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ORIGINAL ARTICLE

Effects of glenoid inclination and acromion index on humeral head translation and glenoid articular cartilage strain

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Background: Previous clinical studies have reported associations between glenoid inclination (GI), the acromion index (AI), and the critical shoulder angle (CSA) on the one hand and the occurrence of glenohumeral osteoarthritis and supraspinatus tendon tears on the other hand. The objective of this work was to analyze the correlations and relative importance of these different anatomic parameters.
Methods: Using a musculoskeletal shoulder model developed from magnetic resonance imaging scans of 1 healthy volunteer, we varied independently GI from 0° to 15° and AI from 0.5 to 0.8. The corresponding CSA varied from 20.9° to 44.1°. We then evaluated humeral head translation and critical strain volume in the glenoid articular cartilage at 60° of abduction in the scapular plane. These values were correlated with GI, AI, and CSA.
Results: Humeral head translation was positively correlated with GI ($R = 0.828$, $P < .0001$), AI ($R = 0.539$, $P < .0001$), and CSA ($R = 0.964$, $P < .0001$). Glenoid articular cartilage strain was also positively correlated with GI ($R = 0.489$, $P = .0004$) but negatively with AI ($R = -0.860$, $P < .0001$) and CSA ($R = -0.285$, $P < .0473$).
Conclusions: The biomechanical shoulder model is consistent with clinical observations. The prediction strength of CSA is confirmed for humeral head translation and thus presumably for rotator cuff tendon tears, whereas the AI seems more appropriate to evaluate the risk of glenohumeral osteoarthritis caused by excessive articular cartilage strain. As a next step, we should corroborate these theoretical findings with clinical data.
Level of evidence: Basic Science Study; Computer Modeling

Keywords: Glenoid inclination; acromion index; critical shoulder angle; humeral head translation; glenohumeral osteoarthritis; musculoskeletal model

Osteoarthritis and rotator cuff tendon tears are the 2 most common shoulder disorders.[26] The long-term soft-tissue degeneration process is assumed to be multicausal,[4,34] and it is well accepted that biomechanical factors play a significant

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role.[3,4,10] More specifically, biomechanical factors might be related to the morphology of the scapula.

Glenoid orientation was the first candidate for association with degeneration.[17,39,41] An upward glenoid inclination (GI) was correlated with an increased occurrence of supraspinatus tendon tears,[17] the opposite,[2] or no effect at all.[22] The acromion extension was subsequently proposed by Nyffeler et al.[29] They introduced the acromion index (AI), which was found to be significantly higher in patients with full-thickness rotator cuff tears than in controls and significantly lower in patients with osteoarthritis than in patients with tendon tears. This association was partly disputed by other research groups.[1,16,30] The critical shoulder angle (CSA), combining both GI and AI, was later proposed by Moor et al[27] (Fig. 1). CSA was reported to be significantly different between healthy subjects, patients suffering from osteoarthritis, and patients with rotator cuff tears. These initial results were recently confirmed, whereas the specific effect of GI was dissociated from CSA.[7] In vivo joint motion and various morphologic parameters were also tested for correlation, but only CSA proved to be significantly higher in subjects with pathologic rotator cuffs than in controls.[31] Two biomechanical cadaveric experiments confirmed the specific effect of AI and GI on glenohumeral joint stability, as well as their relation with CSA.[15,28]

Despite the radiologic observations and recent in vitro simulation studies, the biomechanical rationale between GI, AI, and CSA on the one hand and glenohumeral osteoarthritis and rotator cuff tendon tears on the other hand is not completely understood yet. The relative importance of these 3 anatomic parameters and their hypothetical effects on tendon tears or osteoarthritis are indeed still controversial.[1,16,30]

Therefore, the goal of this work was to evaluate the independent and combined biomechanical effects of 3 anatomic parameters (namely GI, AI, and CSA) on glenoid articular cartilage strain and humeral head translation. To investigate this question, we used a numerical shoulder model and varied independently GI and AI for testing any correlation between those quantities. From the hypothesis that articular cartilage strain is associated with osteoarthritis, and superior humeral head translation with tendon tears,[17,29] we estimated by extension the relative importance of these different anatomic parameters on the reported occurrence of glenohumeral osteoarthritis and rotator cuff tendon tears.

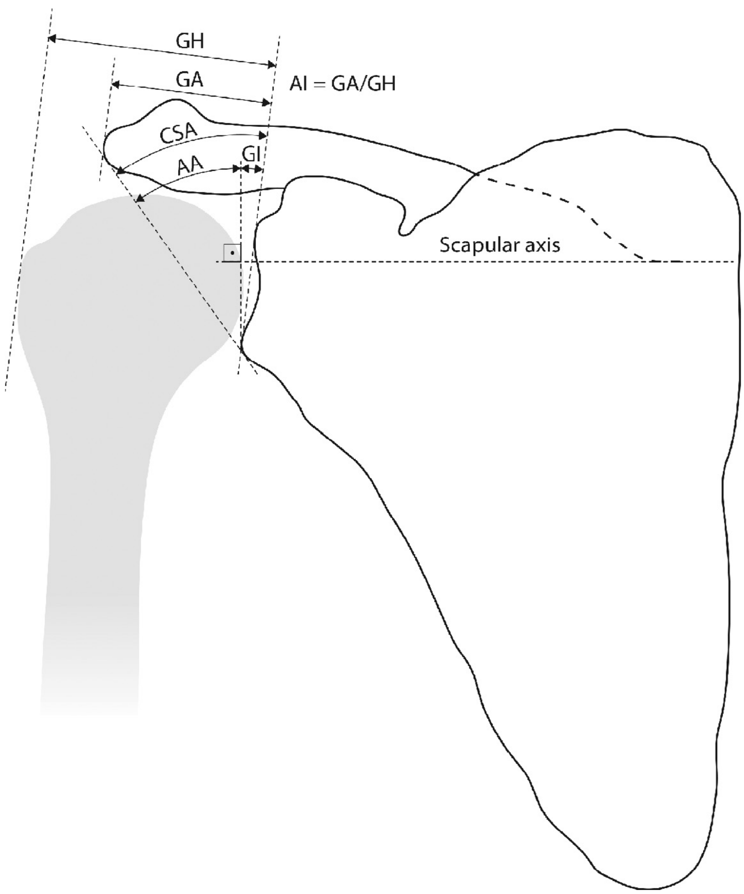


Figure 1 Illustrative diagram of definitions of glenoid inclination (GI),[38] acromion index (AI),[29] acromion angle (AA), and critical shoulder angle (CSA).[27] The glenoacromial distance (GA) and glenohumeral distance (GH) are used to define AI.[29]

Materials and methods

We used a generic numerical model of the shoulder to vary independently the lateral extension of the acromion and GI (Fig. 2, *A*).[19,36] The model was developed from magnetic resonance imaging (MRI) scans of a 27-year-old healthy male volunteer showing no signs of glenohumeral, acromioclavicular, or sternoclavicular joint disorders. MRI scans were obtained using a specific protocol consisting of two 3-dimensional T1-weighted sequences on a 3-T MRI scanner (Trio; Siemens Healthcare, Wuppertal, Germany). The first sequence (repetition time, 12.2 milliseconds; echo time, 4.8 milliseconds) covered the entire glenohumeral joint with an isotropic spatial resolution of 0.6 mm. The second sequence (repetition time, 600 milliseconds; echo time, 9.1 milliseconds) covered the whole right hemithorax with an isotropic spatial resolution of 0.9 mm. We co-registered the 2 sequences and then segmented bones and articular cartilage using Amira (FEI Visualization Sciences Group, Bordeaux, France).

The musculoskeletal model considered the scapula, humerus, clavicle, and rib cage. The glenohumeral, acromioclavicular, and sternoclavicular joints were assumed spherical (no translation). The scapula was constrained to glide on an ellipsoid representing the rib cage.[12,13] Besides, the model contained 24 muscles, divided into 42 segments, and each segment was represented by 3 cables. The origin and insertion sites were interpolated from MRI datasets. The muscle cables were wrapped around cylinders to reproduce the centroid lines of the muscles following the obstacle set approach.[14] The muscle paths were visually verified by superimposing them on MRI scans. The undetermined problem of muscle force coordination was solved using an inverse dynamics approach followed by a null-space optimization.[11,18-20,36] A glenohumeral joint stability criterion based on a cost function was included to maintain the joint force away from the subluxation limit. The arm weight was estimated at 37.5 N (5% of volunteer's weight), applied at 320 mm from the joint center along the humeral axis.[33,40] We simulated an abduction movement in the scapular plane from a rest position up to 120°. The model predicted muscle and glenohumeral joint forces. It was implemented in MATLAB (The MathWorks, Natick, MA, USA).

On the same volunteer, we recorded simultaneously the motion of the arm during abduction in the scapular plane and the electromyography (EMG) signals of 6 shoulder muscles: anterior deltoid, middle deltoid, posterior deltoid, trapezius, teres major, and pectoralis. The arm elevation angle was measured with an accelerometer (BN-ACCL3; Biopac Systems, Goleta, CA, USA), at a sampling rate of 2 kHz. EMG was recorded with an acquisition system (Biopac MP150; Biopac Systems), at the same sampling rate. The surface electrodes (Kendall Medi-Trace 100; Tyco, Markham, ON, Canada) were positioned according to a standard protocol.[32] EMG signal was high pass filtered with a cutoff frequency of 25 Hz, full wave rectified, and time averaged (250 milliseconds). The EMG activity was normalized to maximum isometric voluntary activation measured at 90° of abduction and was compared with muscle force predicted by the musculoskeletal model and normalized to the muscle's theoretical maximum force (Fig. 2, *B*).[12]

To estimate humeral head translation and glenoid articular cartilage strain from the glenohumeral force, we developed a model of the glenohumeral joint from the same MRI scans. However, to estimate bone elasticity and cortical bone thickness, we used computed tomography scans (spatial resolution, $0.4 \times 0.4 \times 0.6$ mm) of 10 patients (4 men and 6 women; mean age, 62 years [range, 24-88 years]) examined for various health problems but with no history of shoulder joint disorders and no signs of glenohumeral osteoarthritis. Deformation of articular cartilage was modeled as hyperelastic, whereas bone was linear elastic. A frictionless contact was assumed between the 2 articular cartilage layers.[21] The humeral rotation and joint force obtained by the musculoskeletal model were superimposed, and the humeral head was free to translate within the glenoid cavity, stabilized only by the deformable cartilage layers. The model was implemented in Abaqus 6.13 (Simulia; Dassault Systèmes, Vélizy-Villacoublay, France).

GI was defined as the angle between the glenoid center line projected onto the scapular plane and the scapular axis (Fig. 1).[8,38] It was positive for upward inclination. For our healthy volunteer, GI was 7°. We varied GI of the model by rotating the glenoid surface around an axis perpendicular to the scapular plane and passing through the glenoid center.[38] We varied GI from 0° to 15° in 6 evenly distributed increments and considered a normal reference value of 7.5° in between.[5]

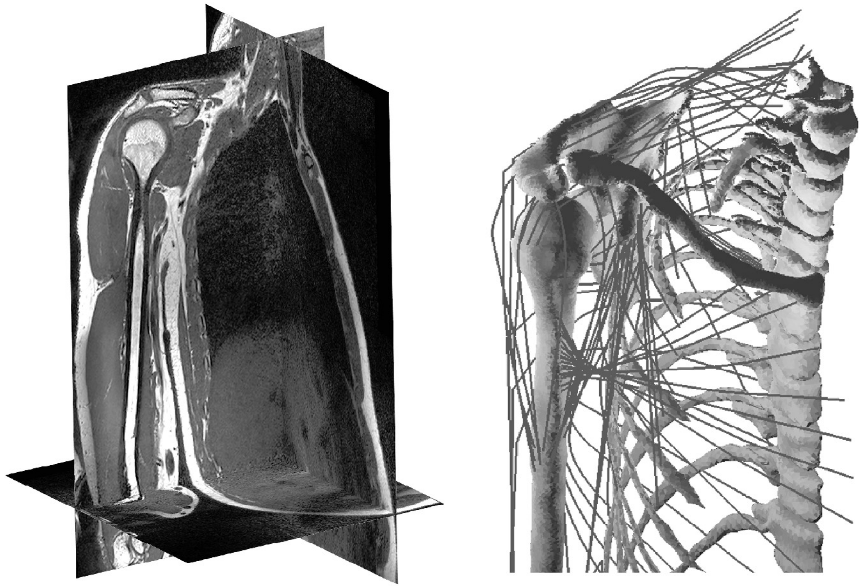
AI was defined as the distance between the glenoid plane and the most lateral point of the acromion divided by the distance between the glenoid plane and the most lateral point of the greater tubercle of the humerus (Fig. 1). This was measured on the scapular plane.[38] For our healthy volunteer, AI was 0.71. We varied AI of the model by extending or shortening the acromion, along a direction perpendicular to the glenoid plane. We varied AI from 0.5 to 0.8 in 6 evenly distributed increments and considered a normal reference value of 0.65 in between.[25,29]

CSA was defined as the angle between 2 lines: The first line connected the inferior border of the glenoid with its superior border, and the second line connected the inferior border of the glenoid with the lateral edge of the acromion (Fig. 1).[27] For our healthy volunteer, CSA was 32.9°. According to the aforementioned ranges and reference values of GI and AI, CSA varied from 20.9° to 44.1° and its normal reference value was 32.5°.

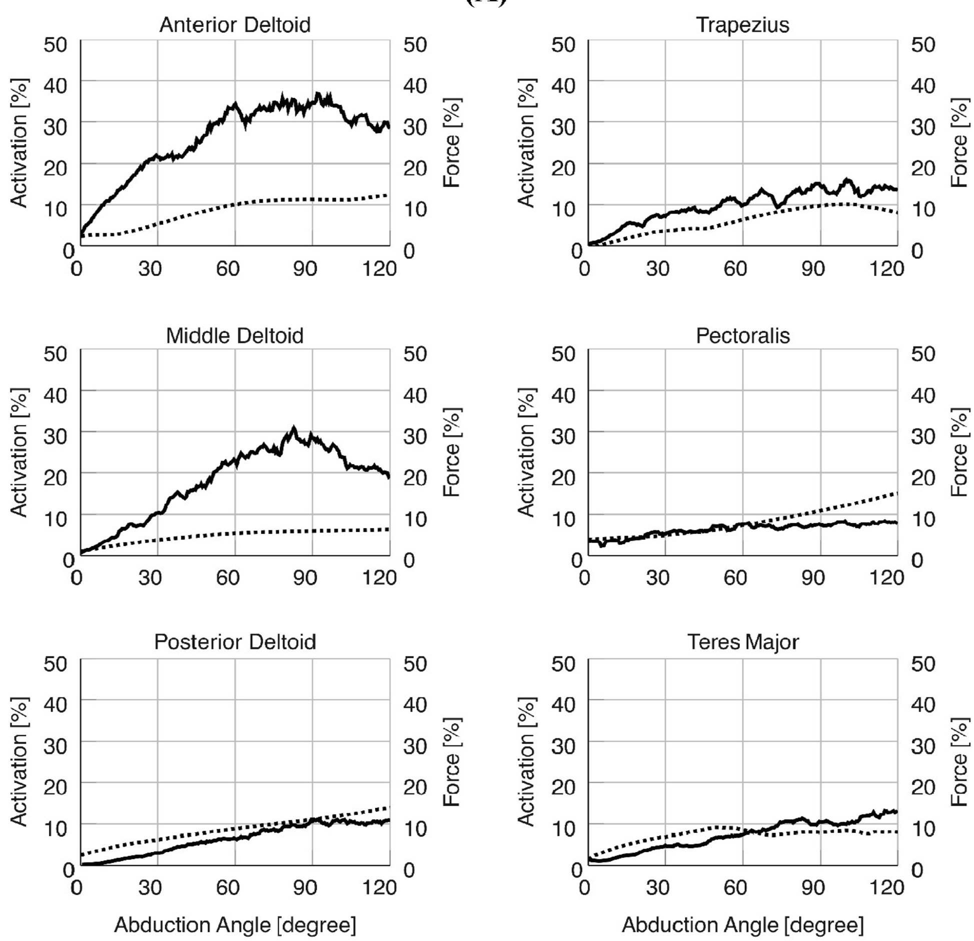
All analyses were performed at 60° of abduction in the scapular plane. Within the range of GI and AI, we evaluated strain in the glenoid articular cartilage and translation of the humeral head. These values were compared with the reference case. Humeral head translation was evaluated in the inferior-superior direction. To compare articular cartilage strain, we first evaluated the (von Mises[24]) strain limit that characterizes 10% of cartilage volume with highest strain for the reference case. Then, we measured for all cases the cartilage volume above this limit and considered the change of volume relative to the reference. Besides, we evaluated the Pearson correlation coefficient between articular cartilage strain and humeral head translation on the one hand and GI, AI, and CSA on the other hand. We used the Wilcoxon rank sum test to evaluate statistically significant ($P < .05$) differences of cartilage strain and humeral head translation between low (≤5°) and high (≥10°) GI, between small (≤0.6) and large (≥0.7) AI, and between low (≤30°) and high (≥35°) CSA.

Results

In comparison with the reference, the relative humeral head inferior-superior translation was positively correlated with both GI and AI (Fig. 3). The correlation with GI was very strong, whereas the correlation with AI was moderate (Table I). However, the relative inferior-superior translation was statistically significantly ($P = .0005$) higher for large AI (+10.5%)



(A)



(B)

Figure 2 (**A**) T1-weighted high-resolution isotropic magnetic resonance imaging scan (*left*) of a healthy volunteer used to develop the musculoskeletal shoulder model (*right*). (**B**) Comparison of relative electromyography activity (*solid lines*) with relative force (*dotted lines*) predicted by the model for 6 muscles during abduction in the scapular plane.

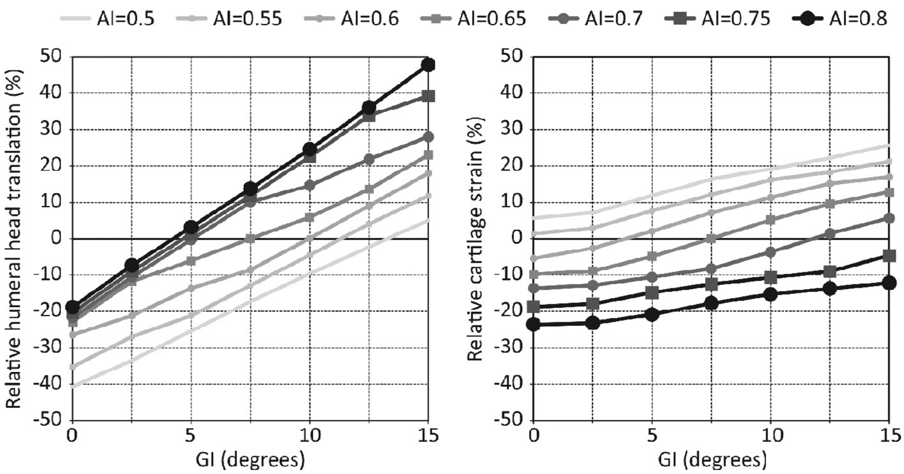


Figure 3 Effects of glenoid inclination (GI) and acromion index (AI) on relative humeral head inferior-superior translation (*left*) and on relative glenoid articular cartilage strain volume (*right*).

Table I Correlation coefficients and associated *P* values between anatomic parameters and humeral head translation, as well as glenoid articular cartilage strain

Anatomic parameter	Humeral head translation		Cartilage strain	
	R	*P*	*R*	*P*
Glenoid inclination	0.828	< .0001	0.489	.0004
Acromion index	0.539	< .0001	–0.860	<.0001
Critical shoulder angle	0.964	< .0001	–0.285	.0473

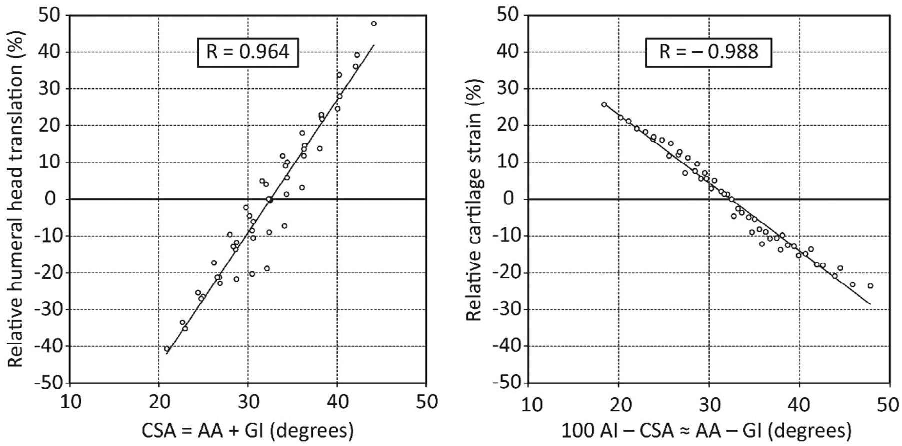


Figure 4 Scatter plots with linear trend lines showing the effects of the critical shoulder angle (CSA) on relative humeral head inferior-superior translation (*left*) and of 100 acromion index (AI) – CSA on relative glenoid articular cartilage strain volume (*right*). *AA*, acromion angle; *GI*, glenoid inclination.

than for small AI (–12.0%). On average, the effect of GI was 1.6 times larger than the effect of AI. The multiple correlation with GI and AI taken together was very strong ($R = 0.988$, $P < .0001$). We found indeed that the quantity GI + 40 AI, corresponding approximately to CSA, was very strongly correlated with humeral head translation. CSA was also very strongly correlated with humeral head translation (Fig. 4).

The relative volume of glenoid articular cartilage with critical strain was positively correlated with GI and negatively correlated with AI (Fig. 3). The correlation with GI was moderate, but the articular cartilage strain volume was statistically significantly ($P = .0012$) higher for higher GI (+6.3%) than for lower GI (–7.1%). The correlation with AI was very strong. On average, the effect of AI was 1.8 times higher than the effect of GI. The multiple correlation with GI and AI taken together was very strong ($R = 0.989$, $P < .0001$). The correlation with CSA was weak, but the articular cartilage strain volume was still statistically significantly ($P = .017$) higher for low CSAs (4.2%) than for high CSAs (–4.9%). Given that AI and CSA are both more easily measured than GI, the very strong correlation observed with GI and AI can be rewritten as a function of AI and CSA. The articular cartilage strain was thus very strongly negatively correlated with 100 AI – CSA (Fig. 4). This new quantity accounted for the strong negative correlation of AI and the weaker positive correlation of GI, through CSA.

The articular cartilage strain was obviously correlated with glenohumeral joint force; its amplitude and direction followed the same trend and correlation with GI and AI (as for cartilage strain). When AI increased, the amplitude decreased (20% of the reference value) and the direction was less compressive (10°). The contact center on the glenoid articular cartilage was shifted more superiorly with higher GI and AI. The decrease of joint force as AI increased was mainly caused by a reduced activity of the rotator cuff muscles, especially the supraspinatus, which was also positively correlated with GI and negatively correlated with AI.

Discussion

Several clinical studies reported a statistical correlation between scapular anatomy and the occurrence of degenerative shoulder diseases. GI and AI were associated with rotator cuff tendon tears and glenohumeral osteoarthritis.[17,27,29,31,39,41] In this study, we used a biomechanical shoulder model to evaluate the relative effects of these 2 different anatomic parameters on upward translation of the humeral head and glenoid articular cartilage strain. Assuming the hypothesis that humeral head translation and articular cartilage strain are mechanically related to rotator cuff tendon tears and glenohumeral osteoarthritis, respectively, the model predictions confirmed all previously reported biomechanical and clinical observations. In addition, the model showed that CSA might be a better parameter than AI or GI to estimate the risk of tendon tears. However, according to this model, CSA might be less accurate than AI or GI to estimate the risk of osteoarthritis.

The 2 anatomic parameters analyzed in this study were AI and GI. For healthy subjects, AI and GI are reported to be 0.65 and 5°, respectively.[17,29] In our study, we preferred to use a normal value of 7.5° for GI to be in the middle of the variability range considered. The minimum GI was 0°, corresponding to the 10th percentile, whereas the maximum GI was 15°, corresponding to the 90th percentile.[38] With these values, the normal CSA was 32.5°, thus close to the 33° reported for asymptomatic patients with normal rotator cuff tendons and no signs of glenohumeral osteoarthritis.[27] AI and GI of our healthy volunteer were 0.71 and 7°, respectively, corresponding to CSA of 32.8°.

As expected, we confirmed and quantified the correlation between the 3 anatomic parameters: CSA ≈ GI + 40 AI.[7] By defining the acromion angle (AA), CSA can be written as the sum of 2 angles: CSA = AA + GI (Fig. 1). Using the 2 aforementioned relationships, we can also approximately rewrite 100 AI – CSA as the difference of these angles: 100 AI – CSA ≈ AA – GI. We thus have shown that AA + GI is highly correlated with humeral head translation and AA – GI is highly correlated with glenoid articular cartilage strain.

Humeral head translation can obviously be related to the subacromial space. As hypothesized by other research groups,[27,29,41] we might thus also suggest that a longer acromion or an upward tilted glenoid would increase the risk of supraspinatus tendon impingement and associated tears. In our model, the supraspinatus tendon was never in contact with the acromion. It seems that the acromion shape in our volunteer was such that it provided sufficient space for the tendon.

The glenoid articular cartilage underwent a complex deformation. We thus chose the equivalent (von Mises[24]) strain to capture the complex deformation in one scalar value. The articular cartilage strain increased as joint force increased. Our results were consistent with radiologic findings that a shorter acromion is associated with a higher risk of glenohumeral osteoarthritis.[27,29] The model predicted an increase in cartilage strain with an upward GI. To our knowledge, no association between GI and glenohumeral osteoarthritis has been reported in the literature so far. The maximum strain (26%) and reference strain (14.3%) were, however, both below the reported critical strain.[9,23,35]

The supraspinatus was the most sensitive muscle to the 2 anatomic parameters. As expected, GI had a smaller effect on supraspinatus forces than AI and consequently on glenohumeral joint forces. Increasing AI increased the deltoid moment arm, thus reducing its required force, as well as the stabilizing effect of the supraspinatus. Consequently, a higher AI was associated with a lower and less compressive joint force, as already suggested.[27,29]

The strength of this work was to provide a generic biomechanical model of the shoulder, allowing to vary independently specific anatomic parameters of the scapula. We were thus able to evaluate the effects of different anatomic parameters on biomechanical quantities such as humeral head translation and glenoid articular cartilage strain, which are hypothetically associated with supraspinatus tendon tears and glenohumeral osteoarthritis, respectively. Although the effects of the 2 anatomic parameters reported here were purely based on a theoretical model, the predicted muscle forces were consistent with the measured EMG activity. The most important limitation of this study was certainly that the model was based on the individual anatomy of a single volunteer. Ideally, we might model a series of patients with different shoulder disorders, as well as a control group, to account for anatomic variability. Besides, the results were obtained for a very specific position of the arm and might be extended for more complex movements of daily-living activities. The effects of AI and GI on muscle and glenohumeral forces were, however, maximal at 60° of abduction.[28,37] We further justify this choice by the fact that most of our daily movements occur below 60° of abduction.[6]

Conclusion

CSA is a combination of GI and AI. It efficiently represents the effects of these 2 parameters on humeral head migration because both GI and AI have the same positive effect. For articular cartilage strain, CSA seems less relevant because GI and AI have opposite effects. Consequently, CSA might be a good indicator of the risk of tendon tear, but AI might be more efficient to predict the risk of osteoarthritis. Although degenerative shoulder diseases are known to be multicausal, anatomic parameters certainly have a strong contribution. As a next step, it will be interesting to correlate these parameters with the surgical outcomes in terms of retear rate after rotator cuff repair and glenoid implant loosening after anatomic total shoulder arthroplasty.

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References

1. Ames JB, Horan MP, Van der Meijden OA, Leake MJ, Millett PJ. Association between acromial index and outcomes following arthroscopic repair of full-thickness rotator cuff tears. J Bone Joint Surg Am 2012;94:1862-9. http://dx.doi.org/10.2106/JBJS.K.01500
2. Bishop JL, Kline SK, Aalderink KJ, Zauel R, Bey MJ. Glenoid inclination: in vivo measures in rotator cuff tear patients and associations with superior glenohumeral joint translation. J Shoulder Elbow Surg 2009;18:231-6. http://dx.doi.org/10.1016/j.jse.2008.08.002
3. Brandt KD, Dieppe P, Radin E. Etiopathogenesis of osteoarthritis. Med Clin North Am 2009;93:1-24. http://dx.doi.org/10.1016/j.mcna.2008.08.009
4. Buckwalter JA, Martin JA. Osteoarthritis. Adv Drug Deliv Rev 2006;58:150-67. http://dx.doi.org/10.1016/j.addr.2006.01.006
5. Churchill RS, Brems JJ, Kotschi H. Glenoid size, inclination, and version: an anatomic study. J Shoulder Elbow Surg 2001;10:327-32.
6. Coley B, Jolles BM, Farron A, Aminian K. Arm position during daily activity. Gait Posture 2008;28:581-7. http://dx.doi.org/10.1016/j.gaitpost.2008.04.014
7. Daggett M, Werner B, Collin P, Gauci MO, Chaoui J, Walch G. Correlation between glenoid inclination and critical shoulder angle: a radiographic and computed tomography study. J Shoulder Elbow Surg 2015;24:1948-53. http://dx.doi.org/10.1016/j.jse.2015.07.013
8. Daggett M, Werner B, Gauci MO, Chaoui J, Walch G. Comparison of glenoid inclination angle using different clinical imaging modalities. J Shoulder Elbow Surg 2016;25:180-5. http://dx.doi.org/10.1016/j.jse.2015.07.001
9. Démarteau O, Pillet L, Inaebnit A, Borens O, Quinn TM. Biomechanical characterization and in vitro mechanical injury of elderly human femoral head cartilage: comparison to adult bovine humeral head cartilage. Osteoarthritis Cartilage 2006;14:589-96. http://dx.doi.org/10.1016/j.joca.2005.12.011
10. Egloff C, Hügle T, Valderrabano V. Biomechanics and pathomechanisms of osteoarthritis. Swiss Med Wkly 2012;142:w13583. http://dx.doi.org/10.4414/smw.2012.13583
11. Engelhardt C, Camine VM, Ingram D, Müllhaupt P, Farron A, Pioletti D, et al. Comparison of an EMG-based and a stress-based method to predict shoulder muscle forces. Comput Methods Biomech Biomed Engin 2015;18:1272-9. http://dx.doi.org/10.1080/10255842.2014.899587
12. Garner BA, Pandy MG. Musculoskeletal model of the upper limb based on the visible human male dataset. Comput Methods Biomech Biomed Engin 2001;4:93-126.
13. Garner BA, Pandy MG. The obstacle-set method for representing muscle paths in musculoskeletal models. Comput Methods Biomech Biomed Engin 2000;3:1-30.
14. Garner BA, Pandy MG. A kinematic model of the upper limb based on the visible human project (VHP) image dataset. Comput Methods Biomech Biomed Engin 1999;2:107-24.
15. Gerber C, Snedeker JG, Baumgartner D, Viehöfer AF. Supraspinatus tendon load during abduction is dependent on the size of the critical shoulder angle: a biomechanical analysis. J Orthop Res 2014;32:952-7. http://dx.doi.org/10.1002/jor.22621
16. Hamid N, Omid R, Yamaguchi K, Steger-May K, Stobbs G, Keener JD. Relationship of radiographic acromial characteristics and rotator cuff disease: a prospective investigation of clinical, radiographic, and sonographic findings. J Shoulder Elbow Surg 2012;21:1289-98. http://dx.doi.org/10.1016/j.jse.2011.09.028
17. Hughes RE, Bryant CR, Hall JM, Wening J, Huston LJ, Kuhn JE, et al. Glenoid inclination is associated with full-thickness rotator cuff tears. Clin Orthop Relat Res 2003;407:86-91.
18. Ingram D, Engelhardt C, Farron A, Terrier A, Müllhaupt P. Improving anterior deltoid activity in a musculoskeletal shoulder model—an analysis of the torque-feasible space at the sternoclavicular joint. Comput Methods Biomech Biomed Engin 2016a;19:450-63. http://dx.doi.org/10.1080/10255842.2015.1042465
19. Ingram D, Engelhardt C, Farron A, Terrier A, Müllhaupt P. Modelling of the human shoulder as a parallel mechanism without constraints. Mech Mach Theory 2016b;100:120-37. http://dx.doi.org/10.1016/j.mechmachtheory.2016.02.004
20. Ingram D, Engelhardt C, Farron A, Terrier A, Müllhaupt P. Muscle moment-arms: a key element in muscle-force estimation. Comput Methods Biomech Biomed Engin 2015;18:506-13. http://dx.doi.org/10.1080/10255842.2013.818666
21. Jones BK, Durney KM, Hung CT, Ateshian GA. The friction coefficient of shoulder joints remains remarkably low over 24h of loading. J Biomech 2015;48:3945-9. http://dx.doi.org/10.1016/j.jbiomech.2015.09.029
22. Kandemir U, Allaire RB, Jolly JT, Debski RE, McMahon PJ. The relationship between the orientation of the glenoid and tears of the rotator cuff. J Bone Joint Surg Br 2006;88:1105-9. http://dx.doi.org/10.1302/0301-620X.88B8.17732
23. Kerin AJ, Wisnom MR, Adams MA. The compressive strength of articular cartilage. Proc Inst Mech Eng H 1998;212:273-80.
24. Khan SAS, Huang S. Continuum theory of plasticity. New York: John Wiley and Sons; 1995. (ISBN No. 0471310433)

25. Kim JR, Ryu KJ, Hong IT, Kim BK, Kim JH. Can a high acromion index predict rotator cuff tears? Int Orthop 2012;36:1019-24. http://dx.doi.org/10.1007/s00264-012-1499-4
26. Mitchell C, Adebajo A, Hay E, Carr A. Shoulder pain: diagnosis and management in primary care. BMJ 2005;331:1124-8. http://dx.doi.org/10.1136/bmj.331.7525.1124
27. Moor BK, Bouaicha S, Rothenfluh DA, Sukthankar A, Gerber C. Is there an association between the individual anatomy of the scapula and the development of rotator cuff tears or osteoarthritis of the glenohumeral joint?: A radiological study of the critical shoulder angle. Bone Joint J 2013;95-B:935-41. http://dx.doi.org/10.1302/0301-620X.95B7.31028
28. Moor BK, Kuster R, Osterhoff G, Baumgartner D, Werner CM, Zumstein MA, et al. Inclination-dependent changes of the critical shoulder angle significantly influence superior glenohumeral joint stability. Clin Biomech (Bristol, Avon) 2016;32:268-73. http://dx.doi.org/10.1016/j.clinbiomech.2015.10.013
29. Nyffeler RW, Werner CM, Sukthankar A, Schmid MR, Gerber C. Association of a large lateral extension of the acromion with rotator cuff tears. J Bone Joint Surg Am 2006;88:800-5. http://dx.doi.org/10.2106/JBJS.D.03042
30. Pandey V, Vijayan D, Tapashetti S, Agarwal L, Kamath A, Acharya K, et al. Does scapular morphology affect the integrity of the rotator cuff? J Shoulder Elbow Surg 2016;25:413-21. http://dx.doi.org/10.1016/j.jse.2015.09.016
31. Peltz CD, Divine G, Drake A, Ramo NL, Zauel R, Moutzouros V, et al. Associations between in-vivo glenohumeral joint motion and morphology. J Biomech 2015;48:3252-7. http://dx.doi.org/10.1016/j.jbiomech.2015.06.030
32. Perotto A, Delagi EF. Anatomical guide for the electromyographer: the limbs and trunk. Springfield, IL: Charles C. Thomas; 2011. (ISBN No. 9780398086480)
33. Poppen NK, Walker PS. Forces at the glenohumeral joint in abduction. Clin Orthop Relat Res 1978;135:165-70.
34. Renström P, Hach T. Insertional tendinopathy in sports. In: Maffulli N, Renström P, Leadbetter WB, editors. Tendon injuries: basic science and clinical medicine. London: Springer; 2005. p. 70-85. (ISBN No. 1852335033, 9781852335038)
35. Sasazaki Y, Shore R, Seedhom BB. Deformation and failure of cartilage in the tensile mode. J Anat 2006;208:681-94. http://dx.doi.org/10.1111/j.1469-7580.2006.00569.x
36. Terrier A, Aeberhard M, Michellod Y, Mullhaupt P, Gillet D, Farron A, et al. A musculoskeletal shoulder model based on pseudo-inverse and null-space optimization. Med Eng Phys 2010;32:1050-6. http://dx.doi.org/10.1016/j.medengphy.2010.07.006
37. Terrier A, Merlini F, Pioletti DP, Farron A. Total shoulder arthroplasty: downward inclination of the glenoid component to balance supraspinatus deficiency. J Shoulder Elbow Surg 2009;18:360-5. http://dx.doi.org/10.1016/j.jse.2008.11.008
38. Terrier A, Ston J, Larrea X, Farron A. Measurements of three-dimensional glenoid erosion when planning the prosthetic replacement of osteoarthritic shoulders. Bone Joint J 2014;96-B:513-8. http://dx.doi.org/10.1302/0301-620X.96B4.32641
39. Tétreault P, Krueger A, Zurakowski D, Gerber C. Glenoid version and rotator cuff tears. J Orthop Res 2004;22:202-7. http://dx.doi.org/10.1016/S0736-0266(03)00116-5
40. Veeger HE, Van der Helm FC, Van der Woude LH, Pronk GM, Rozendal RH. Inertia and muscle contraction parameters for musculoskeletal modelling of the shoulder mechanism. J Biomech 1991;24:615-29.
41. Wong AS, Gallo L, Kuhn JE, Carpenter JE, Hughes RE. The effect of glenoid inclination on superior humeral head migration. J Shoulder Elbow Surg 2003;12:360-4. http://dx.doi.org/10.1016/S1058-2746(03)00026-0