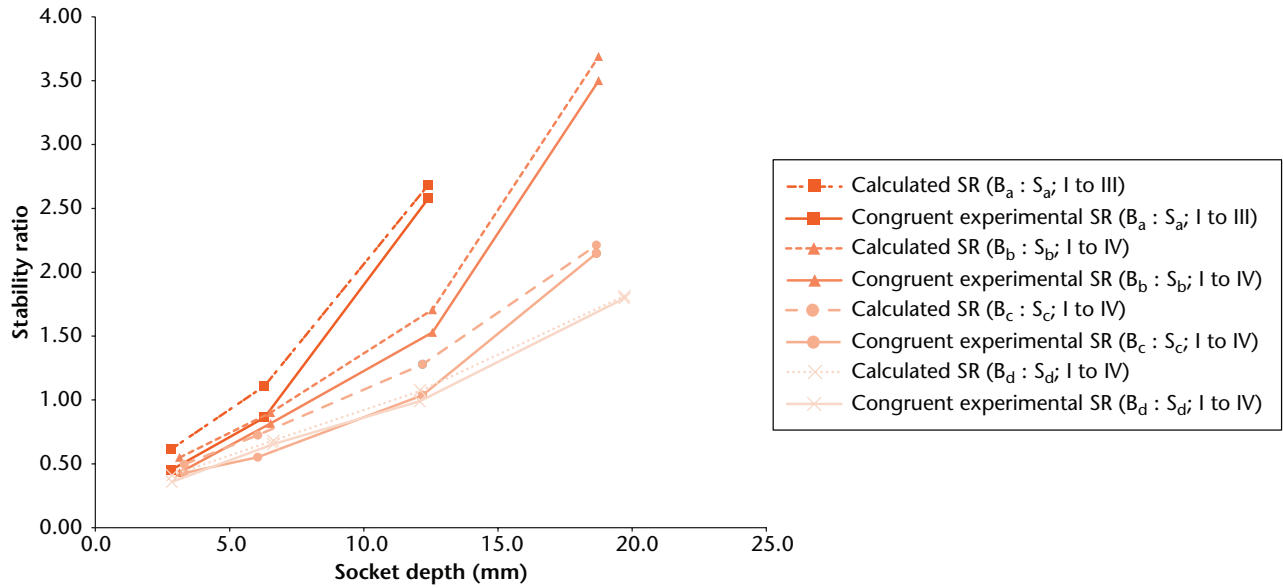


Fig. 3

Graph illustrating the difference between the mean experimental and calculated stability ratio (SR) for different radii of curvature of the ball-and-socket configuration in a congruent system. B_a : S_a to B_d : S_d = radii of curvature of the congruent balls and sockets; I to IV = concavity depths of the sockets.

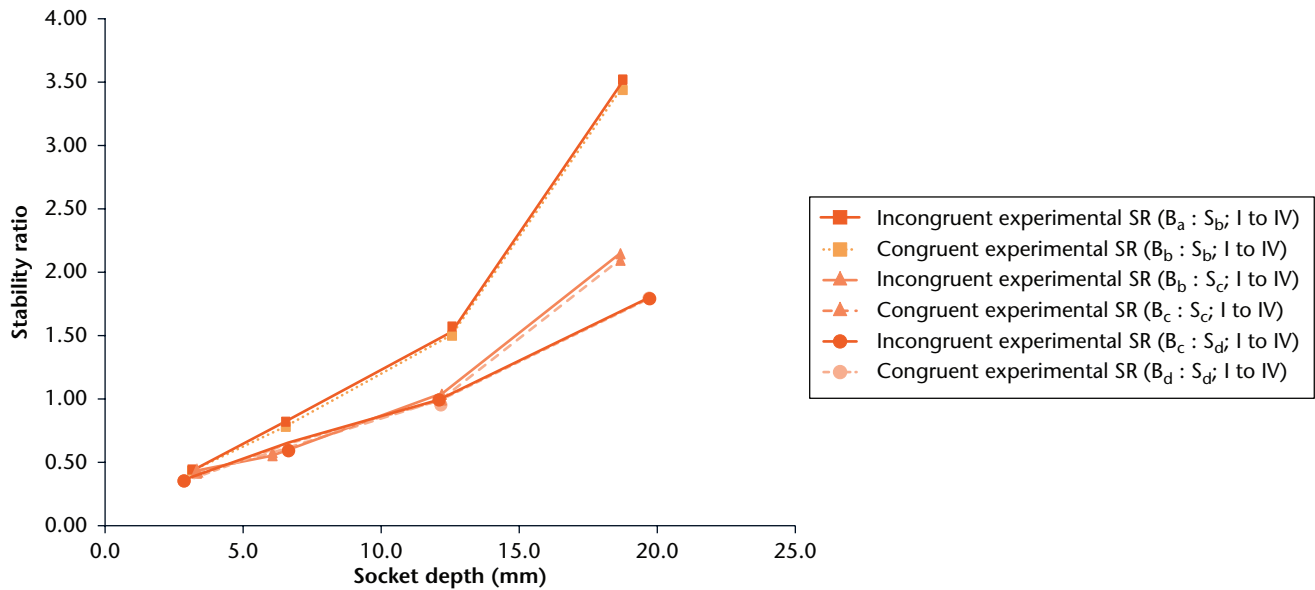


Fig. 4

Graph comparing the effect of experimental radii incongruence to experimental radii congruence regarding the resulting stability ratio (SR). B_b : S_b to B_d : S_d = radii of curvature of the congruent balls and sockets; B_a : S_b to B_c : S_d = radii of curvature of the incongruent balls and sockets; I to IV = concavity depths of the sockets.

technique available to estimate the SR of a glenohumeral joint *in vivo*. Moroder et al¹² presented a CT-based technique, which allows for prediction of the SR of the glenohumeral joint. It was named the bony shoulder stability ratio (BSSR) since it only takes into consideration the bony glenoid morphology visible on CT scans and neglects the stability-contributing effects of soft-tissue structures. The BSSR represents an easy method to calculate the stability ratio created by the bony glenoid concavity and thus offers

the possibility to calculate the actual biomechanical effect of glenoid concavity alterations or glenoid reconstruction surgery *in vivo*. However, in the reported study it could not be clarified whether the mathematical equation based on a theoretical congruent joint is also valid for *in vivo* measurements on an incongruent glenohumeral joint with mismatching radii of curvature.

In the present study we aimed to biomechanically validate the BSSR by comparing the experimental SR of a

congruent system with the calculated SR based on the BSSR approach. According to our results, almost all experimental setups yielded the same results as calculated with the theoretical model. The mean relative difference in this series was 10%. The comparisons with statistically significant differences showed mean relative differences of not more than 12%. Although acceptably small, the presence of differences between the experimental and calculated SRs is evident. Willemot et al²⁰ observed in his cam-follower study on mid-range instability a similar tendency, whereas experimental SRs were constantly smaller than the calculated SRs and relied on elasticity and friction in the experimental model. The validity of the BSSR has previously been confirmed by Finite Element Analysis,¹² which revealed only negligible discrepancies between the computer simulation and the BSSR. Accordingly, our results also prove the validity of the BSSR.

The observed experimental SRs were consistently slightly smaller than the calculated SRs. According to Moroder et al,¹² increasing the radius of curvature is indirectly related to the SR. We assume that due to the constant concavity load, local deformation of the material occurs, leading to an increased local radius of curvature of the socket and resulting in a smaller experimental SR compared with the calculated SR.

Previous studies described the bony morphology of the glenohumeral joint as a “golf ball on a tee” phenomenon.^{12,29} A completely flat “tee” would result in a theoretical BSSR of 0%.¹² On the other side, increasing the concavity depth results in a steep increase of the BSSR. Increasing the concavity depth up to its radius of curvature, the BSSR would increase exponentially and the ball would be secured against any translational force. It was described as “placing the golf ball in an egg cup”.¹² The same finding was observed in this study. A radius of curvature of the ball of 19.1 mm (B_a IV) and a concavity depth of 19.1 mm (S_a IV) led to translational forces exceeding the load cell capacity, and these results had to be excluded.

The BSSR is based on a congruent articulating system with the same radii of curvature for both the glenoid concavity and the humeral head.¹² However, it is known that the cartilage of the humeral head and the glenoid are better conforming than the underlying bone, which feature a mismatch regarding their radii.²¹ According to our study analysing the effect of incongruence on a shoulder model, with a mismatch of 0.75 and 0.80, no significant differences between the congruent and incongruent experimental SRs could be noted. Only one experimental setup resulted in a significant difference between the congruent and incongruent experimental system, however, the mean relative difference was 1% (Fig. 4), and almost negligible. Although Hopkins et al³⁰ observed that congruence in anatomic total shoulder

arthroplasty is linearly related to humeral head translations, they also concluded that the force ratio (i.e. the SR) required to destabilise the shoulder joint is not affected by congruence. Furthermore, Karduna et al³¹ described similar patterns of humeral head translation in native and reconstructed shoulder joints. These findings support our second conclusion, that incongruence has no effect on the SR of a simplistic ball-and-socket joint.

The BSSR was calculated using not only the radius of the glenoid concavity, but also the humeral head radius.¹² A constantly increased BSSR of 10% was observed. It remained unclear which of the radii can be used for valid *in vivo* calculations of the bony shoulder stability. It was postulated that calculating the BSSR using the glenoid concavity radius is key in order to estimate the bony shoulder stability based on the mathematical equation for congruent radii. In the present study, comparing the experimental SR of an incongruent system with the corresponding calculated SR based on the radius of the socket concavity observed a mean relative difference of 10%. In comparison, using the radius of the plastic ball for the corresponding calculated SR, the mean relative difference was over 40%. Our results conform to recently published studies describing that, independently of the humeral head radius, the glenoid concavity depth and radius are the determining variables of the SR.^{12,19} Oosterom et al¹⁹ showed that in shoulder joint arthroplasty, the radius of curvature of the glenoid cavity is, besides the concavity depth, the SR-determining factor. It was observed that varying the humeral head radii results in similar maximum allowable subluxation forces, which are only dependent on the radius of the glenoid concavity.

According to our results, as long as the humeral head radius is no bigger than the radius of the glenoid concavity, calculating the BSSR *in vivo* based on the radius of the glenoid concavity is valid. Although the BSSR relies on a theoretical congruent glenohumeral joint, the present study proved that this method is a valid clinical measure for patients suffering from recurrent glenohumeral instability. Despite this, the mathematical equation is still a simplified method, and does not consider additional factors such as the glenoid cartilage, the labrum with its concavity-increasing effect,³ or the negative intra-articular pressure.³²

Currently, the necessity for bony glenoid reconstruction surgery in patients with anterior shoulder instability is determined by measuring the lack of glenoid surface area.^{13,33-35} Considering glenoid bone loss in its 2D extent, however, seems to be overly simplistic and might underestimate the effect of glenoid concavity alterations on stability. This underestimation might be a possible explanation for the high long-term failure rate after

soft-tissue-based stabilisation procedures.³⁶⁻³⁹ The recently introduced BSSR makes it possible to perform an *in vivo* quantification of the stability ratio created by the glenoid concavity based on CT measurements.¹² This additional information could be useful to determine critical glenoid defects more precisely. Our results prove the validity of the BSSR formula and provide a reasonable explanation as to which variable should be used in order to calculate the patient-specific BSSR in daily clinical practice.

There are limitations in this study, namely the material properties and friction coefficients of the ball-and-socket models. For the validation of the BSSR, a mathematical equation, this systematic error is negligible. Another limitation is the size effect of the incongruent experimental setup with increasingly mismatched radii of curvature. The size of the model could have led to a scaling effect on the force data, thus influencing the results of the incongruent experimental setup.

In conclusion, biomechanical testing confirmed the validity of the BSSR. Incongruence has no effect on the SR of a simplistic ball-and-socket joint. For the calculation of the BSSR *in vivo*, the use of the radius of the glenoid concavity is recommended over the use of the humeral head radius. Finally, our study findings support the use of the BSSR for *in vivo* CT-based determination of bony shoulder stability.

Supplementary material



A description of the relation of the translational (T) and compressive (C) force vectors to the geometric parameters radius (r) and concavity depth (d) of the ball-and-socket configuration can be found alongside this paper at <http://www.bjr.boneandjoint.org.uk/>

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- L. Ernstbrunner: Study and preparation of the manuscript.
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