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

Running title: Glenoid Inclination and Acromion Index Biomechanics

Christoph Engelhardt (PhD)¹; Alain Farron (MD)²; Fabio Becce (MD)³;

Nicolas Place (PhD)^{4, 5}; Dominique P Pioletti (PhD)¹; Alexandre Terrier (PhD)¹

1) Laboratory of Biomechanical Orthopedics

Ecole Polytechnique Fédérale de Lausanne

Lausanne, Switzerland

2) Service of Orthopedics and Traumatology

Lausanne University Hospital, Lausanne, Switzerland

3) Department of Diagnostic and Interventional Radiology

Lausanne University Hospital, Lausanne, Switzerland

4) Institute of Sports Sciences

University of Lausanne, Lausanne, Switzerland

5) Department of Physiology

University of Lausanne, Lausanne, Switzerland

Corresponding author:

Alexandre Terrier, PhD

Laboratory of Biomechanical Orthopedics

Ecole Polytechnique Fédérale de Lausanne

Station 19

CH-1015 Lausanne, Switzerland

Email: alexandre.terrier@epfl.ch

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Abstract

Background: Previous clinical studies have reported associations between glenoid inclination (GI), acromion index (AI), and 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 anatomical parameters.

Methods: Using a musculoskeletal shoulder model developed from MRI scans of one healthy volunteer, we varied independently GI from 0 to 15 degrees, and AI from 0.5 to 0.8. The corresponding CSA varied from 20.9 to 44.1 degrees. We then evaluated humeral head translation and critical strain volume in the glenoid articular cartilage at 60 degrees of abduction in the scapular plane. These values were correlated with GI, AI, and CSA.

Results: Humeral head translation was positively correlated with GI ($R=0.828$, $p<0.0001$), AI ($R=0.539$, $p<0.0001$), and CSA ($R=0.964$, $p<0.0001$). Glenoid articular cartilage strain was also positively correlated with GI ($R=0.489$, $p=0.0004$), but negatively with AI ($R=-0.860$, $p<0.0001$) and CSA ($R=-0.285$, $p<0.0473$).

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, while 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

Introduction

Osteoarthritis and rotator cuff tendon tears are the two most common shoulder disorders.²⁶ The long-term soft tissue degeneration process is assumed to be multi-causal^{4; 34}, and it is well accepted that biomechanical factors play a significant 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. (Fig. 1).²⁷ 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, while the specific effect of GI was dissociated from CSA.⁷ In-vivo joint motion and various morphological parameters were also tested for correlation, but only CSA proved to be significantly higher in subjects with pathological rotator cuffs than in controls.³¹ Two

biomechanical cadaveric experiments confirmed the specific effect of AI and GI on
glenohumeral joint stability, and their relation with CSA.^{15 28}

Despite the radiological 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 those three anatomical parameters and their hypothetical
effects on tendon tears or osteoarthritis are indeed still controversial.^{1; 16; 30}

Therefore, the goal of the present work was to evaluate the independent and combined
biomechanical effects of three anatomical 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 anatomical parameters on the reported
occurrence of glenohumeral osteoarthritis and rotator cuff tendon tears.

Materials and Methods

We used a generic numerical model of the shoulder to vary independently the lateral extension of the acromion and GI (Fig. 2a).^{19; 36} The model was developed from MRI scans of a 27-year-old healthy male volunteer showing no sign of glenohumeral, acromioclavicular, or sternoclavicular joint disorders. MRI scans were obtained using a specific protocol consisting of two 3D T1-weighted sequences on a 3 Tesla MRI scanner (Trio; Siemens Healthcare, Wuppertal, Germany). The first sequence (repetition time, 12.2 ms; echo time, 4.8 ms) covered the entire glenohumeral joint with an isotropic spatial resolution of 0.6 mm. The second sequence (repetition time, 600 ms; echo time, 9.1 ms) covered the whole right hemithorax with an isotropic spatial resolution of 0.9 mm. We co-registered the two 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 constraint 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 three cables. The origin and insertion sites were interpolated from MRI data sets. 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 humerus axis.^{33; 40}

We simulated an abduction movement in the scapular plane from a rest position up to 120 degrees. 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 six 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 system), 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 cut off frequency of 25 Hz, full-wave rectified and time averaged (250 ms). The EMG activity was normalized to maximum isometric voluntary activation measured at 90 degrees of abduction), and compared to muscle force predicted by the musculoskeletal model and normalized to the muscle's theoretical maximum force (Fig. 2b).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 CT scans (spatial resolution, $0.4 \times 0.4 \times 0.6$ mm) of 10 patients (4 males, 6 females; mean age 62 years, range 24-88 years) examined for various health problems, but with no history of shoulder joint disorder and no sign of glenohumeral osteoarthritis. Deformation of articular cartilage was modeled as hyperelastic, while bone was linear elastic. A frictionless contact was assumed between the two articular cartilage layers.²¹ The humerus rotation and joint force

obtained by the musculoskeletal model was superimposed, and the humeral head was free to translate within the glenoid cavity, stabilized only by the deformable cartilage layers. It 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 degrees. 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 degrees in 6 increments evenly distributed, and considered a normal reference value of 7.5 degrees 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 increments evenly distributed, and considered a normal reference value of 0.65 in-between.^{25; 29}

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

167 All analyses were performed at 60 degrees of abduction in the scapular plane. Within the
168 range of GI and AI, we evaluated strain in the glenoid articular cartilage and translation of the
169 humeral head. These values were compared to the reference case. Humeral head translation
170 was evaluated in the inferior-superior direction. To compare articular cartilage strain, we first
171 evaluated the (von Mises²⁴) strain limit that characterizes 10% of cartilage volume with
172 highest strain for the reference case. Then, we measured for all cases the cartilage volume
173 above this limit, and considered the change of volume relative to the reference. Besides, we
174 evaluated the Pearson correlation coefficient between articular cartilage strain, and humeral
175 head translation on the one hand, and GI, AI, and CSA on the other hand. We used Wilcoxon
176 rank-sum test to evaluate statistically significant ($p < 0.05$) differences of cartilage strain and
177 humeral head translation, between low (≤ 5 degrees) and high (≥ 10 degrees) GI, between
178 small (≤ 0.6) and large (≥ 0.7) AI, and between low (≤ 30 degrees) and high (≥ 35 degrees)
179 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, while the correlation with AI was moderate (Table 1). However, the relative inferior-superior translation was statistically significantly ($p = 0.0005$) higher for large AI (+ 10.5%) 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 ($R = 0.988$, $p < 0.0001$). 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 ($p = 0.0012$) 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 ($R = 0.989$, $p < 0.0001$). The correlation with CSA was weak, but the articular cartilage strain volume was still statistically significantly ($p = 0.017$) 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.

204 The articular cartilage strain was obviously correlated with glenohumeral joint force; its
205 amplitude and direction followed the same trend and correlation with GI and AI (as for
206 cartilage strain). When AI increased, the amplitude decreased (20% of the reference value)
207 and the direction was less compressive (10 degrees). The contact center on the glenoid
208 articular cartilage was shifted more superiorly with higher GI and AI. The decrease of joint
209 force as AI increased was mainly caused by a reduced activity of the rotator cuff muscles,
210 especially the supraspinatus, which was also positively correlated with GI, and negatively
211 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 the present study, we used a biomechanical shoulder model to evaluate the relative effects of these two different anatomical 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 revealed 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 two anatomical parameters analyzed here were AI and GI. For healthy subjects, AI and GI are reported to be 0.65 and 5 degrees^{17; 29} respectively. In our study, we preferred using a normal value of 7.5 degrees for GI, in order to be in the middle of the variability range considered. The minimum GI was 0 degree, corresponding to the 10th percentile while the maximum GI was 15 degrees, corresponding to the 90th percentile.³⁸ With these values, the normal CSA was 32.5 degrees, thus close to the 33 degrees reported for asymptomatic patients with normal rotator cuff tendons and no sign of glenohumeral osteoarthritis.²⁷ AI and GI of our healthy volunteer were 0.71 and 7 degrees, respectively, corresponding to 32.8 degrees of CSA.

As expected, we confirmed and quantified the correlation between the three anatomical parameters $CSA \approx GI + 40 AI$.⁷ By defining the acromion angle (AA), CSA can be written as

the sum of two angles, $CSA = AA + GI$ (Fig. 1). Using the above two relationships, we can also approximately rewrite $100 AI - CSA$ as the difference of these angles, $100 AI - CSA \approx AA - GI$. We thus have 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 of 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 Mises²⁴) strain to capture the complex deformation in one scalar value. The articular cartilage strain increased as joint force increased. Our results were consistent with radiological 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 (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 two anatomical 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, and 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 the present work was to provide a generic biomechanical model of the shoulder, allowing to vary independently specific anatomical parameters of the scapula. We were thus able to evaluate the effects of different anatomical 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 two anatomical 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, and a control group, to account for anatomical 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 degrees of abduction.^{28; 37} We further justify this choice by the fact that most of our daily movements occur below 60 degrees of abduction.⁶

279 **Conclusion**

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

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Figure and table legends

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

Figure 2a. T1-weighted high-resolution isotropic MRI scan (left) of a healthy volunteer used to develop the musculoskeletal shoulder model (right).

Figure 2b. Comparison of relative EMG activity (continuous line) with relative force (dotted) predicted by model, for six 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).

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

Table 1. Correlation coefficients and associated p-values between anatomical parameters and humeral head translation and glenoid articular cartilage strain.

Anatomical parameters	Humeral head translation		Cartilage strain	
	R	p	R	p
Glenoid inclination	0.828	<0.0001	0.489	0.0004
Acromion index	0.539	<0.0001	– 0.860	<0.0001
Critical shoulder angle	0.964	<0.0001	– 0.285	0.0473