



HAL
open science

A biomechanical confirmation of the relationship between critical shoulder angle (CSA) and articular joint loading

Guillaume Villatte, Eline van Der Kruk, Asim Bhuta, Matthias Zumstein, Beat Moor, Roger J.H. Emery, Anthony M.J. Bull, Peter Reilly

► To cite this version:

Guillaume Villatte, Eline van Der Kruk, Asim Bhuta, Matthias Zumstein, Beat Moor, et al.. A biomechanical confirmation of the relationship between critical shoulder angle (CSA) and articular joint loading. *Journal of Shoulder and Elbow Surgery*, 2020, 29 (10), pp.1967-1973. 10.1016/j.jse.2020.03.002 . hal-03138748

HAL Id: hal-03138748

<https://uca.hal.science/hal-03138748v1>

Submitted on 21 Sep 2022

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution - NonCommercial 4.0 International License

A biomechanical confirmation of the relationship between critical shoulder angle (CSA) and articular joint loading.

Guillaume Villatte MD^{1,2}, Eline van der Kruk PhD³, Asim I. Bhuta PhD³, Matthias Zumstein MD⁴, Beat Moor MD⁴, Roger J. H. Emery Pr⁵, Anthony M.J. Bull Pr¹, Peter Reilly MS FRCS¹.

1. Department of Orthopaedic Surgery and Traumatology, Hôpital Gabriel Montpied, CHU de Clermont Ferrand BP 69, 63003 Clermont Ferrand Cedex 01, France. Phone number: +334 73 75 45 83; Fax number: +334 73 75 45 04 ✉
2. Université Clermont Auvergne, SIGMA Clermont, Institut de Chimie de Clermont-Ferrand, BP 10448, F-63000 Clermont-Ferrand, France.
CNRS, UMR 6296, ICCF, F-63178 Aubière, France.
3. Bioengineering Department, Imperial College, Exhibition Road, London SW7 2AZ, United Kingdom
4. Department of Orthopaedic Surgery and Traumatology, Inselspital, University of Bern, Inselspital, Freiburgstrasse, Bern, Switzerland.
5. Division of Surgery, Imperial College, London, United Kingdom.

Corresponding author: Guillaume Villatte MD, CHU de Clermont-Ferrand, Service d'orthopédie et traumatology, 58 rue Montalembert, Clermont-Ferrand, 63000 FRANCE
guivillatte@gmail.com

Conflict of interest: none.

Funding: This study was funded in part by Swiss Orthopaedics.

Institutional review board approval was not required for this basic science study.

1 **A biomechanical confirmation of the relationship between critical shoulder angle (CSA)**
2 **and articular joint loading**

3

4 **Abstract**

5 **Background:** The Critical Shoulder Angle (CSA) has been shown to be correlated with
6 shoulder disease states. The biomechanical hypothesis to explain this correlation is that the
7 CSA changes the shear and compressive forces on the shoulder. The objective of this study is
8 to test this hypothesis by use of a validated computational shoulder model. Specifically, this
9 study assesses the impact on glenohumeral biomechanics of modifying the CSA.

10 **Methods:** An inverse dynamics three-dimensional musculoskeletal model of the shoulder was
11 used to quantify muscle forces and glenohumeral joint forces. The CSA was changed by
12 altering the attachment point of the middle deltoid into a normal CSA (33°), a reduced CSA
13 of 28°, and an increased CSA of 38°. Subject-specific kinematics of slow and fast speed
14 abduction in the scapular plane, and slow and fast forward flexion measured by a 3D motion
15 capture system were used to quantify joint reaction shear and compressive forces.

16 **Results:** Increasing the CSA results in increased superior-inferior forces (shearing forces;
17 integrated over the range of motion; $p < 0.05$). Reducing CSA results in increased latero-
18 medial (compressive) forces for both the maximum and integrated sum of the forces over the
19 whole motion; $p < 0.01$).

20 **Discussion/Conclusion:** Changes in the CSA modify glenohumeral joint biomechanics with
21 increasing CSA producing higher shear forces that would contribute to rotator cuff overuse,
22 whereas reducing the CSA results in higher compressive forces which contribute to joint
23 wear.

24 **Level of evidence:** Basic Science Study; Computer Modeling

25

26 **Keywords:** Critical shoulder angle (CSA), glenohumeral joint, joint wear, rotator cuff,
27 computational shoulder model.

28

29 The shape of the scapula and especially of the acromion has historically been considered as a
30 potential etiology for shoulder pathologies including those of the gleno-humeral joint (GHJ).

31 Codman¹⁰, Armstrong³ and Neer²⁶ described the association of specific acromion shapes
32 with degenerative rotator cuff tear (RCT), leading to the well-known impingement syndrome
33 and the extrinsic mechanical conflict theory. Since then, a broader understanding of

34 degenerative RCT physiopathology³⁵ (ageing of the tendon, modification of local
35 vascularization, genetic disposition) has challenged this theory, thus questioning the absolute
36 role of the acromion shape in this process. Research over the past 15 years has continued to

37 focus on the shape of the acromion in the coronal plane, including proposed radiological
38 parameters to describe the lateral extension of the acromion^{5,28}. A recent and widely cited

39 study from Moor et al proposed the concept of the Critical Shoulder Angle (CSA)²⁴, a
40 measure which takes into account the tilt of the glenoid (inclination) and the lateral extension
41 of the acromion. In a population of 279 patients, they found that the mean CSA was

42 significantly different between a disease-free shoulder group (33.1°), an RCT group (38.0°),
43 and a primary osteoarthritis group (OA, 28.1°). Numerous clinical observational studies have
44 confirmed these findings^{4,5,8,11-13,15,16,23,25,38,43}.

45

46 The link between the clinical observations and the CSA are hypothesized to be biomechanical
47 in nature^{2,27,22,14,40,42}, by changing the magnitude and direction of the deltoid force. The

48 hypothesis of this study is that an increased CSA would result in higher shearing forces that
49 would be associated with RCT and a decreased CSA would result in higher compressive
50 forces, associated with primary osteoarthritis.

51
52
53
54
55
56
57
58
59
60
61
62
63
64
65
66
67
68
69
70
71
72
73
74
75

The objective of this study is to test the hypothesis by assessing the impact on GHJ biomechanics of modifying the CSA by use of a validated computational shoulder model.

Material and Methods

The United Kingdom National Shoulder Model (UKNSM)

An inverse dynamics three-dimensional musculoskeletal model of the upper limb⁹ was used to quantify muscle and glenohumeral joint forces. This model quantifies forces in 87 muscle elements, three ligaments and joint reaction forces of the sternoclavicular, acromioclavicular, scapulothoracic, glenohumeral and elbow joint (Figure 1). The analysis begins by solving the determinate inverse dynamics intersegmental moments based on measured kinematics. Then an optimization algorithm is used to minimize the sum of muscle stresses squared to solve the muscle load-sharing redundancy. The model has been validated for glenohumeral joint force measures through comparison to instrumented anatomical shoulder replacement measurements^{7,44} for a driving task²⁹ and other tasks of daily living¹⁹ and for muscle forces through comparison with electromyography¹⁸. The model is customized to each subject by scaling segment lengths and body segment parameters.¹⁷ In brief, clavicle and scapula segments were homogeneously scaled based on relative segment lengths between model and subject. An ellipsoid represented the scapulo thoracic gliding-plane; this was non-homogeneously scaled using an optimization procedure to minimize the difference between digitized anatomical landmarks and the final ellipsoid. A partially closed chain method is used to optimize scapula and clavicle kinematics, in which the least squares difference to the measured scapular and clavicle kinematics is minimized and the scapula medial border is constrained to not penetrate the thorax wall (represented by an elipsoid).³²

76 Tests conditions

77 The scapula within the UKNSM was imported into computer aided engineering software to
78 allow the effect of medializing and lateralizing the acromion to be modelled, thus changing
79 the CSA and therefore the three-dimensional position of the attachment point of the middle
80 deltoid. This was implemented in the software by sketching new points and lines parallel to
81 the plane of measurement of the CSA and coincident with the original middle deltoid
82 attachment point. The changes were made to create 3 different CSAs: a normal CSA (33°), a
83 reduced CSA of 28° , and an increased CSA of 38° that reflect the changes previously reported
84 as clinically significant ²⁴.

85

86 To test the effect of different subject-specific kinematics, a previously obtained dataset of
87 kinematics was used ²⁰. These kinematics were measured using a nine camera optical motion
88 tracking system with a set of twenty-one retro-reflective markers used to track the thorax,
89 clavicle, humerus, and forearm segments ^{36,37,45}. The kinematics of six healthy male subjects
90 were used (age 25 years \pm 2 years) who each performed four motions with a 2 kg hand load to
91 provide a resistance to motion without fatiguing the subjects. These motions were: slow and
92 fast speed abduction (in the scapular plane), and slow and fast forward flexion ³⁴. Each subject
93 performed three trials per motion. These datasets were passed through the UKNSM after
94 appropriate subject scaling ³².

95 Outcomes measures

96 All output measures were normalized to humero-thoracic elevation and all forces were
97 normalized to the subject's body weight and integrated over the range of motion from 30° to
98 120° of humero-thoracic elevation. The following parameters were analyzed to test the effects
99 of CSA changes on GHJ biomechanics:

100 - the magnitude (maximum and integrated over the whole motion) of the GHJ shearing forces
101 (SF), representing the superior-inferior (SI) forces and the antero-posterior (AP) forces acting
102 in the sagittal plane that are exerted on the joint during motion.

103 - the magnitude (maximum and integrated over the whole motion) of the GHJ compressive
104 forces (CF), representing the forces acting in the frontal plane (latero-medial) that are exerted
105 on the joint during motion.

106

107 Statistical Analysis

108 Repeated measures two-way ANOVA (RM 2-Way ANOVA), with Bonferroni post-hoc
109 correction was conducted on the results using SPSS software (2014; IBM Corp., Armonk,
110 NY, USA). The assumptions of the RM 2-Way ANOVA method were tested for all measures.
111 The independent variables are CSA (normal, increased, reduced) and Motion (fast and slow,
112 forward flexion and scapular plane abduction); the dependent variables are the joint forces
113 (integrated AP shear, max AP shear, integrated SI shear, max SI shear, integrated CF, max
114 CF). Mauchly's test indicated that the assumption of sphericity had been violated for the
115 main effects of CSA and Motion for several measures, therefore degrees of freedom were
116 corrected using Greenhouse-Geisser estimates of sphericity (ϵ).

117

118 Results

119 Statistically significant differences were found for the integrated SI shear force, the integrated
120 CF and the maximum CF (Table 1). These statistical results are presented in Figure 2. In
121 summary, an increased CSA angle resulted in 111% higher integrated SI shear forces
122 ($p < 0.05$) when compared to normal. For the compressive forces, a reduced CSA angle
123 resulted in a significant increase of the CF (integrated: 2.8% increase, $p < 0.01$; maximum:
124 2.8% increase, $p < 0.05$) compared to normal CSA and also when compared to increased CSA

125 (integrated: 5.5% increase, $p < 0.01$; maximum 5.3% increase, $p < 0.05$). There were no main
126 effects found for Motion, nor an interaction effect of Motion and CSA.

127 The mean maximum SI forces were 13% BW, 12% BW and 21% BW for reduced, normal
128 and increased CSA, respectively. The maximum CF were 132% BW, 136% BW and 129%
129 BW for reduced, normal and increased CSA, respectively.

130

131 **Discussion**

132 This is the first study to assess the effects of changes in CSA on GHJ biomechanics through a
133 computational shoulder model in order to test the mechanically-based hypothesis. The results
134 confirm the initial hypothesis based on literature⁴¹, that is to say increasing the CSA results in
135 increased superior-inferior forces (shearing forces), whereas decreasing the CSA results in
136 increased latero-medial (compressive force) forces (Figure 3).

137

138 Our results are also consistent with those of two cadaver studies previously published about
139 the subject. Even if the model and analysis method are different, Vielhofer and Gerber found
140 that with an increased CSA, the ratio of glenohumeral joint shear to joint compression forces
141 is increased (peak difference of 23% at 50° of thoraco-humeral abduction compared to a
142 normal CSA)⁴⁰, requiring substantially increased compensatory supraspinatus loads
143 (increased by 13-33% between 33° and 37° of elevation compared to a normal CSA)¹⁴.

144

145 These cadaver studies combined with the study presented here provide simple mechanical
146 explanations for the results:

- 147 • an increased CSA would result in a lateralized proximal deltoid insertion.
148 Consequently, the vector force of the deltoid during abduction would be more vertical,
149 requiring a greater horizontal force from the cuff to stabilize the joint (by

150 counterbalancing the shearing forces). Ultimately, this increase in muscle use could
151 potentially, in combination with other factors, lead to a degenerative RCT in the long-
152 term; and

- 153 • a reduced CSA would result in a medialized proximal deltoid insertion. Consequently,
154 the vector force of the deltoid during abduction would be more oblique (resultant
155 internal translation), which in addition to the vector force of the cuff (mostly
156 horizontal), could increase the load (compressive forces) on the GHJ. Finally, this
157 could lead to OA in the long-term.

158

159 It is known that small elevated mechanical loading is associated with the instigation and
160 progression of osteoarthritis^{1,30}, suggesting that, although small in percentage terms, the
161 statistical differences in key mechanical variables found here may also be clinical significant.

162

163 Computational simulation models are frequently used to analyze human joint biomechanics
164 and have been validated in studies that quantified articular loading in activities of daily living,
165 and the biomechanical consequences of a pathology, surgery, and arthroplasty^{9,20,31,39}.

166 Concerning shoulder modelling, the UKNSM (formerly Newcastle Shoulder Model)⁹ is one
167 the oldest validated inverse dynamics-based models³³. Body segment parameters are based on
168 a large group of young living patients²¹. There are limitations with such models and so,
169 although, the model has been validated by comparison to instrumented joint replacements and
170 electromyography, such computer simulations remain “models” and are, therefore, a surrogate
171 of direct in-vivo biomechanical measurements.

172

173 Apart from technical considerations of the computational model, this study has some other
174 limitations. Tests were only performed in simplified motions of pure scapular abduction or

175 flexion, whereas most daily activities have ranges of motion that combine abduction and
176 flexion with obligate rotations²⁰. Moreover, the model is based on a range of subjects with
177 normal anatomy, and this study varied the CSA in isolation, whereas there might be other
178 changes present with a change in CSA angle, such as glenoid version or muscle stiffness that
179 may influence the model outputs. Additionally, a change in anatomy might also result in a
180 further change in kinematics, although this was mitigated in this study by using a set of data
181 from six healthy subjects, rather than just from one subject. Finally, we could have studied
182 the different components of the CSA separately but even if the lateral acromial roof extension
183 has a greater influence in pathogenesis of degenerative RCT and concentric OA than acromial
184 height or glenoid inclination, the CSA remain the best factor to predict these pathologies⁶.

185

186 **Conclusion**

187 Through a validated computational shoulder model, combined with in vivo motion analysis
188 experiments, this study demonstrates that changes in the CSA modify GHJ biomechanics.

189 Increasing the CSA results in higher shear forces, requiring increased rotator cuff use to
190 neutralize the shear which is potentially damaging in the long term. Decreasing the CSA
191 results in a higher joint compressive force which leads to increased joint wear.

192 These findings support previous clinical observational and biomechanical studies that
193 alterations in CSA may have a role in common shoulder pathologies such RCT or OA.

194 Consequently, surgical restoration to a “normal” CSA is recommended when treating patients
195 with such pathologies, for example, lateral acromioplasty after rotator cuff repair or ensuring
196 control of glenoid inclination when conducting arthroplasty surgery.

197 **References**

- 198 1. Apreleva M, Parsons IM, Warner JJ, Fu FH, Woo SL. Experimental investigation of
199 reaction forces at the glenohumeral joint during active abduction. *J. Shoulder Elbow*
200 *Surg.* 2000 Oct;9(5):409–417.

- 201 2. Apreleva M, Parsons IM, Warner JJP, Fu FH, Woo SL-Y. Experimental investigation of
202 reaction forces at the glenohumeral joint during active abduction. *J. Shoulder Elbow*
203 *Surg.* 2000 Sep 1;9(5):409–417.
- 204 3. Armstrong JR. Excision of the acromion in treatment of the supraspinatus syndrome;
205 report of 95 excisions. *J. Bone Joint Surg. Br.* 1949 Aug;31B(3):436–442.
- 206 4. Balke M, Liem D, Greshake O, Hoehner J, Bouillon B, Banerjee M. Differences in
207 acromial morphology of shoulders in patients with degenerative and traumatic
208 supraspinatus tendon tears. *Knee Surg. Sports Traumatol. Arthrosc. Off. J. ESSKA.*
209 2016 Jul;24(7):2200–2205. doi:10.1007/s00167-014-3499-y
- 210 5. Banas MP, Miller RJ, Totterman S. Relationship between the lateral acromion angle and
211 rotator cuff disease. *J. Shoulder Elbow Surg.* 1995 Dec;4(6):454–461.
- 212 6. Beeler S, Hasler A, Götschi T, Meyer DC, Gerber C. Critical shoulder angle: Acromial
213 coverage is more relevant than glenoid inclination. *J. Orthop. Res.* 2019 Jan
214 1;37(1):205–210. doi:10.1002/jor.24053
- 215 7. Bergmann G, Graichen F, Bender A, Kääh M, Rohlmann A, Westerhoff P. In vivo
216 glenohumeral contact forces--measurements in the first patient 7 months postoperatively.
217 *J. Biomech.* 2007;40(10):2139–2149. doi:10.1016/j.jbiomech.2006.10.037
- 218 8. Blonna D, Giani A, Bellato E, Mattei L, Caló M, Rossi R, et al. Predominance of the
219 critical shoulder angle in the pathogenesis of degenerative diseases of the shoulder. *J.*
220 *Shoulder Elbow Surg.* 2016 Aug;25(8):1328–1336. doi:10.1016/j.jse.2015.11.059
- 221 9. Charlton IW, Johnson GR. A model for the prediction of the forces at the glenohumeral
222 joint. *Proc. Inst. Mech. Eng. [H].* 2006 Nov;220(8):801–812.
223 doi:10.1243/09544119JEIM147
- 224 10. Codman EA. The shoulder; rupture of the supraspinatus tendon and other lesions in or
225 about the subacromial bursa. Boston, Mass: T. Todd Company, printers; 1934.
- 226 11. Daggett M, Werner B, Collin P, Gauci M-O, Chaoui J, Walch G. Correlation between
227 glenoid inclination and critical shoulder angle: a radiographic and computed tomography

- 228 study. *J. Shoulder Elbow Surg.* 2015 Dec;24(12):1948–1953.
229 doi:10.1016/j.jse.2015.07.013
- 230 12. Garcia GH, Liu JN, Degen RM, Johnson CC, Wong AC, Dines DM, et al. Higher critical
231 shoulder angle increases the risk of retear after rotator cuff repair. *J. Shoulder Elbow*
232 *Surg.* 2017;26(2):241–245. doi:10.1016/j.jse.2016.07.009
- 233 13. Gerber C, Catanzaro S, Betz M, Ernstbrunner L. Arthroscopic Correction of the Critical
234 Shoulder Angle Through Lateral Acromioplasty: A Safe Adjunct to Rotator Cuff Repair.
235 *Arthrosc. J. Arthrosc. Relat. Surg. Off. Publ. Arthrosc. Assoc. N. Am. Int. Arthrosc.*
236 *Assoc.* 2018 Mar;34(3):771–780. doi:10.1016/j.arthro.2017.08.255
- 237 14. Gerber C, Snedeker JG, Baumgartner D, Viehöfer AF. Supraspinatus tendon load during
238 abduction is dependent on the size of the critical shoulder angle: A biomechanical
239 analysis. *J. Orthop. Res. Off. Publ. Orthop. Res. Soc.* 2014 Jul;32(7):952–957.
240 doi:10.1002/jor.22621
- 241 15. Gomide LC, Carmo TC do, Bergo GHM, Oliveira GA, Macedo IS. Relationship
242 between the critical shoulder angle and the development of rotator cuff lesions: a
243 retrospective epidemiological study. *Rev. Bras. Ortop.* 2017 Jul;52(4):423–427.
244 doi:10.1016/j.rboe.2017.06.002
- 245 16. Heuberer PR, Plachel F, Willinger L, Moroder P, Laky B, Pauzenberger L, et al. Critical
246 shoulder angle combined with age predict five shoulder pathologies: a retrospective
247 analysis of 1000 cases. *BMC Musculoskelet. Disord.* 2017 Jun 15;18(1):259.
248 doi:10.1186/s12891-017-1559-4
- 249 17. Johnson GR, Spalding D, Nowitzke A, Bogduk N. Modelling the muscles of the scapula
250 morphometric and coordinate data and functional implications. *J. Biomech.* 1996 Aug
251 1;29(8):1039–1051.
- 252 18. Klemt C, Nolte D, Ding Z, Rane L, Quest RA, Finnegan ME, et al. Anthropometric
253 Scaling of Anatomical Datasets for Subject-Specific Musculoskeletal Modelling of the
254 Shoulder. *Ann. Biomed. Eng.* 2019 Apr;47(4):924–936. doi:10.1007/s10439-019-02207-
255 2

- 256 19. Klemt C, Prinold JA, Morgans S, Smith SHL, Nolte D, Reilly P, et al. Analysis of
257 shoulder compressive and shear forces during functional activities of daily life. *Clin.*
258 *Biomech.* Bristol Avon. 2018;54:34–41. doi:10.1016/j.clinbiomech.2018.03.006
- 259 20. Klemt C, Prinold JA, Morgans S, Smith SHL, Nolte D, Reilly P, et al. Analysis of
260 shoulder compressive and shear forces during functional activities of daily life. *Clin.*
261 *Biomech.* Bristol Avon. 2018 May;54:34–41. doi:10.1016/j.clinbiomech.2018.03.006
- 262 21. de Leva P. Adjustments to Zatsiorsky-Seluyanov’s segment inertia parameters. *J.*
263 *Biomech.* 1996 Sep;29(9):1223–1230.
- 264 22. Ludewig PM, Phadke V, Braman JP, Hassett DR, Cieminski CJ, LaPrade RF. Motion of
265 the shoulder complex during multiplanar humeral elevation. *J. Bone Joint Surg. Am.*
266 2009 Feb;91(2):378–389. doi:10.2106/JBJS.G.01483
- 267 23. Mantell MT, Nelson R, Lowe JT, Endrizzi DP, Jawa A. Critical shoulder angle is
268 associated with full-thickness rotator cuff tears in patients with glenohumeral
269 osteoarthritis. *J. Shoulder Elbow Surg.* 2017 Dec;26(12):e376–e381.
270 doi:10.1016/j.jse.2017.05.020
- 271 24. Moor BK, Bouaicha S, Rothenfluh DA, Sukthankar A, Gerber C. Is there an association
272 between the individual anatomy of the scapula and the development of rotator cuff tears
273 or osteoarthritis of the glenohumeral joint?: A radiological study of the critical shoulder
274 angle. *Bone Jt. J.* 2013 Jul;95-B(7):935–941. doi:10.1302/0301-620X.95B7.31028
- 275 25. Moor BK, Wieser K, Slankamenac K, Gerber C, Bouaicha S. Relationship of individual
276 scapular anatomy and degenerative rotator cuff tears. *J. Shoulder Elbow Surg.* 2014
277 Apr;23(4):536–541. doi:10.1016/j.jse.2013.11.008
- 278 26. Neer CS. Anterior acromioplasty for the chronic impingement syndrome in the shoulder:
279 a preliminary report. *J. Bone Joint Surg. Am.* 1972 Jan;54(1):41–50.
- 280 27. Nikooyan AA, Veeger HEJ, Westerhoff P, Graichen F, Bergmann G, van der Helm FCT.
281 Validation of the Delft Shoulder and Elbow Model using in-vivo glenohumeral joint
282 contact forces. *J. Biomech.* 2010 Nov 16;43(15):3007–3014.
283 doi:10.1016/j.jbiomech.2010.06.015

- 284 28. Nyffeler RW, Werner CML, Sukthankar A, Schmid MR, Gerber C. Association of a
285 large lateral extension of the acromion with rotator cuff tears. *J. Bone Joint Surg. Am.*
286 2006 Apr;88(4):800–805. doi:10.2106/JBJS.D.03042
- 287 29. Pandis P, Prinold JAI, Bull AMJ. Shoulder muscle forces during driving: Sudden
288 steering can load the rotator cuff beyond its repair limit. *Clin. Biomech. Bristol Avon.*
289 2015 Oct;30(8):839–846. doi:10.1016/j.clinbiomech.2015.06.004
- 290 30. Parsons IM, Apreleva M, Fu FH, Woo SLY. The effect of rotator cuff tears on reaction
291 forces at the glenohumeral joint. *J. Orthop. Res. Off. Publ. Orthop. Res. Soc.* 2002
292 May;20(3):439–446. doi:10.1016/S0736-0266(01)00137-1
- 293 31. Praagman M, Stokdijk M, Veeger HE, Visser B. Predicting mechanical load of the
294 glenohumeral joint, using net joint moments. *Clin. Biomech. Bristol Avon.* 2000
295 Jun;15(5):315–321.
- 296 32. Prinold JAI, Bull AMJ. Scaling and kinematics optimisation of the scapula and thorax in
297 upper limb musculoskeletal models. *J. Biomech.* 2014 Aug 22;47(11):2813–2819.
298 doi:10.1016/j.jbiomech.2014.05.015
- 299 33. Prinold JAI, Masjedi M, Johnson GR, Bull AMJ. Musculoskeletal shoulder models: a
300 technical review and proposals for research foci. *Proc. Inst. Mech. Eng. [H].* 2013
301 Oct;227(10):1041–1057. doi:10.1177/0954411913492303
- 302 34. Prinold JAI, Villette CC, Bull AMJ. The influence of extreme speeds on scapula
303 kinematics and the importance of controlling the plane of elevation. *Clin. Biomech.*
304 *Bristol Avon.* 2013 Dec;28(9–10):973–980. doi:10.1016/j.clinbiomech.2013.10.008
- 305 35. Rees JL. The pathogenesis and surgical treatment of tears of the rotator cuff. *J. Bone*
306 *Joint Surg. Br.* 2008 Jul;90(7):827–832. doi:10.1302/0301-620X.90B7.19874
- 307 36. Shaheen AF, Alexander CM, Bull AMJ. Effects of attachment position and shoulder
308 orientation during calibration on the accuracy of the acromial tracker. *J. Biomech.* 2011
309 Apr 29;44(7):1410–1413. doi:10.1016/j.jbiomech.2011.01.013

- 310 37. Shaheen AF, Alexander CM, Bull AMJ. Tracking the scapula using the scapula locator
311 with and without feedback from pressure-sensors: A comparative study. *J. Biomech.*
312 2011 May 17;44(8):1633–1636. doi:10.1016/j.jbiomech.2011.02.139
- 313 38. Spiegl UJ, Horan MP, Smith SW, Ho CP, Millett PJ. The critical shoulder angle is
314 associated with rotator cuff tears and shoulder osteoarthritis and is better assessed with
315 radiographs over MRI. *Knee Surg. Sports Traumatol. Arthrosc. Off. J. ESSKA.* 2016
316 Jul;24(7):2244–2251. doi:10.1007/s00167-015-3587-7
- 317 39. Van Drongelen S, Van der Woude LH, Janssen TW, Angenot EL, Chadwick EK, Veeger
318 DH. Mechanical load on the upper extremity during wheelchair activities. *Arch. Phys.*
319 *Med. Rehabil.* 2005 Jun;86(6):1214–1220. doi:10.1016/j.apmr.2004.09.023
- 320 40. Viehöfer AF, Gerber C, Favre P, Bachmann E, Snedeker JG. A larger critical shoulder
321 angle requires more rotator cuff activity to preserve joint stability. *J. Orthop. Res. Off.*
322 *Publ. Orthop. Res. Soc.* 2016;34(6):961–968. doi:10.1002/jor.23104
- 323 41. Viehöfer AF, Gerber C, Favre P, Bachmann E, Snedeker JG. A larger critical shoulder
324 angle requires more rotator cuff activity to preserve joint stability. *J. Orthop. Res.*
325 2016;34(6):961–968.
- 326 42. Viehöfer AF, Snedeker JG, Baumgartner D, Gerber C. Glenohumeral joint reaction
327 forces increase with critical shoulder angles representative of osteoarthritis-A
328 biomechanical analysis. *J. Orthop. Res. Off. Publ. Orthop. Res. Soc.* 2016;34(6):1047–
329 1052. doi:10.1002/jor.23122
- 330 43. Watanabe A, Ono Q, Nishigami T, Hirooka T, Machida H. Differences in Risk Factors
331 for Rotator Cuff Tears between Elderly Patients and Young Patients. *Acta Med.*
332 *Okayama.* 2018 Feb;72(1):67–72. doi:10.18926/AMO/55665
- 333 44. Westerhoff P, Graichen F, Bender A, Halder A, Beier A, Rohlmann A, et al. In vivo
334 measurement of shoulder joint loads during activities of daily living. *J. Biomech.* 2009
335 Aug 25;42(12):1840–1849. doi:10.1016/j.jbiomech.2009.05.035
- 336 45. Wu G, van der Helm FCT, Veeger HEJD, Makhsous M, Van Roy P, Anglin C, et al. ISB
337 recommendation on definitions of joint coordinate systems of various joints for the

338 reporting of human joint motion--Part II: shoulder, elbow, wrist and hand. J. Biomech.
339 2005 May;38(5):981–992. <https://doi.org/10.1016/j.jbiomech.2004.05.042>

340

341 **Figure 1. Illustration of the UKSNM.**

342

343 **Figure 2.** Statistically significant changes in joint forces due to changed CSA. These
344 conditions that showed a main effect in the ANOVA analysis. The error bars indicate standard
345 deviation.

346

347 **Figure 3.** Vector plot of the maximum joint reaction forces in the medio-lateral and superior-
348 inferior direction for the three CSA angles. The integrated shear force in the superior-inferior
349 direction (SI) was significantly larger for increased CSA compared to normal CSA. The
350 reduced CSA showed significantly higher compressive forces (CF) compared to normal CSA
351 and increased CSA.

352

353 **Table 1.** Repeated measures ANOVA. Shown are the main effects for the separate force
354 directions (AP, SI, CF), and the pairwise comparisons for the force directions that
355 significantly differed between CSA conditions. Nor = Normal CSA (33°), Red = Reduced
356 CSA (28°), Inc = Increased CSA (38°).

357

358

Table 1. Repeated measures ANOVA. Shown are the main effects for the separate force directions (AP, SI, CF), and the pairwise comparisons for the force directions that significantly differed between CSA conditions. Nor = Normal CSA (33°), Red = Reduced CSA (28°), Inc = Increased CSA (38°).

Variable	Mauchly's sphericity	Main effect		Pairwise CSA		
				Nor-Red	Nor- Inc	Red- Inc
integrated AP shear	$\chi^2(2)=9.5$, p<.01, $\epsilon=.52$	p = 0.598				
max AP shear	$\chi^2(2)=11.6$, p<.01, $\epsilon=.51$	p = 0.595				
integrated SI shear		p = 0.026	F(2,10) = 5.34		p = 0.044	
max SI shear	$\chi^2(2)=[]$, p<.05, $\epsilon=.55$	p = 0.068				
integrated CF	$\chi^2(2)=6.23$, p<.05, $\epsilon=.56$	p = 0.003	F(1.1, 5.6)=24.55	p = 0.001		p = 0.01
max CF	$\chi^2(2)=6.84$, p<.05, $\epsilon=.55$	p = 0.009	F (2,10) =14.97	p = 0.008		p = 0.03





