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Acromioclavicular joint biomechanics: a systematic review

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Background: The aim of this systematic review was to investigate the available literature on the biomechanical characteristics of the acromioclavicular (AC) joint to identify trends in translational parameters and contributions of the various ligamentous structures supporting the joint.
Methods: A comprehensive literature search was conducted in the Web of Science, Scopus, and PubMed databases until October 2023 to identify articles reporting on the biomechanical characteristics of the AC joint. Non cadaveric or projects involving reconstruction were excluded. Consistent parameters evaluated were anterior, posterior, superior, and inferior translation. The data were extracted from the included articles and summarized.
Results: 11 biomechanical papers were reviewed from six different countries — United States ($n = 6$), France ($n = 1$), Austria ($n = 1$), Thailand ($n = 1$), United Kingdom ($n = 1$), and Japan ($n = 1$). The total number of specimens included across the reviewed papers was 141. All 11 papers reported the data on an intact model (coracoclavicular and AC ligaments intact). Seven papers assessed the translational results of the AC sectioned condition, finding a greater increase in anterior-posterior (AP) laxity relative to SI. 3 papers evaluated coracoclavicular ligament sectioning, finding increased superior-inferior laxity relative to AP. Only one study involved ligament sectioning isolating the anterior-inferior bundle of the AC joint.
Conclusion: This review highlights the key AP and superior-inferior constraints of both the intact and ligament sectioned AC joint. The inconsistency of AC joint testing parameters and the lack of thorough translation studies indicate a necessity for increased attention in the overall assessment of shoulder stability to close the gap in the foundational biomechanical research.

The acromioclavicular (AC) joint is a highly mobile joint that provides essential stability and mobility to the shoulder girdle, enabling overhead arm movement.[12,17,27,29] The AC joint is stabilized by several ligaments, the AC ligament which comprises the superior, inferior, anterior, and posterior bundles, and the coracoclavicular (CC) ligaments (conoid and trapezoid ligaments).[33] Traditionally, the CC ligaments have been thought of as the main stabilizers of the AC joint, for providing superior and inferior stability.[8,11,21] The AC ligament bundles have been distinctly described in the literature as containing a thicker, more stabilizing superior-posterior bundle, and a thinner more varied anterior-inferior (AI) bundle.[19,25] The anatomy of the AC joint has been thoroughly studied,[2,13,16] however a detailed and comprehensive biomechanical understanding of the AC joint is lacking in the literature.

The function and movement of the AC joint is of importance as this joint is involved in approximately 40% of shoulder injuries and 10% of all injuries in collision sports such as football, lacrosse, and ice hockey.[32,34] Surprisingly, with over 150 different AC joint repair techniques, there is a lack of a gold standard.[1,3,4,24] A comprehensive understanding of the AC joint biomechanics is necessary for surgeons to appropriately design a repair or reconstruction that addresses the stability characteristics of the AC and CC ligaments.

The aim of this systematic review was to investigate the available literature on the biomechanical characteristics of the AC joint to identify translational contributions of the various ligamentous structures supporting the joint.

Methods

Identification and selection of articles

To identify studies reporting the biomechanical characteristics of the AC joint, Web of Science, Scopus, and PubMed databases were searched from inception to October 2023.

Institutional review board approval was not applicable for this systematic review.

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The search strategy was developed by one reviewer (G.M.F.) by consulting the Peer Review of Electronic Search Strategies criteria.[23]

The following search strategy was used: (AC OR AC ligament OR AC joint OR AC ligament OR CC ligament OR CC OR CC ligament) AND (biomechanic OR stability OR rotation OR translation OR kinematic) AND (section OR cut OR isolate OR intact).

Study selection was performed by two reviewers (G.M.F., R.S.B.). Titles and abstracts were subjected to independent screening. Full articles were retrieved when titles and abstracts were potentially relevant based on the inclusion criteria. The references of selected articles were reviewed for further studies. Subsequently, the identified records from the searches were compiled into a database, and duplicates were effectively eliminated utilizing EndNote (X9; Clarivate Analytics, Philadelphia, PA, USA). Studies were eligible for inclusion if they were: 1) English language, 2) human cadaveric, and 3) a biomechanical characterization of the AC joint. Studies were excluded if they: 1) used shoulder girdle movement rather than loading to displace, 2) resected the clavicle, 3) involved a reconstruction or surgical outcome, or 4) did not include translation data in the anterior-posterior (AP) or superior-inferior (SI) planes.

Data collection

Data extraction was performed by one reviewer (G.M.F.). Regarding the data points of interest, the corresponding values were extracted and collected for future analysis in an Excel spreadsheet (Microsoft Corp., Redmond, WA, USA). Outcomes of interest included: number of specimens tested, device/setup used for displacement, compression applied, translation load applied, displacement direction (superior, inferior, anterior, and posterior), and translation amount. While some studies reported in-situ force of ligaments, percent contribution of a ligament, or load to failure data, these outcomes were not collected. If a study did not explicitly mention the presence of an outcome, it was assumed the characteristic was not present in that test. The senior author monitored correctness of data extraction, resolved differences between the investigators regarding study eligibility and supervised the process (T.Q.L.). This review was reported in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses.[28] A meta-analysis was not performed due to the heterogeneity of compression and translation loads, testing protocol, and specimen set-up.

Results

Literature search

Overall, 902 records were identified through PubMed, Web of Science, and Scopus databases. After screening 902 abstracts, 881 were excluded for not being in the field of interest, being noncadaveric, or being a nonbiomechanical study. 21 were selected, and their full text was retrieved. No additional records were found screening the references of these articles. The remaining exclusions were for the reasons pertaining to an AC reconstruction (n = 4), using shoulder girdle movement rather than independent clavicle or acromial translation loading (n = 3), and nonsimilar methods of collecting translation data (n = 3). Eleven articles were included in the qualitative analysis.[6,8,9,11,15,18-22,31] The flowchart of the literature search is described in Figure 1.

Quality assessment (Quality Appraisal for Cadaveric Studies scale)

The quality assessment of the studies included in this systematic review was critically appraised using the Quality Appraisal for Cadaveric Studies scale (Table I).[37] The scale consists of a checklist encompassing 13 items. Each is to be scored with either 0 (no/not stated) or 1 (yes/present) point. Points are only assigned if a criterion is met without any doubt. To enhance comparability of results, quality rating is expressed as a percentage value (reached score/maximum score (%)). The rest of the scale items were generally assessed as good quality. The overall quality appraisal of the included studies was 9.8 points out of 13.

Qualitative analysis

After screening the selected databases, eleven articles describing the biomechanical characteristics of the intact or ligament sectioned AC joint were included in the qualitative analysis (Table II). Studies used were published over the span of 36 years (from 1986 to 2022). The total number of cadaveric AC joints these studies used is 141. The studies used in this review came from six different countries — United States (n = 6),[6,8,9,11,18,22] France (n = 1),[31] Austria (n = 1),[15] Thailand (n = 1),[19] United Kingdom (n = 1),[21] and Japan (n = 1).[20]

Biomechanical testing

The eleven biomechanical studies selected examined translation through several different methods — using a tracking device to measure translation while externally applying load (n = 5),[6,8,9,19,20] using a load-displacement testing machine to track force applied and displacement (n = 4),[11,18,21,22] using ultrasound to measure displacement and a pressure sensor to apply load (n = 1),[15] and lastly using X-ray and optical tracking to measure displacement (n = 1).[31] Nine of the studies reviewed performed testing on cadaveric shoulders with the clavicle and scapula dissected of all soft tissue besides the ligaments of interest while three studies used a corpse or cadaver torso.[15,20,31]

Compression results

Compression across the AC joint allows for contact between the distal end of the clavicle and the acromion. Three studies used compression loads across the AC joint during translational testing.[6,8,9] In Debski et al and Costic et al compression was achieved by a robotic manipulator in their testing system.[6,9] In Dawson et al compression was created by applying load to an off-balancing lever arm from the authors' custom testing system.[8] While Debski et al only used a 10 N AC joint compression load, Costic et al and Dawson et al used two or more AC joint compression loads. Costic et al found that 70 N AC joint compression decreased translation significantly in the posterior direction. Dawson et al, comparing 10 N, 20 N, and 30 N compression, found that increased AC joint compressive load decreased translation, especially in AP rather than SI planes. Figure 2 describes the loading planes and compression direction for the AC joint.

Loading results

Several of the studies reported load-controlled experiments and reported the translation (n = 7).[6,8,9,18,19,21,22] Only Dawson et al used more than one load to report load dependent effects showing that the greater translational load resulted in increased translation in both the AP and SI planes.[8] The loads applied in Dawson et al were 10 N and 15 N while several of the other studies evaluated used greater loads of 50 N or 70 N. The translation results of various loads applied are not comparable across studies as the methodology is varied.

Intact ligaments: anterior-posterior translation

The studies examined in this review measured either both AP and superior-inferior translation (n = 8),[6,8,9,11,19,21,22,31] only AP translation (n = 2),[15,18] or only superior translation (n = 1).[20]

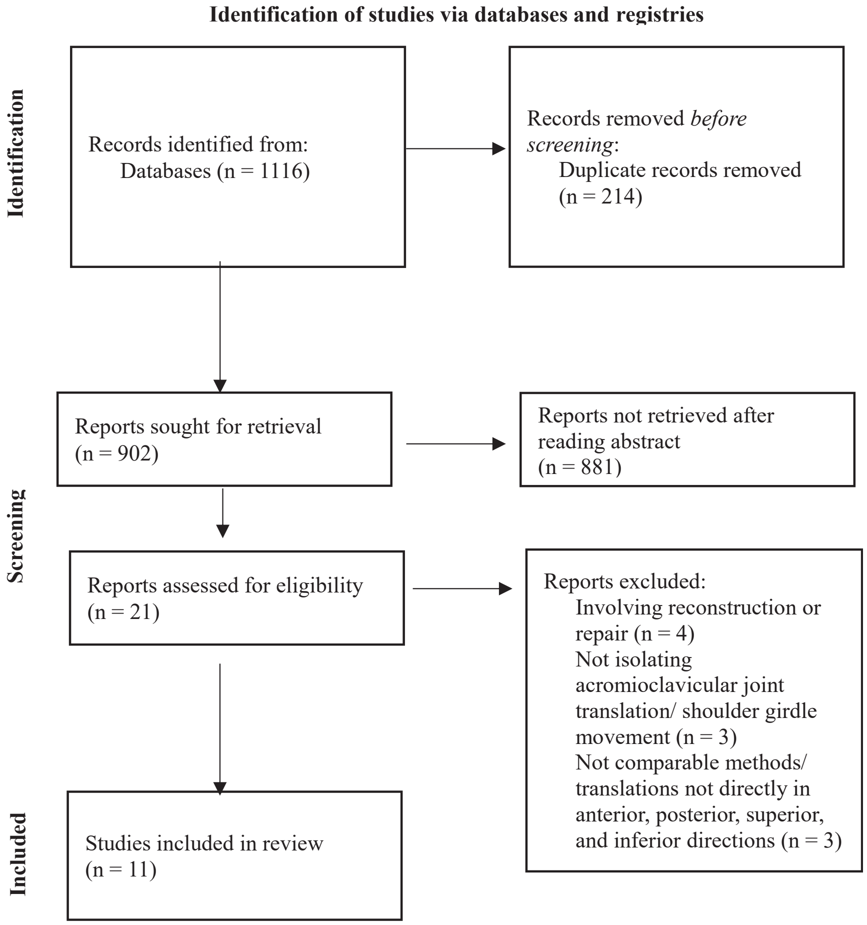

Figure 1 Prisma study selection flow diagram.

Four studies reported AP translation with similar methods by testing translation with a Universal Force Sensor testing system, MicroScribe digitizer (Revware, Raleigh, NC, USA), or electromagnetic device while applying an external load.[6,8,9,20] In Costic et al, the authors found the average translation for the intact AC joint to be 5.0 ± 0.9 mm in the anterior direction and 6.6 ± 2.5 mm in the posterior directions with 10 N compression and 70 N of loading.[6] Dawson et al, found the AP translation to be 6.7 ± 1.1 mm with 10 N compression and 10 N load and 8.0 ± 1.1 mm with 10 N compression and 15 N load.[8] Debski et al, measured 6.4 mm anterior translation and 3.6 mm posterior translation with 10 N compression and 70 N loading.[9] Lastly, Kurata et al, 2022 found 3.7 ± 1.1 mm posterior translation with 70 N loading and no reported compression.[20]

Four studies reported AP translation by load-displacement testing on a materials-testing machine.[11,18,21,22] Fukuda et al, reports the AP displacement as 8.4 ± 2.8 mm during the steepest increase in load (100 N max).[11] Klimkiewicz et al describes the posterior translation as 9.2 ± 2.6 mm with 70 N load.[18] Lee et al describes the anterior displacement as 7.9 ± 4.3 mm and posterior displacement as 7.2 ± 2.6 mm with 50 N loading.[21] Lastly, Mazzocca et al found anterior displacement to be 9.0 ± 4.4 mm and posterior displacement to be 8.0 ± 4.0 with 25 N loading for 10 cycles.[22]

Hobusch et al used ultrasound imaging to measure the joint displacement while applying pressure with a force sensing restrictor at 100 kg•ohm.[15] This paper found the average AP translation for an intact AC joint to be 1.3 ± 0.9 mm. Rochcongar et al used X-ray and optical tracking to measure displacement while applying a load by manually pulling on the clavicle.[31] The anterior translation was found to be 7.5 mm with a confidence interval of [5.2-9.8], with manual pulling.

Intact ligaments: superior-inferior translation

Five studies reported superior-inferior translation with similar methods of tracking translation with a Universal Force Sensor testing system, MicroScribe digitizer, or electromagnetic device and applying an external load.[6,8,9,19,20] Costic et al reported the superior translation during 10 N compression and 70 N loading to be 3.6 ± 1.6 mm.[6] Dawson et al reported the combined superior-inferior translation to be 4.1 ± 0.4 mm with 10 N compression and 10 N loading and 5.3 ± 0.4 mm with 10 N compression and 15 N loading.[8] Debski et al reported the superior translation to be 1.6 mm with 10 N compression and 70 N loading.[9] Kurata et al 2022 reported the unloaded intact superior translation to be 0 mm while Kurata et al 2021 reported the 70 N loaded superior translation to be 3.7 ± 1.0 mm.[19,20]

Three studies reported superior-inferior translation by load-displacement testing on a materials-testing machine.[11,21,22] Fukuda et al reported 9.7 ± 3.6 mm superior-inferior translation during a steep increase in force on the material-testing machine.[11] Mazzocca et al reported 5.8 ± 3.0 mm superior translation and 3.6 ± 2.6 mm inferior translation with 50 N loading.[22] Lee et al reported superior translation of 5.8 ± 3.0 mm and inferior translation of 3.6 ± 2.6 mm with 50 N of load.[21]

Table I
Quality appraisal for Cadaveric Studies scale (QUACS scale).

Included studies	1	2	3	4	5	6	7	8	9	10	11	12	13	Total score	Maximum score %
Costic et al[6]	1	0	1	1	0	0	1	1	1	0	1	1	0	8	61.5%
Dawson et al[8]	1	1	1	0	0	0	1	1	1	0	1	1	0	8	61.5%
Debski et al[9]	1	1	1	1	0	0	1	1	1	1	1	1	0	10	76.9%
Fukuda et al[11]	1	1	1	1	0	0	1	1	1	1	1	1	0	10	76.9%
Hobush et al[15]	1	1	1	1	1	1	1	1	1	1	1	1	1	13	100%
Klimkiewicz et al[18]	1	1	1	0	0	0	1	1	1	1	1	1	1	10	76.9%
Kurata et al 2021[19]	1	1	1	0	0	0	1	1	1	0	1	1	1	9	69.2%
Kurata et al 2022[20]	1	1	1	0	0	0	1	1	1	1	1	1	1	10	76.9%
Lee et al[21]	1	1	1	0	0	0	1	1	1	1	1	1	1	10	76.9%
Mazzocca et al[22]	1	1	1	1	0	0	1	1	1	1	1	1	1	11	84.6%
Rochcongar et al[31]	1	1	1	0	0	0	1	1	1	1	1	1	0	9	69.2%
Average														9.8	75.5%

QUACS, Quality Appraisal for Cadaveric Studies scale.
Items of QUACS scale: 1. Objective stated; 2. Basic information about sample is included; 3. Applied methods are described comprehensibly; 4. Study reports condition of the examined specimens; 5. Education of dissecting researchers is stated; 6. Findings are observed by more than one researcher; 7. Results presented thoroughly and precise; 8. Statistical methods appropriate; 9. Details about consistency of findings are given; 10. Photographs of the observations are included; 11. Study is discussed within the context of the current evidence; 12. Clinical implications of the results are discussed; 13. Limitations of the study are addressed.

One study, Rochcongar et al, reported 8.1 mm [6.1-10.2] superior displacement using an X-ray and optical tracking system with applied manual pulling.[31]

Ligament sectioning

All eleven studies used in this systematic review reported intact translation data, in which neither the CC ligaments (conoid or trapezoid) nor any bundle of the AC ligament was sectioned (Fig. 3). Seven of the included studies reported AC ligament sectioned translation data, in which only the CC ligaments were intact.[6,8,9,15,19,20,31] Four studies were involved with sectioning different permutations of the CC ligaments, while the AC ligament was intact.[8,19,20,22] Three papers report both the entire AC and CC ligaments sectioned.[15,20,31] These three studies performed their kinematic testing in intact upper extremities which allowed for testing the translation of both sectioned AC and CC ligaments while leaving supporting soft tissues intact. Lastly, only in Kurata et al 2021 was the AI bundle of AC ligament sectioned, with the CC ligaments intact.[19]

Starting with the studies reporting translation data in AC ligament sectioned, CC ligaments (conoid and trapezoid) intact; Costic et al found the superior, anterior, and posterior translation with 10 N compression and 70 N loading to be 5.3 ± 2.9 mm, 7.5 ± 3.3 mm and 12.7 ± 6.1 mm, which increased from intact by 1.7 mm, 2.5 mm, and 6.1 mm respectively.[6] Dawson et al found that with the AC ligament sectioned the combined AP translation for 10 N compression and 10 N loading was 15.4 ± 1.2 mm and for SI 5.8 ± 0.5 mm, which increased by 8.7 mm and 1.7 mm from intact, respectively.[8] Debski et al was the only study in this analysis that reported the change in translation from intact. The authors found that after the AC ligament was sectioned, the superior, anterior, and posterior translation increased by 1.6 mm, 6.4 mm, and 3.6 mm respectively with 10 N compression and 70 N loading.[9] Hobusch et al reported the AC ligament sectioned condition resulted in 1.4 ± 1.2 mm of translation in the combined AP plane, 0.1 mm increase from intact with the same applied load of 100 kg•ohm.[15] Kurata et al 2022 reported the AC ligament sectioned condition translated 0.3 ± 0.7 mm in the superior direction by manual pulling, 0.3 mm increase from intact.[20] Kurata et al 2021 reported the AC ligament sectioned condition translated 8.3 ± 1.6 mm superiorly and 5.6 ± 2.0 mm posteriorly and increased from intact by 4.6 mm and 1.9 mm respectively with the same 70 N load.[19] Lastly in Rochcongar et al the authors measured the AC ligament sectioned condition to have 11.2 mm [7.7-14.8] translation superiorly and 9.0 mm [7.0-11.0] anteriorly, which increased from intact by 3.1 mm and 1.5 mm respectively.[31]

Dawson et al isolated the AC ligament by sectioning both CC ligaments in which the translation with 10 N compression and 10 N loading was measured to be 8.0 ± 1.2 mm in the AP and 8.0 ± 0.5 mm in SI directions, which increased by 1.3 mm and 3.9 mm from intact respectively.[8] In both Kurata studies, the trapezoid ligament was sectioned following the AC ligament sectioning to isolate the contributions of the trapezoid ligament. In Kurata et al 2022, the AC and trapezoid ligaments sectioned group measured a 6.5 ± 1.1 mm increase in superior translation from intact.[20] In Kurata et al 2021 the AC and trapezoid ligaments sectioned group measured 9.5 ± 1.5 mm of superior translation and 9.8 ± 3.0 mm of posterior translation, which was a 5.8 mm and a 6.1 mm increase from intact respectively.[19] These results differ in magnitude due to set up method in which Kurata et al 2022 used upper extremities with musculature intact while Kurata et al 2021 used dissected and isolated AC joints. Lastly, Mazzocca et al tested the biomechanics of the conoid and trapezoid ligaments with the AC ligament intact. The authors found that with the conoid ligament sectioned, the superior, anterior, and posterior translations were 10.0 ± 3.5 mm, 11.1 ± 5.4 mm and 19.0 ± 8.7 mm, which were a 4.7 mm, 2.1 mm and 11.0 mm and increase from intact respectively. And for the condition in which the trapezoid ligament was sectioned, the superior, anterior, and posterior translations were 6.7 ± 3.8 mm, 11.6 ± 4.5 mm and 17.8 ± 10.9 mm, which were a 1.4 mm, 2.6 mm and 9.8 mm increase from intact respectively.[22]

In three of the studies, the entire AC and CC ligaments were sectioned.[15,20,31] Only studies that used intact upper extremities were able to perform these measurements as the clavicle would be too unstable to load in a dissected model. Hobusch et al found that with both AC and CC ligaments sectioned, the AP translation was 1.9 ± 1.3 mm, which was a 0.6 mm increase from intact.[15] In Kurata et al 2022, the superior translation in an AC and CC ligament sectioned model was a 10.7 ± 1.4 mm increase from intact.[20] Lastly in Rochcongar et al with both AC and CC ligaments sectioned the translation was 16.5 mm [9.7-23.8] superiorly and 12.4 mm [9.1-15.6] anteriorly, which increased from intact by 8.4 mm and 4.9 mm respectively.[31]

Lastly, the only study that evaluated the effects of sectioning the AI bundle of the AC ligament was Kurata et al 2021. In the condition in which only the AI bundle was sectioned, the clavicle translated 3.8 ± 1.1 mm superiorly and 3.7 ± 1.1 mm posteriorly, which increased from intact by 0.1 mm and 0.0 mm respectively.[19]

Table II
Qualitative comparison of acromioclavicular joint biomechanical studies.

Author & year	Study design	No. of specimens	Ligament conditions	Compression load (N)	Loading (N)	Translation measured	Main results
Costic et al, 2003[6]	UFS	12	AC and CC intact	10 N	70 N	S, P, A	Adding compression decreased P trans. for intact
			AC cut	70 N			Adding compression decreased P and S trans. for AC cut
Dawson et al, 2009[8]	External loading & MicroScribe digitizer	12	AC and CC intact	10 N	10 N	AP, SI	Increase in AP trans. with AC cut
			AC cut CC cut	20 N 30 N	15 N		Increase in SI with CC cut
Debski et al, 2001[9]	UFS	11	AC and CC intact AC cut	10 N	70 N	S, P, A	Increase in A and P trans. with AC cut
Fukuda et al, 1986[11]	MTS	12	AC and CC intact	NA	100 N max	AP, SI	No sig difference in intact AC AP vs. SI displacement
Hobusch et al, 2019[15]	Ultrasound	20	AC and CC intact AC cut AC and CC cut	NA	100 kg ohm with Pressure sensor	AP	Cutting AC and especially after cutting CC, increase in AP trans.
Klimkiewicz et al, 1999[18]	MTS	6	AC and CC intact A bundle cut P bundle cut I bundle cut S bundle cut	NA	70 N	P	Cutting superior and posterior bundles results in the most P displacement
Kurata et al, 2022[19]	STAR	6	AC and CC intact	NA	Manual pulling	S	Cutting trapezoid and then cutting all CC resulting in more S displacement
			AC cut AC and trapezoid cut AC, trapezoid, and conoid cut				Only CC ligs cut resulted in distal clavicle “overriding”
Kurata et al, 2021[20]	STAR	6	AC and CC intact	NA	70 N	S, P	Cutting AI did not increase S or P posterior trans.
			AI bundle cut AC cut AC and trapezoid cut				Cutting all of AC and cutting trap. increased S and P trans.
Lee et al, 2020[21]	UFS	16	AC and CC intact	NA	50 N	S, P, A, I	AC and CC intact specimen has more A and P laxity than S and I
Mazzocca et al, 2008[11]	MTS	30	AC and CC intact Conoid cut Trapezoid cut	NA	25 N	S, P, A	Cutting conoid resulted in more P and S trans. during load displacement testing than trapezoid
Rochcongar et al, 2012[31]	X-ray	10	AC and CC intact AC cut AC and CC cut	NA	Manual pulling	S, AP	Cutting AC alone did not sig. increase S trans. but did increase AP trans.

UFS, Universal Force-Moment Sensor; *MTS*, material testing machine; *STAR*, electromagnetic tracking device; *AC*, acromioclavicular ligament; *CC*, coracoclavicular ligaments (conoid and trapezoid); *AI*, anterior-inferior ligament bundle; *S*, superior; *P*, posterior; *A*, anterior; *I*, inferior; *SI*, combined superior-inferior; *AP*, combined anterior-posterior. Data collected from 11 included studies.

Discussion

This systematic review investigated the biomechanical characteristics of the AC joint. Overall, the AC literature has explored biomechanics through cadaveric studies, clinical trials, computational modeling, and reviews that are focused on the stability of repairs and reconstructions.

Testing systems

To summarize, the 11 studies included used a variety of methods to measure translation including robotic testing systems, MicroScribe or electromagnetic tracking devices (n = 5),[6,8,9,19,20] materials-testing machines (n = 4),[11,18,21,22] ultrasound/pressure sensors (n = 1),[15] and X-ray optical tracking systems (n = 1).[31] Each of these testing protocols has advantages and disadvantages. The use of an external loading and manual digitizing like in Dawson et al allowed for 6 degrees of freedom of the joint in the authors' custom testing system, and 3 degrees of freedom with rotation locked.[8] Load displacement testing, like used in Klimkiewicz et al, allows for higher testing loads and multiple loading cycles which can analyze tensile ligamentous properties.[18] However, with a uniaxial materials testing system, only one plane of translation can be measured without repositioning the specimen.

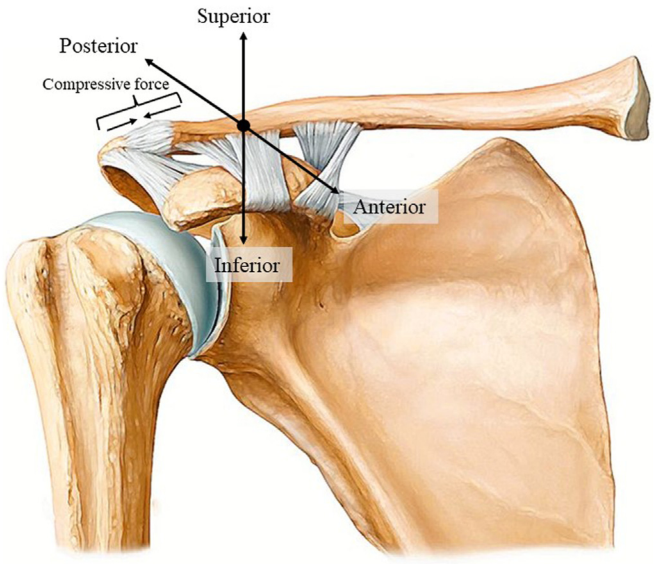

Figure 2 Depiction of the four planes of translation, anterior, posterior, superior, and inferior, for distal clavicle loading. Direction of compression force applied between the acromion and clavicle.

Effects of compression and loading

The findings from Debski et al and Costic et al demonstrating that increased compression across the AC joint significantly decreased AP translations but not superior-inferior translations, could be related to the bony morphology of this joint.[6,9] Colegate-Stone et al describes the three main three-dimensional morphological groups of the AC joint — flat, oblique, and curved.[5] Similarly, in Crönlein et al, the AC joint congruency was evaluated and demonstrated that three groups exist, overhanging acromion, neutral shaped, and overhanging clavicle.[7] Other studies have observed the diversity of the AC joint, but none have adequately connected translation properties to the various morphological types.[10,30] The compression results from Debski and Costic et al showed that the superior-inferior plane does not experience the same limitations as the AP plane with increasing compression. The noncongruence of AC joints could explain the seemingly disproportional effect of increasing compression on translation. Further biomechanical testing is required to understand the bony morphology and soft tissue restrictions of translation.

The papers analyzed in this review applied various translation loads to the AC joint-70 N (n = 4),[6,9,18,19] 50 N (n = 1),[21] 15 N (n = 1),[8] and 10 N (n = 1).[8] However, the magnitudes of translation measured in these studies did not proportionately reflect the loads used. Looking solely at Dawson et al, a 5 N increase in load increased AP translation in all ligament sectioned conditions.[8] However, comparing these results to studies that applied a 70 N load, the translations are not reasonably greater in magnitude.[6,9,18,19] This reveals the dependence of loading on the specimen set-up and study methodology. Due to the variation in how the selected studies designed their loading protocol and the way in which the data were collected, the effects of loading and compression cannot be compared across the included studies. Only within a study that applied multiple loads, like Dawson et al, can the effects of load be evaluated.

Biomechanical characteristics of the intact AC joint

The studies evaluated in this review all tested an intact AC joint, however the mode of measuring the planes of translations varied. For example, Dawson et al, Fukuda et al, and Hobusch et al described the total AP or superior-inferior translation whereas the remainder of the studies isolated superior, posterior, inferior, and anterior translation.[8,11,15] It is an important consideration for biomechanical studies that measuring the total translation (AP vs. isolated anterior and isolated posterior) may be more accurate as it does not rely on finding a repeatable anatomic neutral position. However, measuring the isolated planes of translation enables distinct characterizations of the AC and CC ligaments. Overall, regardless of whether the studies reported total translation or separate, AP translation was greater than superior-inferior translation. This describes that the intact AC joint experiences greater AP laxity than SI laxity, which is an important stability finding that should be considered in anatomic AC repairs and reconstructions.

Lastly, only one study reported isolated inferior translations.[21] The biomechanical AC joint literature is generally more interested in superior and posterior translations as these are the planes that the clavicle is directed in most AC injuries. However, in the most extreme case, Rockwood grade VI, the clavicle is depressed under the acromion in the inferior direction.[35] Further biomechanical studies are needed to evaluate this plane of motion as it is important to understand the ligamentous contributions around grade VI AC injury.

Ligament sectioning

The studies involved in this review looked at the effects of the isolated AC ligament, CC ligaments, and even the AI bundle of the AC ligament. In the seven studies that investigated translation following AC ligament sectioning, leaving both CC ligaments intact, most found an increase in the AP translation.[6,8,9,15,19,20,31] The CC ligaments serve as an inferior tether on the clavicle; however, they do not have as strong of a stabilizing contribution in the anterior and posterior planes. In Dawson et al sectioning the CC ligaments with an intact AC ligament generally showed an increase in SI translation from the intact condition while sectioning the AC ligaments with the CC ligaments intact did not demonstrate a significant increase in SI but did show an increase in AP translation.[8] While these results point to the discussion that the AC ligament is solely responsible for AP stability and the CC ligaments are responsible for SI stability, this is a generalization. As seen in most of the studies evaluated, sectioning either the AC or CC ligaments will increase the translation in both AP and SI planes. It is important for surgeons to consider the need for both AP and SI stability when reconstructing the AC joint. While most AC joint repairs focus on addressing SI stability by involving a tether or screw from the clavicle to the coracoid,[1] more rigidity may result in less arm abduction as the AC joint's laxity in the AP and SI planes allow for full overhead motion.[12,17,27,29] Designing the right AC joint repair or reconstruction is dependent on recreating the AC ligament and CC ligaments kinematic properties. In Nolte et al, the authors described that to date there has been an emphasis on restoring the CC ligament complex.[26] The authors emphasized that recent research, describing the importance of the AC ligaments, should encourage repairs that aim at also addressing the AC ligaments contributions to joint stability.

Only one paper was concerned with sectioning the anterior-inferior bundle of the AC ligament, Kurata et al 2021.[19] It was described in Nakazawa et al, that there are two distinctly acting bundles of the AC ligament, the thicker and stabilizing SP bundle, and the varied and sometimes nonexisting AI bundle.[25] Lee et al found that sectioning the AI bundle only increased translation by 0.1 mm in the superior direction but no difference in the posterior direction.[21] However, in the next condition of this study, sectioning the rest of the AC ligament, the SP bundle, resulted in an increase in

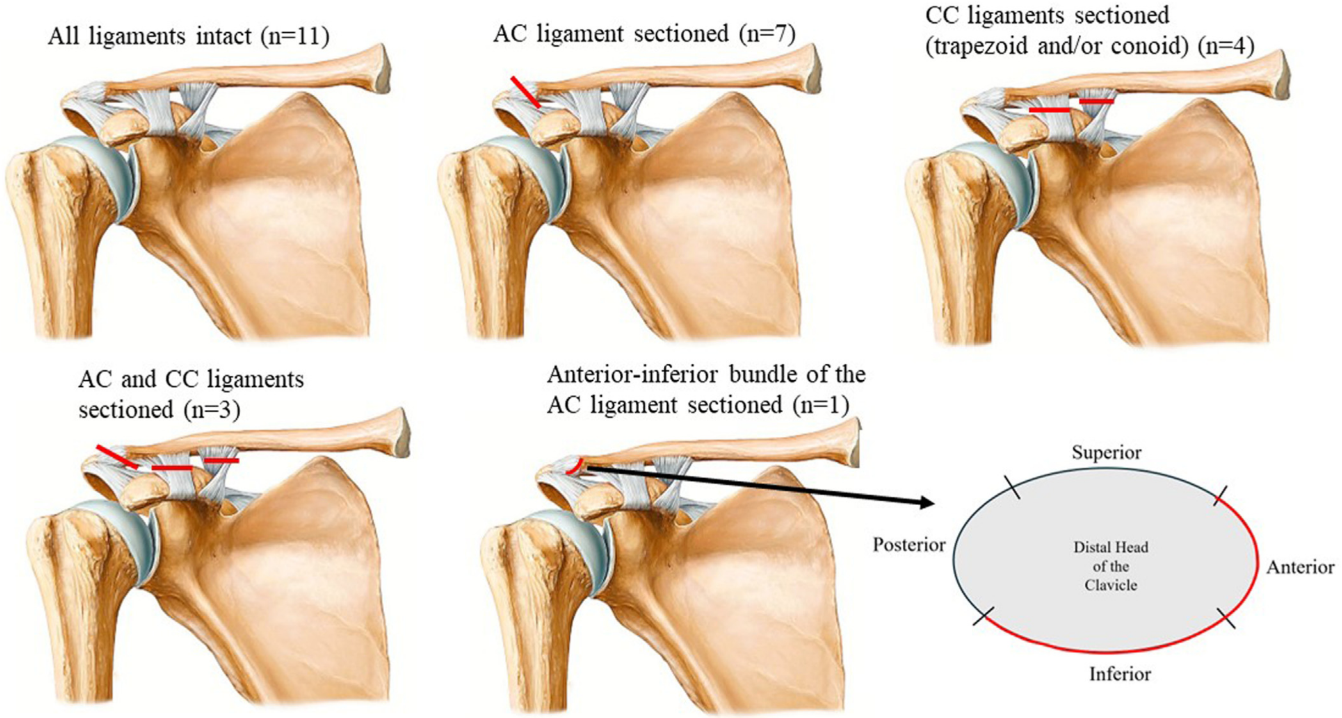

Figure 3 Depiction of location of ligament sectioning for the included studies. *AC*, acromioclavicular; *CC*, coracoclavicular.

superior and posterior translation(cite). In a computerized model, Velasquez Garcia et al evaluated the AI bundle of the AC joint.[36] Conclusions from this study were that the AI bundle contributes more to joint constraint while the SP bundle aids to avoid extreme anterior and superior translations. Beyond the above-mentioned studies, there is scarce literature on the contributions of the SP and AI bundles to AC joint stability.

While not comparable to the other eight studies evaluated in this review, there is great value in performing upper extremity AC joint research like in Hobusch et al, Kurata et al 2022, and Rochcongar et al[15,20,31] While it is necessary for biomechanic studies to show the foundational properties of the isolated AC joint, these three studies demonstrate the next step of involving upper extremity degrees of freedom in their testing setup. Involving the shoulder girdle acknowledges the complexity of the AC joint beyond ligamentous support.

Study limitations

This systematic review has several limitations. First, due to the limited literature and wide heterogeneity on the topic a direct comparison across studies was not able to be performed. This qualitative evaluation on the existing literature on AC joint biomechanics will hopefully inform the readership on a need to continue researching the foundational biomechanics of this joint and build on the methods of the mentioned studies to define a gold-standard of how this joint should be studied. Additionally, this review could not thoroughly evaluate the biomechanics as some parameters were left out. The in-situ force of ligaments, rotational properties of the joint, and material properties through load to failure testing were not included due to lack of reporting and variability of the data. This review is limited in its evaluation of this joint as it only discusses translation. Future research should include additional descriptive parameters of the AC joint. Lastly, the quality of these papers limits the impact of this review as four of the included articles date from 2003 or earlier. While biomechanical research is evolving exponentially in other areas of the body, the AC joint does not boast the same growth. As with any cadaveric study, the AC joint degrades with age and use.[14] Thus, evaluating cadaveric rather than clinical biomechanical papers comes with its own limitations on generalizability.

Conclusion

This review highlights the key AP and superior-inferior constraints of both the intact and ligament sectioned AC joint. The inconsistency of AC joint testing parameters and the lack of studies whose primary outcome is translation data, points to the necessity to close the gap in foundational biomechanical research as the AC joint is an important part of shoulder stability.

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