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Multiple acromion lengths and glenoid implant inclinations can result in the same critical shoulder angle with large differences in articular joint loading—a musculoskeletal study

Dan Soyeux, MSc[a], Margaux Peixoto, MSc[a], Patrice Tétreault, MD[b], Mickaël Begon, PhD[c,d], Nicola Hagemeister, PhD[a,*]

[a]*Laboratoire d'Innovation Ouverte en Technologies de la Santé, École de Technologie Supérieure, Montréal, Québec, Canada*
[b]*Centre Hospitalier de l'Universite de Montréal, Montréal, Québec, Canada*
[c]*École de Kinésiologie et des Sciences de l'Activité Physique, Faculté de Médecine, Montréal, Québec, Canada*
[d]*Centre de Recherche Azrieli du CHU Sainte-Justine, Montréal, Québec, Canada*

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Background: Glenoid implant loosening is the most common complication of anatomical total shoulder arthroplasty. It is caused by high glenohumeral shear forces and by an eccentric loading of the glenoid implant provoking its "rocking". The critical shoulder angle (CSA) varies with the glenoid inclination and the acromion length. A higher CSA has been correlated with earlier radiological signs of glenoid loosening. However, the reliability of the CSA in predicting the risk factors of glenoid loosening has yet to be determined since the same CSA can result from multiple scapular anatomies.
Methods: An inverse-dynamic musculoskeletal model in *Anybody Modeling System* of the shoulder with anatomical implants allowing glenohumeral translations was used. The acromion length and the glenoid implant inclination were varied to create multiple CSA configurations. Muscle forces, the force, and the moment applied to the glenoid implant were simulated during a shoulder abduction to compare the risks of glenoid loosening.
Results: Increasing the CSA with an upward-tilted glenoid and a longer acromion led to more eccentric forces applied to the glenoid. The moment and shear applied to the glenoid implant increased with a higher CSA and were minimal for the smaller CSAs. Depending on the combination of inclination and acromion length, the shear and the moment were highly variable for the same CSA.
Conclusion: Measuring the CSA as a global indicator may be insufficient to accurately predict the risk of glenoid loosening. It suggests that the acromion length could be considered during surgical planning to determine the adequate glenoid implant inclination.

Glenoid implant loosening is the main long-term complication of anatomical total shoulder arthroplasty (aTSA). It represents 24 to 39% of the long-term complications and requires revision surgery in 28% of the cases.[2,12] The mechanism of glenoid loosening seems to be the "rocking-horse" phenomenon. In excessive humeral head translation with respect to the glenoid implant, abnormal eccentric loads are applied to the glenoid implant.[9] The load eccentricity could then create a moment of force on the glenoid implant,[16] which lifts the edge of the implant and fragilizes its fixation, leading to its loosening.[9] Higher forces applied to the glenoid implant, especially shear forces, could also risk glenoid loosening by increasing the likelihood of its cement failure.[14] Potential risk factors associated with glenoid loosening have been identified, such as rotator cuff tear,[9] implant cementing quality,[12] and glenoid implant malposition.[33] In particular, computational and cadaveric studies showed that an abnormal orientation of the glenoid implant leads to larger glenohumeral joint forces and larger glenohumeral translations.[14,18,26,30] The critical shoulder angle (CSA) is an anatomical parameter that increases with an upward-tilted glenoid and a longer acromion.[24] For a nonprosthetic shoulder, a high CSA was associated with the prevalence of rotator cuff tear (≥35°) and smaller values (≤28°) with osteoarthritis.[24,32] Watling et al (2018)[43] recently found a correlation between a higher CSA and earlier radiological signs of anatomical glenoid implant

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*Corresponding author: Nicola Hagemeister, PhD, Centre de recherche du Centre Hospitalier de l'Université de Montréal, Tour Viger 900, rue Saint-Denis, Local R11.322, Montréal, Québec H2X 0A9, Canada.

E-mail address: Nicola.hagemeister@etsmtl.ca (N. Hagemeister).

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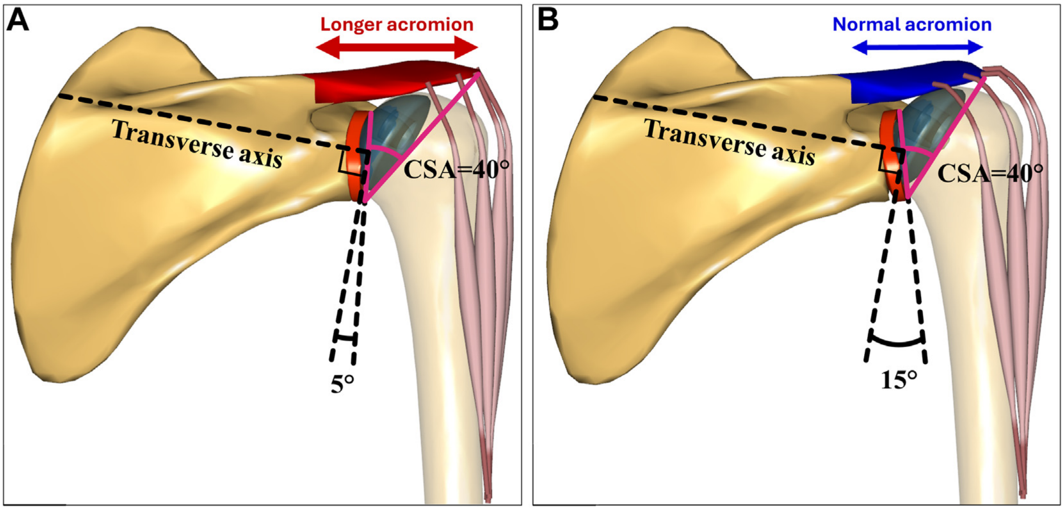

Figure 1 Similar critical shoulder angle of 40° with different glenoid inclinations and acromion lengths as defined by Watling et al (2018), ie, the angle in an anteroposterior view of the scapula between a first line connecting the superior and the inferior margins of the glenoid implant and a second line connecting the inferior margin of the glenoid implant to the most lateral point of the acromion. (**A**) Increased acromion length by 13.4 mm with a 5° glenoid inclination. (**B**) Increased glenoid inclination to 15° with a normal acromion length.

Table I
Color-coded studied CSA values according to glenoid inclination and acromion lengthening with **27.7°** the CSA of the reference configuration.

	Acromion lengthening [mm]				
Glenoid inclination	−10.8	−5.7	0.0	+6.6	+13.4
−10°	12.2°	15.9°	19.7°	23.6°	27.2°
−5°	15.9°	19.8°	23.7°	27.8°	31.4°
0°	19.7°	23.7°	**27.7°**	31.7°	35.7°
5°	23.4°	27.6°	31.7°	36.0°	39.9°
10°	27.2°	31.4°	35.7°	40.2°	44.2°
15°	30.9°	35.3°	39.7°	44.3°	48.5°

CSA, critical shoulder angle.
27.7° is the CSA of the reference configuration (*colored in white*).
Lower CSA, are *colored in blue* and higher CSA, are *colored in orange*.

loosening. Moreover, a higher CSA has been associated with higher shear forces applied to the glenoid[3,11,25,40,42] or the glenoid implant,[18] and with higher glenohumeral translations[6,14,17,18,29,35] which could risk glenoid loosening. This suggests that the CSA could be used during the surgical planning of aTSA to predict the potential risks of glenoid loosening depending on the chosen glenoid implant orientation and on the patient's scapular anatomy. However, to our knowledge, the position of the contact point between the implant components was only evaluated by the finite element model of Terrier et al (2009)[35] for two glenoid implant inclinations. Due to this limitation of experimental and computational studies in evaluating the position of the contact point between the implant components, experimental and computational studies did not evaluate the moment applied to the glenoid implant to compare the risks of glenoid loosening for different CSA.[6,14,17,18,29,35] Hence, the biomechanical mechanism leading to higher risks of glenoid loosening for a high CSA is not fully understood. Besides, the CSA is a combination of two variables: the acromion length and the glenoid implant inclination. The same CSA can then correspond to multiple combinations of these variables (Fig. 1 *A* and *B*). Thus, a specific glenoid implant inclination could create a different CSA depending on the acromion length of the patient since its length is greatly variable between individuals.[27,38] However, we only found two experimental studies[3,41] and one finite element study,[5] varying both the acromion length and the glenoid inclination. These studies altered the CSA by independently varying the acromion length and the glenoid inclination instead of defining multiple combinations of acromion length and glenoid inclination for each studied CSA. It then appears that the CSA's reliability in predicting the potential risks of glenoid loosening during surgical planning depending on the acromial anatomy remains unclear.

The purpose of this study is to assess the effect of altering the glenoid implant inclination on biomechanical risk factors of glenoid loosening with multiple combinations of acromion length. The shear force and the moment applied to the glenoid implant are compared across several configurations of CSA to evaluate its reliability in predicting the risks of glenoid loosening. We hypothesize that for the same CSA value, the shear and the moment applied to the glenoid implant greatly vary, depending on the inclination and acromion length.

Materials and methods

Musculoskeletal model

We used a computational musculoskeletal model of the right upper limb previously developed in the *Anybody Modeling System* (AnyBody Technology A/S, Aalborg, Denmark), representing a 50th percentile 75 kg healthy men measuring 1.80 m.[31] This model developed by Sins et al, (2014)[31] integrated an anatomical nonconforming total shoulder implant based on commercially available implant designs. The humeral component's diameter was 51 mm and the glenoid's was 57.4 mm to match the dimensions of the bones. The implants' positioning and sizes were validated by our senior orthopedic surgeon. Then, these components were rigidly attached to the scapula and the humerus. The glenohumeral articulation was represented as a 6-degree of freedom joint (3 rotations and 3 translations) instead of a ball and socket joint. The humeral translations were simulated using the *force-dependent kinematics algorithm*.[1] Briefly, the glenohumeral translations were calculated by finding the position where a quasistatic equilibrium was obtained in the joint. Due to the rigid-body nature of the model, the glenohumeral translations provoked the humeral implant penetration into the glenohumeral implant. This

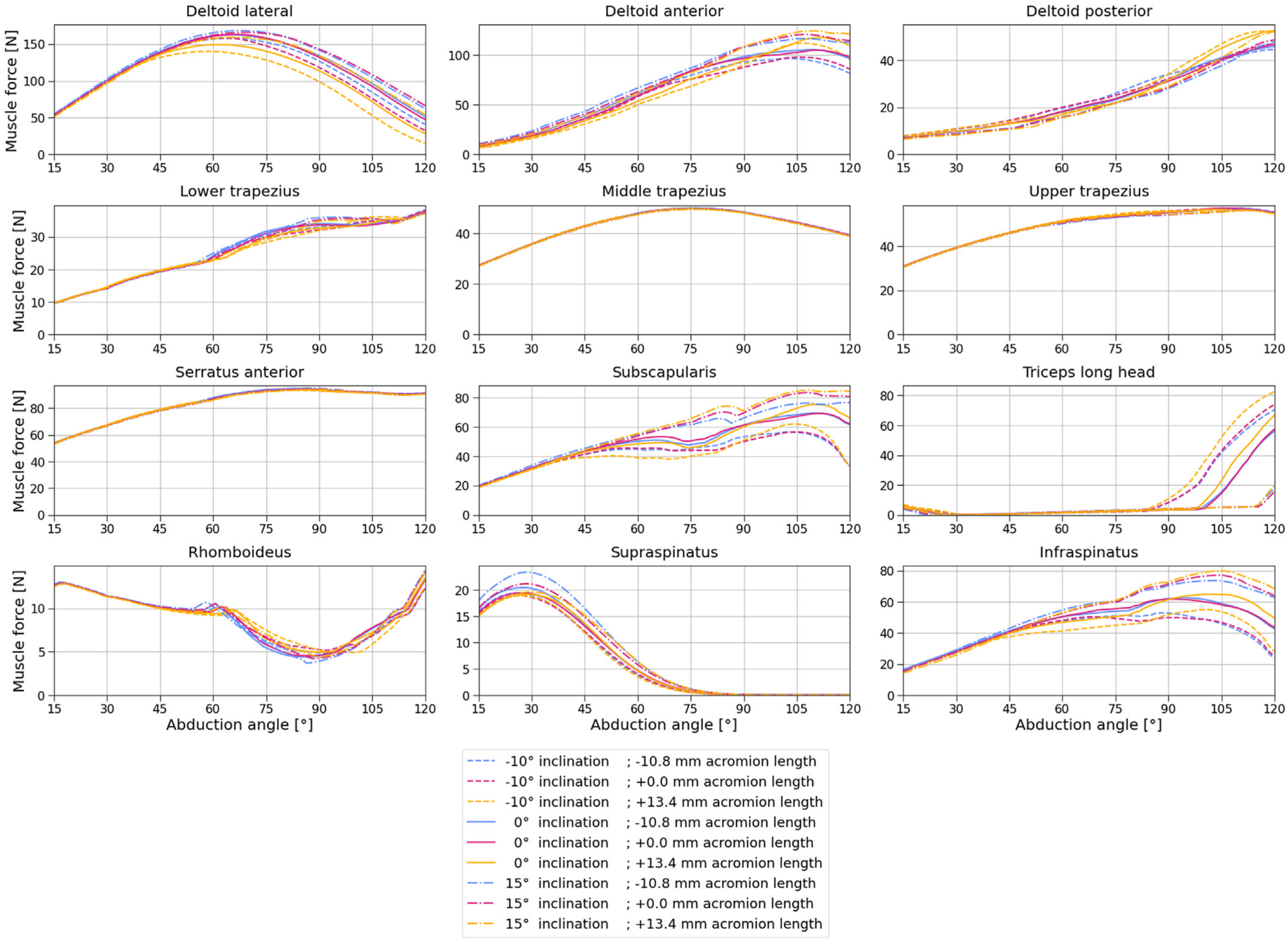

Figure 2 Muscle forces for different acromion lengths and glenoid inclinations.

penetration corresponds to the deformation of the least rigid implant component (the glenoid implant in polyethylene) due to glenohumeral translations. The contact force between the implant components then represents the required force to apply to the glenoid implant to deform it of a certain volume 31. The contact force between the humeral and glenoid components was evaluated by multiplying the volume of penetration of the humeral implant into the glenoid implant, with a pressure module of polyethylene 10^{10} (N/m^3). This value was adjusted to ensure a maximal penetration of 0.4 mm to match the results of previousstudies.[15,36] The position of the center of pressure (COP) on the glenoid implant was calculated as the average position of penetrating vertices. The original model[31] was modified to add a constant force of 4.5 N posteriorly and 1.5 N inferiorly on the humerus head for every CSA configuration. This force was adjusted to obtain a COP of the reference configuration at the center of the glenoid implant surface (ie,. the intersection of the inferior-superior and anterior-posterior axis of the glenoid implant) at 15° of abduction to compare the effect of altering the CSA.

The model also included the sternoclavicular and acromioclavicular joints to represent the scapulohumeral rhythm using De Groot and Brand's[13] equations, which ensures a realistic scapula orientation during arm elevations. The model included 22 muscle groups, including the deltoid (posterior, lateral, and anterior parts), the rotator cuff muscles, the trapezius, the serratus anterior, the rhomboideus, the biceps, the triceps, and the pectoralis, represented by the Hill-type model.[46] Contrary to the original model of Sins et al (2014),[31] our model was based on the 2.4.2 version of the *Anybody Managed Model Repository,* particularly to introduce a more physiological deltoid wrapping around the humerus.[34]

Critical shoulder anglevariation

Critical shoulder anglemeasurement

The CSA in the context of an aTSA was measured in the frontal plane of the scapula, according to the methodology introduced by Watling et al (2018).[43] The CSA is an angle measured between a first line that connects the superior and inferior margin of the glenoid implant (ie, the inferior-superior axis) and a second line connecting the inferior margin of the glenoid implant and the most lateral point of the acromion (Fig. 1). The CSA increases with a longer acromion (Fig. 1*A*) or an upward inclination of the glenoid (Fig. 1*B*). The glenoid implant was tilted, and the CSA was measured using 3D slicer 5.4.0 (https://www.slicer.org/ 3D Slicer; The Slicer Community, Earth, TX, USA).[7] The glenoid implant rotation matrices were calculated using the 3D slicer extension Slicer*IGT*[39] and were imported into the musculoskeletal model.

Glenoid inclination

The glenoid inclination is defined as the angle between the inferior-superior axis of the glenoid and a second line perpendicular to the scapula transverse axis, going through the center of the glenoid[4] (Fig. 1). The transverse axis is defined as the line

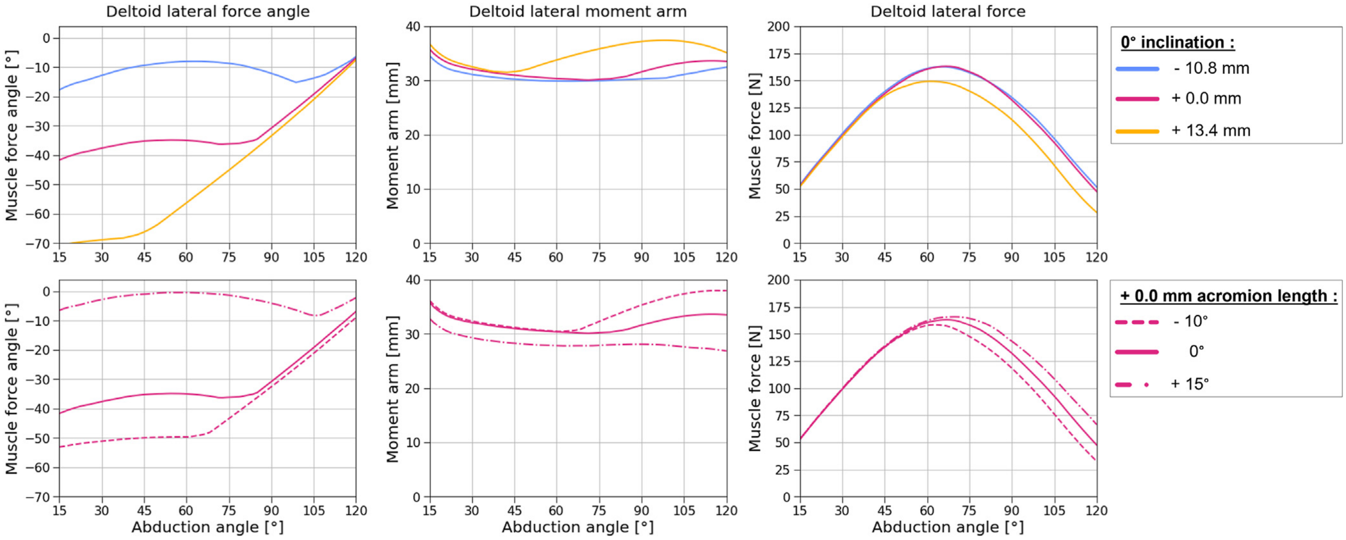

Figure 3 Angle, in the scapular plane between the scapula mediolateral axis in the scapular plane, the lateral deltoid's force on the scapula (an angle of −90° corresponds to an inferior orientation of the force), moment arm of the lateral deltoid, lateral deltoid force for multiple acromion shifts with a neutral inclination (*Top*), and with different glenoid implant inclinations with a normal acromion (*Bottom*).

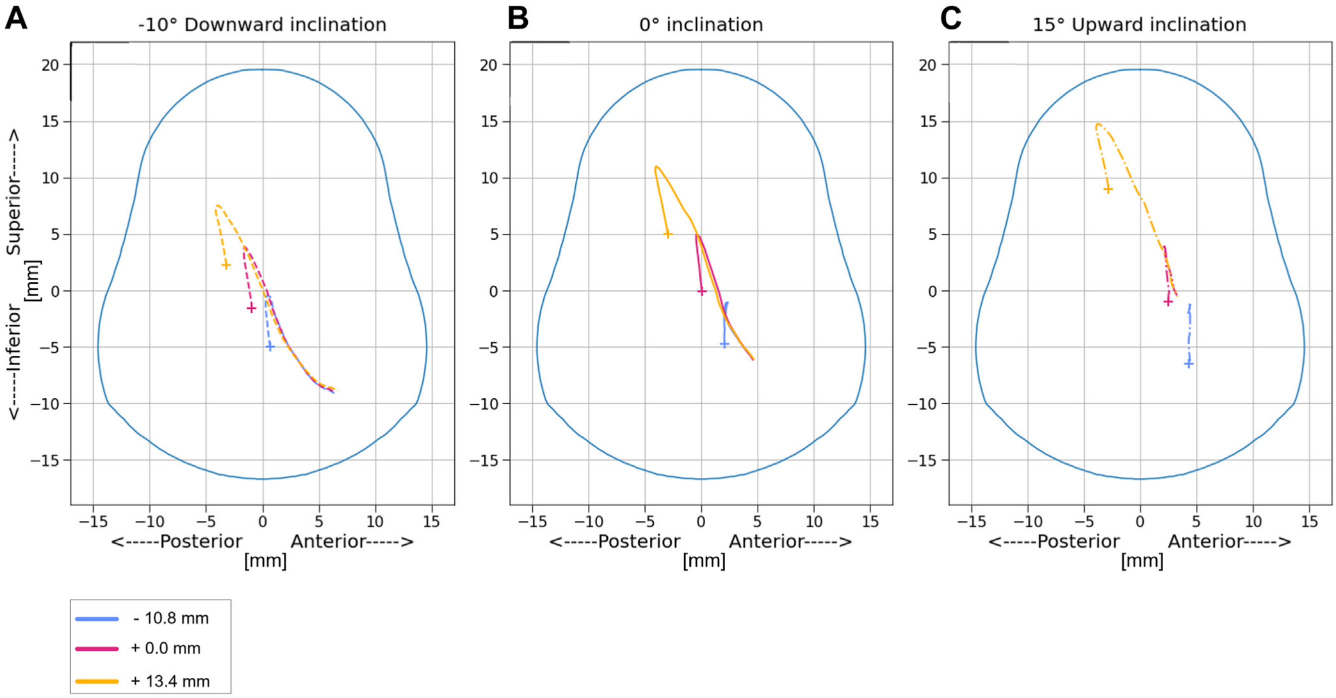

Figure 4 *Center* of pressure on the glenoid implant for different acromion shifts with a glenoid implant inclination of −10° (**A**), 0° (**B**), and 15° (**C**). The *cross* is the position of the center of pressure at 15° of abduction.

connecting the junction of the scapular spine with the vertebral border of the scapula with the center of the glenoid.[4] A positive inclination value corresponds to an upward-facing glenoid.[4] This measure was adapted to the context of aTSA by using the inferior-superior axis of the glenoid implant instead of the axis of the intact glenoid. The glenoid implant inclination was varied by steps of 5° within the anatomical range (−10° to 15°)[4] to match the range of inclinations simulated in similar biomechanical studies.[5,6,18,29,35] The inclination was varied similarly to Engelhardt's et al computational study[5] by rotating the glenoid implant around an axis parallel to the anteroposterior axis of the glenoid implant and going through the center of the glenoid implant surface to maintain the glenoid version (ie, the anterior-posterior rotation angle) at 4°.

Acromion length

The lateral end of the acromion was shifted medio-laterally to simulate different acromion lengths, which moved the four origin points of the lateral deltoid lines of action (Fig. 1). This shift ranged between −10.8 (shorter acromion) and +13.4 mm (longer acromion). The configuration with 0.0° inclination and +0.0 mm

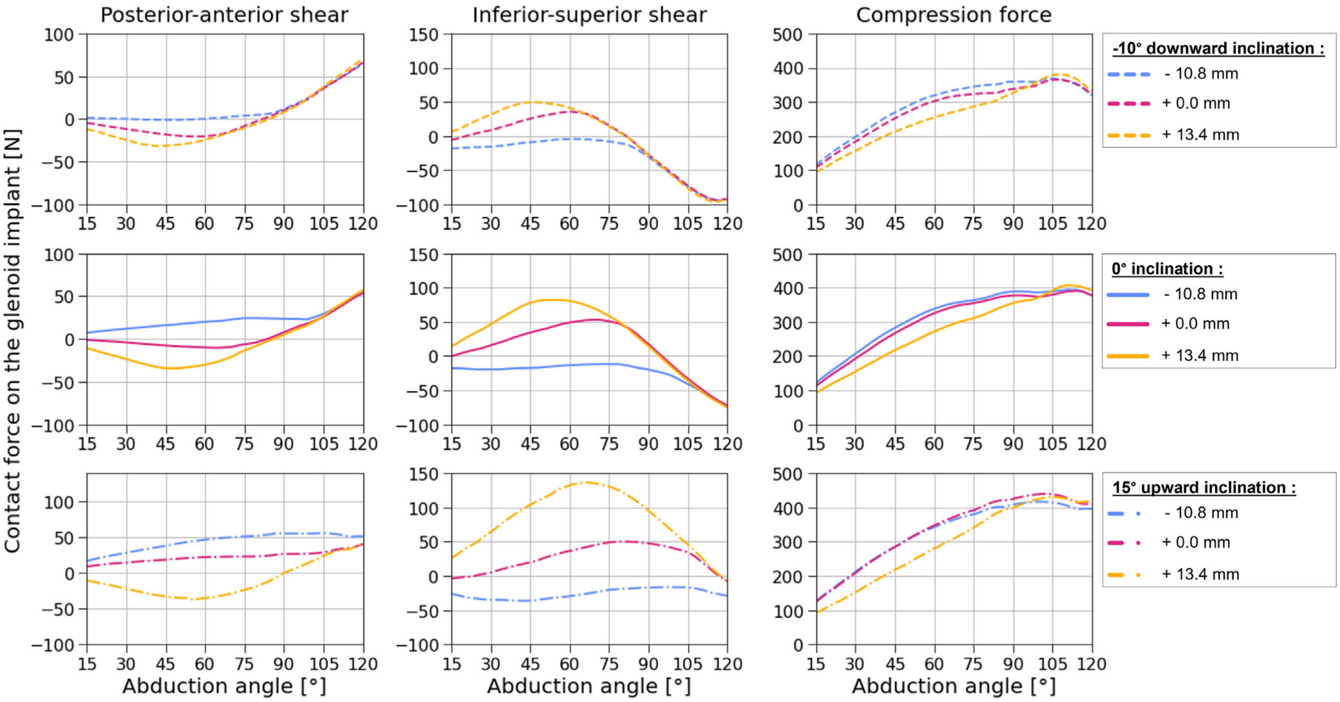

Figure 5 Contact forces applied to the glenoid implant for multiple acromion shifts with a −10° (*Top*), 0° (*Middle*), and 15° (*Bottom*) inclination. Forces are projected on the glenoid implant coordinate system. Contact forces are projected on the posterior-anterior axis (*Left*), inferior-superior axis (*Middle*), and medial-lateral axis (*Right*).

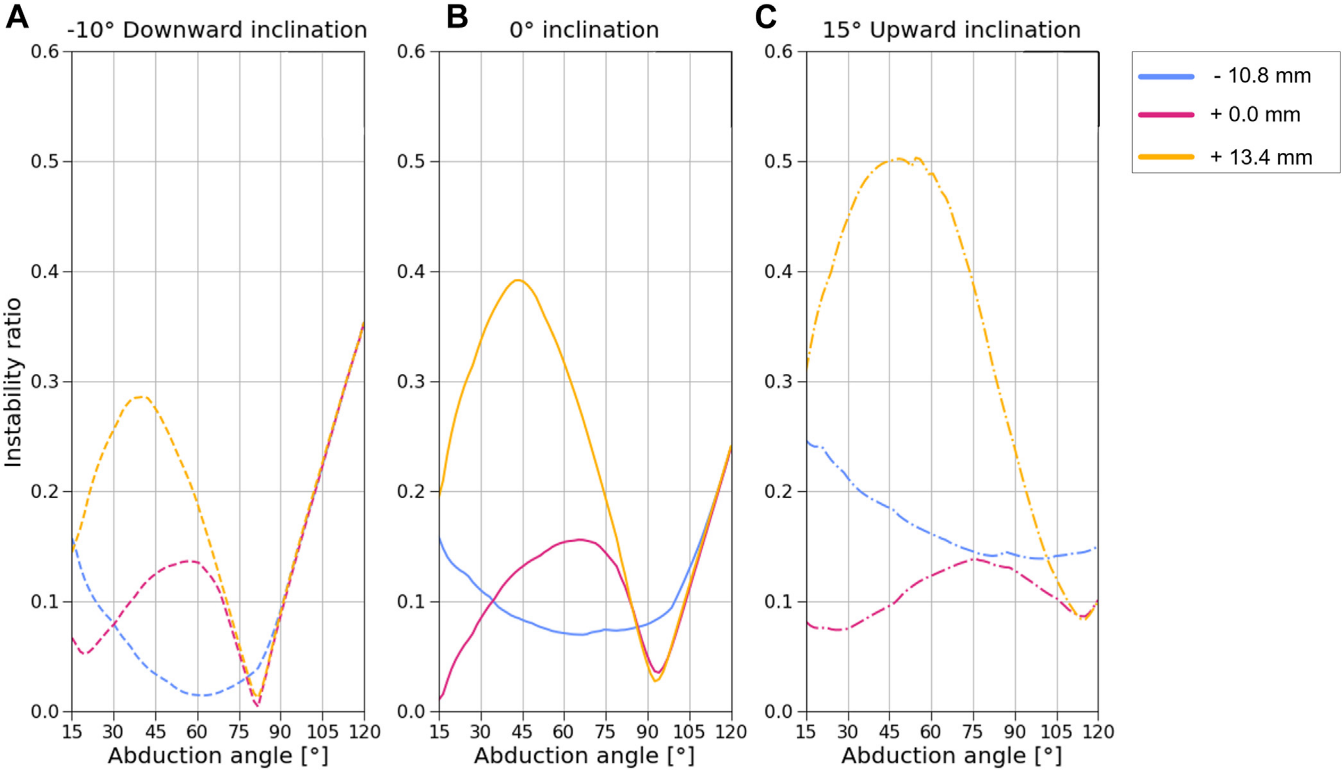

Figure 6 Instability ratio for multiple acromion shifts with a glenoid implant inclination of −10° (**A**), 0° (**B**), and 15° (**C**).

acromion lengthening, resulting in a CSA of 27.7°, was chosen as the reference configuration. The acromion lengthenings were determined to obtain CSAs by steps of 4° from the reference CSA of 27.7° (with an average error of 0.3°) (Table I).

Critical shoulder anglevariation

Thirty scapula geometries were generated by altering the glenoid implant's inclination (n = 6) and the acromion's length (n = 5), resulting in CSAs between 12.2° and 48.5° (Table I). This range of

CSA included the anatomical range measured by Moor et al[24] (18.0° to 43.5°), with additional abnormal CSAs simulating an inadequate choice of glenoid implant inclination.

Musculoskeletal simulations and analyses

An inverse dynamic simulation of a shoulder elevation in the scapular plane from 15° to 120° with a 1.5° angle increment was performed to evaluate muscle kinematics (ie, muscle direction and moment arms), the glenohumeral translations, the contact force applied to the glenoid implant, and its COP time histories in the glenoid implant coordinate system. Muscle forces (f_i) were obtained by minimizing the function $G = \sum_i \left(\frac{f_i}{N_i}\right)^3$ where N_i is the maximal muscle isometric force. This muscle recruitment criterion was chosen to ensure the convergence of the model, with an allowed convergence error of the *force dependant kinematics* algorithm of 0.1 N. All graphs were produced with the *Anypytools* Python package.[21]

To compare the instability of the glenohumeral joint of the multiple CSA configurations, the glenohumeral instability ratio was calculated as the ratio of shear forces over compression forces on the glenoid implant.[11] Two scores were introduced to compare the potential risks of glenoid loosening of the CSA configurations. The first score is the integral of the total shear force's magnitude applied to the glenoid implant during the abduction (N.s). The second score is the integral of the norm of the moment applied to the glenoid implant about the center of its surface (N.m.s). An integral over time was used to indicate the global potential risk of glenoid loosening of a CSA configuration during the abduction movement.

Results

Muscle kinematics

Only the deltoid, the subscapularis, the infraspinatus, and the triceps long head were sensitive to the CSA variations (Fig. 2). The force of the trapezius, the serratus anterior, the rhomboideus, and the supraspinatus varied by less than 5 N, which represents less than 2% of their maximal force. The remaining muscles were nearly inactive during the abduction movement ($f_i < 5$ N).

Lateral deltoid kinematics

During the abduction movement, the lateral deltoid wraps around the humeral head to reach the tip of the acromion. More lateral deltoid wrapping was observed for the original size acromion (Fig. 1*B*) than for a longer acromion (Fig. 1*A*). In particular, for a 13.4 mm longer acromion, an almost vertical angle (−80°) between the lateral deltoid's force and the mediolateral axis of the scapula was reached, compared to an almost horizontal force (−15°) when the acromion was 10.8 mm shorter (Fig. 3 *Top*). Hence, the lateral deltoid force on the scapula introduced more vertical shear forces when the acromion was lengthened, destabilizing the glenohumeral joint. However, the lateral deltoid moment arm was increaseds by 8 mm for a 13.4 mm longer acromion (Fig. 3 *Top*), which decreased the required lateral deltoid force to abduct the arm by 20 N. On the contrary, reducing the length of the acromion by 10.8 mm reduced the moment arm by only 2 mm, which induced a negligible lateral deltoid force difference of 3 N compared to the reference configuration (Fig. 3 *Top*). After 90° of abduction, the difference in deltoid force orientation between a normal and lengthened acromion was negligible ($\theta < 3°$) (Fig. 3 *Top*).

However, increasing the glenoid inclination from 0° to 15° increased the wrapping of the lateral deltoid around the humeral head, which oriented its force horizontally (−5°) compared to a −50° orientation of the force for a −10° glenoid inclination (Fig. 3 *Bottom*). Then, a more upward inclination decreased the moment arm by up to 5 mm, which required 20 N more lateral deltoid force. Similarly, a −10° inclination increased the lateral deltoid moment arm after 90° of abduction, decreasing its force by 20 N.

Table II

Color-coded shear scores according to the acromion lengthening and glenoid inclination (ie, integral of the total shear force applied to the glenoid during the abduction in N.s) with respect to the reference value (0.0 mm acromion lengthening and 0° glenoid inclination).

	Acromion lengthening [mm]				
Glenoid inclination	−10.8	−5.7	0.0	+6.6	+13.4
−10°	3728	3699	4630	5455	5865
−5°	3394	3089	4589	5758	6215
0°	3930	2606	**4408**	6283	6830
5°	5051	3052	3928	6960	7801
10°	5983	3945	3851	7545	9158
15°	6348	4676	4501	8367	10769

4408 N.s is the shear score of the reference configuration (*colored in white*). Lower scores are *colored in blue* and higher scores are *colored in orange*.

Table III

Color-coded moment scores according to the acromion lengthening and glenoid inclination (ie, integral of the total moment applied on the glenoid implant during the abduction in N.m.s) with respect to the reference value (0.0 mm acromion lengthening and 0° change in glenoid inclination).

	Acromion lengthening [mm]				
Glenoid inclination	−10.8	−5.7	0.0	+6.6	+13.4
−10°	127	119	149	175	188
−5°	119	104	150	188	202
0°	135	93	**146**	206	224
5°	170	108	133	229	257
10°	200	135	132	249	304
15°	212	158	153	277	361

146 N.m.s is the moment score of the reference configuration (*colored in white*). Lower scores are *colored in blue* and higher scores are *colored in orange*.

Anterior and posterior deltoid, and rotator cuff kinematics

A 13.4 mm longer acromion was associated with up to 20 N higher anterior and posterior deltoid forces after 100° of abduction and up to 7 N higher subscapularis and infraspinatus forces (Fig. 2). However, negligible muscle force variations resulted from a shortened acromion ($f_i < 5$ N). A 15° upward inclination also increased the anterior deltoid's force by 20 N after 100° of abduction and raised the force of the subscapularis and the infraspinatus by up to 20 N. Hence, the force of the rotator cuff muscles was maximal for the highest CSA configurations (Fig. 2). The triceps long-head force increased by 20 N for a −10° downward inclination and decreased to 0 N for a 15° inclination. A 13.4 mm longer acromion increased the triceps long-head force by up to 8 N (Fig. 2).

Decreasing the inclination to −10° (Fig. 4A) reduced the peak superior COP displacement by 4 mm for a 13.4 mm longer acromion and by 2 mm for a normal acromion length compared to a 0° inclination (Fig. 4*B*). At 120° of abduction, the downward inclination allowed the COP to reach a 4 mm more inferior and 3 mm anterior part of the glenoid compared to a 0° inclination. For the 0° inclination (Fig. 4*B*), a 13.4 mm longer acromion condition increased the COP displacement by 5 mm superiorly and 3 mm posteriorly until 90° of abduction compared to the reference configuration. On the contrary, for a 10.8 mm shorter acromion, the COP displacement shifted 5 mm inferiorly and 2 mm anteriorly. After 90° of abduction, the position of the COP was similar between all acromion lengths for inclinations inferior to 5° since the lateral deltoid wrapping was similar (Fig. 4 *A* and *B*). Raising the inclination to 15° upward (Fig. 4*C*) increased the COP displacement by 4

Table IV
Percentage of variation between the maximum and minimum moment and shear scores for each group of CSA.

Average CSA	12.2°	15.9°	19.7°	23.7°	27.5°	31.4°	35.7°	39.9°	44.2°	48.5°
(n = 30)	(n = 1)	(n = 2)	(n = 3)	(n = 4)	(n = 5)	(n = 5)	(n = 4)	(n = 3)	(n = 2)	(n = 1)
Moment score	-	8%	33%	52%	49%	38%	45%	42%	9%	-
Shear score	-	0%	30%	47%	46%	37%	42%	40%	9%	-

CSA, critical shoulder angle.
The CSA configurations were grouped by the closest values of CSA and their CSAs were averaged.

mm superiorly for all acromion lengths after 90° of abduction compared to a 0° inclination (Fig. 4*B*), which maintained the COP in the superior part of the glenoid. The superior COP displacement was maximal for the highest CSA configuration (ie, 15° inclination and +13.4 mm acromion length) (Fig. 4*C*).

Contact forces

Decreasing the inclination to −10° (Fig. 5 *Top*), decreased the superior shear by up to 25 N before 90°, which decreased the instability ratio (Fig. 6*A*) compared to a 0° inclination (Fig. 6*B*). After 90°, the shear was oriented more inferiorly by 45 N, and the compression decreased by up to 50 N, which greatly increased the instability ratio (Fig. 6*A*) compared to a 0° inclination (Fig. 6*B*).

For a 0° glenoid inclination (Fig. 5 *Middle*), with a 13.4 mm acromion lengthening, superior and posterior shear forces increased by 20 and 15 N and compressive forces decreased by 44 N (Fig. 5), resulting in an increased instability ratio (Fig. 6*B*). On the contrary, a 10.8 mm shorter acromion decreased the instability ratio by reducing the shear forces and increasing the compression. After 105° of abduction, variations of shear forces and instability ratio due to the acromion length were negligible.

Until 90° of abduction, increasing the inclination from 0° to 15° with the original acromion length introduced a higher increase of shear than compression (Fig. 5 *Bottom*), resulting in an increased instability ratio (Fig. 6*C*). Then, after 90° of abduction, the instability ratio reduced due to increased compression forces and to the contact forces being oriented more horizontally instead of inferiorly. The instability ratio was then maximal for the highest CSA configuration (Fig. 6*C*).

Shear and moment scores

The moment applied to the glenoid implant was maximal between 45 and 60° of abduction and was produced at 88 to 98% by the compressive forces and by the inferior-superior COP displacement. A longer acromion and a greater glenoid inclination increased the shear and the moment scores (Tables II and III). Hence, maximal scores were obtained for configurations with an elongated acromion and a positive glenoid inclination (Tables II and III). Both scores were reduced by decreasing the inclination or decreasing the length of the acromion. However, the minimal scores were obtained for a 5.7 mm shortened acromion and inclinations between −10 and 5° (Tables II and III). This is due to the scores increasing while shortening the acromion by more than 5.7 mm. In particular, for a 15° inclination, scores of 4676 N.s and 158 N.m.s were obtained for a 5.7 mm acromion shortening. When shortening the acromion by 10.8 mm, the scores increased to 6348 N.s (+35%) and 212 N.m.s (+34%).

The scores obtained for the same CSA value were highly variable depending on the combination of inclination and acromion length (Table IV). For the same CSA value, the scores varied between 8% and 52%. The highest variations (30% to 52%) were obtained for CSAs between 19.7° and 39.9° that had three to five configurations achieving the same CSA.

Discussion

In the present study, we assessed the effect of CSA variation on glenoid loosening risk factors using a musculoskeletal model of a shoulder with aTSA. Watling et al (2018) 43 found a correlation between a higher CSA and earlier radiological signs of glenoid loosening after an aTSA. However, to our knowledge, no clear biomechanical explanation of the mechanism linking the CSA to glenoid loosening was found. Moreover, to our knowledge, no biomechanical study assessed the variability of shoulder biomechanics between multiple glenoid inclinations and acromion lengths achieving the same CSA value. Our results suggest that increasing the CSA with either a more upward glenoid implant inclination or a longer acromion led to larger shear and moment scores applied to the glenoid implant (ie, integral of the shear and moment over time), which may risk earlier glenoid loosening. However, depending on the inclination and acromion length configuration, the results measured for the same CSA value were highly variable.

Critical shoulder anglerelevance

In the literature, the interaction between the glenoid inclination and the acromion length was unclear, especially in the context of aTSA. Indeed, few studies varied both the acromion length and the glenoid inclination. We found one aTSA study[3] and two studies on a nonprosthetic shoulder,[5,41] varying both parameters. Our results reinforce that a large CSA could increase the risks of glenoid loosening. Indeed, large joint instabilities, moment, and shear contact forces were estimated throughout the abduction when the acromion length and the glenoid inclination both increased. On the contrary, the lowest shear and moment scores were obtained for the lowest glenoid inclinations and an acromion shortening of 5.7 mm. However, one must keep in mind that a single CSA can correspond to multiple combinations of acromion lengths and glenoid inclinations. The studies varying both the inclination and the acromion length varied these parameters individually instead of studying multiple combinations achieving the same CSA value.[3,5,41] Our result showed that the same CSA could have up to 52% difference in moment and shear scores depending on the glenoid inclination and acromion length. The high result variability for the same CSA could be the source of the conflicting results of the literature on the clinical impacts of the CSA. Our study suggests that only measuring the CSA could be insufficient to fully predict the risks of glenoid loosening. Instead, both the inclination and the acromion length could be measured and used to correct the CSA to decrease the risk of glenoid loosening. However, more clinical studies are needed to determine if these differences in shear and moment are clinically significant.

Glenoid inclination

The literature shows that increasing glenoid inclination provokes higher superior humeral translations in the context of anatomic arthroplasty[29] or intact shoulders.[3,5,19] The increased superior glenohumeral instability leads to higher risks of superior subluxation of the shoulder joint.[3,8,25] This could be explained by the fact that less force is needed to superiorly destabilize the humerus because of the upward inclination.[44] Our study confirms the destabilizing effect of a more upward glenoid implant inclination with a higher COP eccentricity at the early stages of the abduction. However, at higher abduction angles, the upward inclination had a stabilizing effect by preventing the COP from reaching the inferior part of the glenoid implant, reducing the moment applied to the glenoid. Nevertheless, throughout the abduction, the moment scores still increased with higher glenoid implant inclination even with this stabilizing effect. Our results might suggest that a more upward glenoid implant inclination could increase the risk of glenoid loosening with higher moment and shear applied to the glenoid implant. Moreover, several studies suggest that a downward inclination could counteract the glenohumeral joint instabilities introduced by rotator cuff tear.[19,20,35] Our study confirms the stabilizing effect of a downward glenoid implant inclination that decreased the COP superior displacement. This suggests that the risks of glenoid loosening could be reduced with a downward inclination since it decreased the moment and the shear applied to the glenoid implant.

Acromion length

To our knowledge, no biomechanical studies assessed the effect of the acromion length in the context of aTSA. Our study confirms that the acromion length's influence is similar to what is observed in a nonprosthetic shoulder: a longer acromion introduced higher superior shear forces and lower compression forces, which greatly increased the instability ratio.[3,5,11,40,42] Our study also confirms that a longer acromion oriented the lateral deltoid more superiorly, which decreased the required abduction force[3,5,37,41] and increased superior humeral head translations.[5,37] Consequently, more eccentric forces were applied to the glenoid implant, which greatly increased the total moment applied to the glenoid. After 90° of abduction, the influence of the acromion length was negligible since the lateral deltoid force directions were similar. Then, shortening the acromion length with acromioplasty could reduce the risks of potential glenoid loosening by reducing the shear forces and the moment applied to the glenoid. However, shortening the acromion too much (>5.7 mm) increased the scores by (34%) increasing the anterior-posterior shear and the moment around the inferior-superior axis. This suggests that acromioplasty could raise the risks of glenoid loosening if the acromion is already short. In addition, acromioplasty has a limited impact on the CSA. According to the literature, acromioplasty reduces the CSA by 3.7° to 4.2° on average by reducing the acromion length by 6 mm on average.[10,28] It suggests that acromioplasty could be used as a supplementary CSA correction but seems insufficient to limit the risks of glenoid loosening without also correcting the glenoid implant inclination.

Limits of the study

The outputs of the musculoskeletal model used were compared with the glenohumeral translations measured for healthy subjects, the position of the COP on the glenoid implant, and the glenohumeral contact force.[31] However, most of the data used to validate this model were from healthy shoulders, experimental studies, and computational models. Hence, more in-vivo studies, especially in aTSA, would be required to validate our model.

Another limitation to our study is the small variation of the force produced by the rotator cuff. The subscapularis and the infraspinatus were more active to stabilize the highly unstable CSA configurations. However, the supraspinatus remained slightly sensitive to the rise of instability, and the teres minor was almost inactive during the movement, while these muscles are known to play a crucial role in joint stabilization.[23] It suggests exploring other muscle recruitment criterion to improve the synergy between the abductors and the stabilizer muscles. Moreover, our model only studied an abduction movement and simplified the scapulohumeral rhythm as a constant healthy rhythm, while it is highly variable between individuals, especially for unhealthy shoulders.[45] Furthermore, the acromion lengthening used did not account for the different acromion shapes. These simplifications could be mitigated by scaling our model to aTSA patient's anatomy and kinematics and by studying daily life movements.

Due to the rigid body nature of the model, the implants were undeformable and rigidly attached to the bones. With these hypotheses, the parts' stress or strain could not be evaluated. Consequently, the direct link between the CSA and the stress on the implant's fixation could not be assessed. Similarly, the bone quality underneath the glenoid implant could not be considered when correcting the glenoid implant inclination, although adequate bone support underneath the glenoid implant is essential for limiting glenoid loosening.[22] These limitations may suggest the possibility of combining our musculoskeletal model with a finite element analysis in future studies to estimate these unmeasured risk factors of glenoid loosening.

Conclusion

Increasing the CSA with a more upward-oriented glenoid and a longer acromion leads to larger moment and shear forces being applied to the glenoid implant in the context of aTSA. An upward glenoid implant inclination could then increase the risks of glenoid loosening,especially when the acromion is long. In the case of a long acromion, the effect of acromioplasty seems limited to adequately reduce the risk of glenoid loosening. We then recommend maintaining a neutral inclination or reducing the CSA with a downward inclination to stabilize the glenohumeral joint and potentially reduce the risks of loosening. Since multiple combinations of acromion length and glenoid implant inclination can result in the same CSA with large differences in moment and shear forces, measuring the CSA as a global indicator may be insufficient to accurately predict the risk of glenoid loosening. It suggests that the acromion length could be considered during surgical planning to determine the adequate glenoid implant inclination.

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