



Three-dimensional kinematics in patients with anterior shoulder instability – A systematic review with *meta*-analysis

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ABSTRACT

Anterior Shoulder Instability (ASI) is a common orthopedic condition often resulting in altered shoulder kinematics. Understanding the biomechanics of the unstable shoulder is critical to determine the most appropriate treatment. This study aims to conduct the first systematic review and *meta*-analysis of three-dimensional (3D) shoulder kinematic studies in ASI patients. A broad search was conducted within PubMed, Scopus, and Cochrane Library following the PRISMA guidelines. All cross-sectional or longitudinal studies with 3D motion analysis describing shoulder kinematics in patients with ASI were included. The quality of each study was assessed using the MINORS criteria. Qualitative and quantitative analyses were performed. Nine studies were included in the qualitative analysis and two in the *meta*-analysis. The qualitative review detected conflicting evidence for some parameters. The humeral head had a greater anterior translation in unstable shoulders in three of the studies analyzed, while the difference was not significant in one and another found higher variability for global humeral translation for instability patients. Two studies showed decreased rotation range of motion for unstable shoulders while one did not find significant differences. Conflicting results were also found regarding changes in scapulohumeral rhythm and scapular orientation. The *meta*-analysis indicated a greater scapulohumeral rhythm on the coronal plane for the instability group, suggesting a relatively greater contribution of motion at the glenohumeral joint compared with the scapulothoracic joint for arm abduction, and reduced glenohumeral peak angles for unstable shoulders. Identifying and quantifying kinematic changes associated with ASI are vital for refining treatment interventions.

1. Introduction

The glenohumeral joint is the most commonly dislocated joint in the body, with a shoulder dislocation incidence rate of 23 per 100,000 person-years (Leroux et al., 2014; Zacchilli & Owens, 2010), affecting especially younger males, reaching up to 98.3/100,000 person-years in this group (Leroux et al., 2014). This high dislocation rate has been attributed to the small size of the glenoid relative to the humeral head, which, by relying on soft tissue stabilization, allows an impressive range

of motion (ROM) but renders the joint highly susceptible to dislocation, especially following a traumatic event or in the presence of ligament hyperlaxity or rotator cuff malfunction (Owens et al., 2007).

Anterior Shoulder Instability (ASI) is the most common direction for shoulder dislocation, and its treatment may vary from nonoperative to surgical management (Leroux et al., 2014; Zacchilli & Owens, 2010). Surgical options may include labral repairs or anterior glenoid bone reconstruction procedures with bone grafts (Provencher et al., 2021). After treatment, outcomes rely on the structural strength and healing of

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the affected tissues. However, shoulder kinematics, resulting from the interaction of glenohumeral and scapulothoracic movements and a combination of strength, muscular coordination, and neuromuscular control, including adopted compensation strategies, are likely altered to some degree even after treatment, influencing outcomes. Therefore, identifying and quantifying the variables involved on the biomechanics of the unstable shoulder may be critical for determining the most appropriate treatment option.

Three-dimensional (3D) motion analysis tools have been developed and validated to assess the dynamic motion of the shoulder (Ludewig et al., 2009), objectively measuring shoulder segments and angular movements. In shoulder instability patients, prior studies have yielded some conflicting results in 3D shoulder kinematics, possibly underscoring methodological inconsistencies (Dellabiancia et al., 2017; Matias & Pascoal, 2006; Ernstbrunner et al., 2022). Thus, it is relevant to summarize and critically assess the existing evidence to improve the understanding of unstable shoulder biomechanics, as they provide insights into compensatory mechanisms and neuromuscular control. In abduction, for example, the unstable shoulder has been reported to demonstrate increased scapular upward rotation with a reduced glenohumeral motion (Ernstbrunner et al., 2022). Other studies have also noted higher muscle activity of the infraspinatus, middle trapezius, and posterior deltoid muscles in patients with an unstable shoulder compared to healthy subjects (Spanhove et al., 2022). These kinematic nuances should be considered when planning interventions, facilitating precise rehabilitation to restore optimal shoulder function and stability (Ludewig & Reynolds, 2009). To the best of our knowledge, there are no systematic reviews analyzing shoulder biomechanics in patients with Anterior Shoulder Instability.

Therefore, the aim of this study was to perform a systematic review and meta-analysis of the existing evidence regarding 3D shoulder kinematics in patients with ASI. We hypothesized that shoulder biomechanics, as measured by scapulohumeral rhythm, scapular motion, and glenohumeral and humerothoracic angles, would be significantly different from uninjured/stable shoulders after the first dislocation episode and even after treatment, presenting a higher scapulohumeral rhythm and decreased peak glenohumeral angles for unstable shoulders. This review will provide a better understanding of shoulder kinematics in ASI patients, which could potentially influence treatment interventions and guide prognosis.

2. Methods

2.1. Registration

Before the initial search, registration of the systematic review with the International Prospective Register of Systematic Reviews (PROSPERO) was completed (CRD42022314583).

2.2. Eligibility criteria

2.2.1. Type of studies

We included all cross-sectional or longitudinal studies with 3D motion analysis describing shoulder kinematics in patients with ASI, limited to those written in English. Studies that solely reported on clinical or radiological outcomes and those that measured ROM solely using other measurement tools, such as a goniometer, or muscle activation or strength alone were excluded. Anatomical and cadaveric studies were also excluded. No publication date or status restrictions were imposed.

2.2.2. Participants

Participants diagnosed with ASI of any age, gender, race, socioeconomic status and nonoperative treatment were included in this analysis. Studies reporting data only of ASI patients that had been submitted to surgical treatment, or that had associated conditions such as rotator cuff

tears, osteoarthritis, stiffness, any cognitive incompetency, voluntary shoulder dislocation, and any musculoskeletal, neurologic, or genetic abnormality (such as Ehlers-Danlos syndrome) other than shoulder instability were excluded.

2.2.2.1. Control group. To be included, all studies must show a comparison between the symptomatic limb and healthy participants or with the asymptomatic contralateral healthy shoulders.

2.3. Information sources

Studies were primarily identified by research in electronic databases. Secondary identification was done by expert consultation and scanning reference lists in potentially relevant articles. This search was applied to PubMed, Scopus, and Cochrane Library on September 29th, 2023. (See [Supplementary Material 1](#) for details).

2.4. Study selection

Eligibility assessment was made by two blinded investigators (FFG and TOG) following the reporting guidelines for meta-analysis Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) and using the Covidence systematic review software (Veritas Health Innovation, Melbourne, Australia) (Liberati et al., 2009). Initially, titles and abstracts were screened for inclusion and exclusion criteria. Full-length texts of the selected studies were obtained for screening purposes. Disagreements between reviewers were resolved through consensus. The references of all included articles were reviewed to ensure all relevant studies were included.

2.5. Data extraction

A data extraction form comprising pertinent information was created. Two researchers independently conducted rounds of data extraction, during which they searched for tables, graphs, and text. Disagreements were resolved through discussion. If they were unable to reach a consensus, a third author made the decision. Data regarding the aims and type of each study, ASI characteristics, participant and group descriptions, as well as kinematic assessment methods and procedures, were extracted for this systematic review. The biomechanical parameters determined and the main findings of the studies were analyzed. Outcomes such as muscle forces and activation were not included in this systematic review.

2.6. Risk of bias in individual studies

We assessed each study's quality using the Methodological Index for Non-Randomized Studies (MINORS) criteria, a validated instrument designed to assess the methodological quality of non-randomized surgical studies, whether comparative or non-comparative (Slim et al., 2003). Two investigators (JAB and VLB) independently rated each study after full-text analysis and a mean value between the scores obtained by the two observers was calculated for each of the 12 variables. The score for each variable ranges from 0 to 2, as: 0, if not reported; 1, when reported, but inadequate; and 2, when reported and adequate. Highest scores indicate lower risk of bias, being 16 the ideal global score for non-comparative studies and 24 for comparative studies (Slim et al., 2003).

2.7. Summary measures

Standardized mean differences of glenohumeral peak angles, scapular peak angles and scapulohumeral rhythm during arm elevation were the primary summary measures. A random effects model was used, and 95 % confidence interval was calculated. A standard mean difference was calculated instead of mean difference because different equipment

and methodologies were used between studies.

2.8. Methods of quantitative analysis

We estimated scapular angles from one study (Läderrmann et al., 2016) based on the reported glenohumeral and humerothoracic peak angles (Scapular upward rotation = Humerothoracic elevation – Glenohumeral elevation) (Inman et al., 1996; Scibek, 2012; Staker et al., 2021). Standard Deviations (SD) for the scapulohumeral rhythm were obtained using a simulation method with bootstrapping (Davison & Hinkley, 1997).

Scapulohumeral rhythm was not originally reported on the 2 studies included in the meta-analysis and was calculated using the following formula: Scapulohumeral rhythm = (Glenohumeral elevation)/

(Scapular upward rotation) (Lee et al., 2016; Robert-Lachaine et al., 2016). SDs were calculated using the following formula: $\frac{D_x}{x} = \sqrt{\left(\frac{D_a}{a}\right)^2 + \left(\frac{D_b}{b}\right)^2}$. Consider mean as “a” and “b” and its associated SD as Da and Db respectively (Skoog et al., 2007; Ku, 1966).

In this meta-analysis, a random-effects model was employed to synthesize any continuous outcome data. The effect size was calculated with Cohen’s d, which quantifies the standardized mean difference between groups. To combine the results from individual studies, we applied the inverse-variance weight approach, which inherently accounts for both within-study and between-study variance. The estimation method chosen was the DerSimonian-Laird method, a widely accepted approach for random-effects meta-analysis. Notably, no standard error adjustment

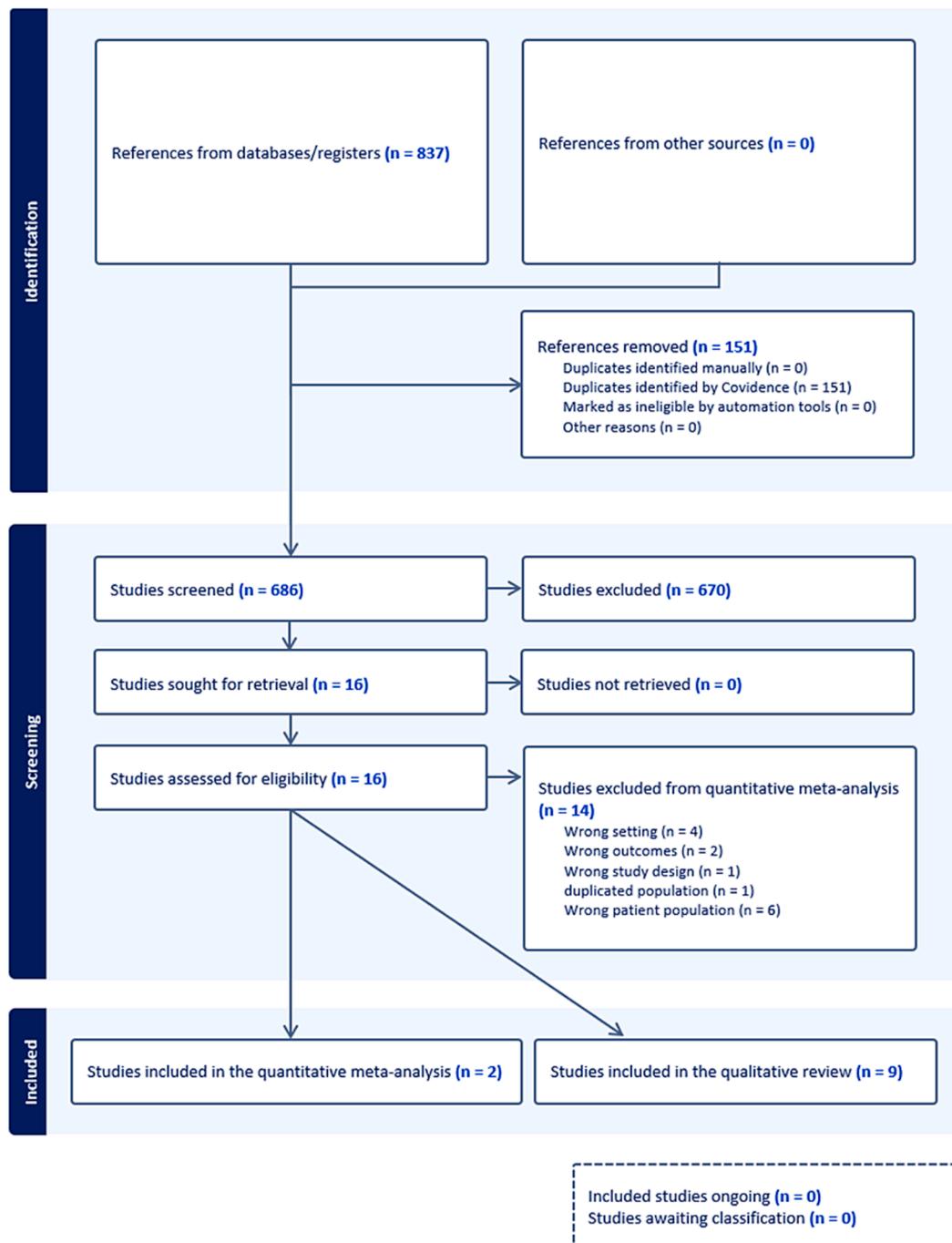


Fig. 1. PRISMA 2009 (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) flowchart diagram of the study.

was performed, ensuring that our results faithfully reflect the observed study variances. Heterogeneity was tested with Chi² test and I² statistics. Variance estimation among the effects observed in different studies (between-study variance) was calculated with Tau².

The interpretation of heterogeneity followed Cochrane Handbook for Systematic Reviews of Interventions (Higgins et al., 2019). Chi² test was interpreted as statistically significant if < 0.05. I² statistics followed this guide for interpretation: 0 % to 40 % might not be important; 30 % to 60 %, may represent moderate heterogeneity; 50 % to 90 %, may represent substantial heterogeneity; 75 % to 100 %, considerable heterogeneity (Huedo-Medina et al., 2006).

Statistical analysis was performed with SPSS Software, version 29.

3. Results

3.1. Study selection

The initial search identified 837 articles through PubMed, Scopus, and Cochrane Library. 151 studies were duplicates and were removed, leaving 686 articles included for the title and abstract review. Studies that did not meet the Eligibility Criteria were excluded. From these, 16 articles were selected for full-text review. Nine studies were included for data extraction and qualitative analysis, among which 2 studies reported on similar and quantitatively comparable variables and were included in quantitative meta-analysis (Fig. 1).

3.2. Risk of bias within studies included in the qualitative review

Considering 16 the ideal global score for non-comparative studies and 24 for comparative studies, the quality of the studies included in this systematic review was low based on MINORS criteria (Table 1).

3.3. Results of individual studies

Table 2 summarizes the main findings in each study, including publication date, participants, angles analyzed during arm elevation, type of equipment used for 3D motion analysis, and the main findings of each study.

3.4. Included studies characteristics

3.4.1. Studies methodology

All the studies included in the qualitative review had a cross-sectional or longitudinal design (Table 2). Four studies used optical measurement for motion analysis, with three studies using passive tracking markers (Arzi et al., 2014; Dellabiancia et al., 2017; Lädemann et al., 2016) and one study using active tracking markers (Marchi et al., 2014). Two studies used electromagnetic 3D motion analysis systems (Hung & Darling, 2014; Matias & Pascoal, 2006). The last three studies used CT scan evaluation associated or not with radiographic images (Ernstbrunner et al., 2022; Kim et al., 2017; Peltz et al., 2015).

3.4.2. Participants

A total of 97 patients with ASI and 72 asymptomatic shoulders were analyzed. The study population relevant to this review included patients with ASI treated non-surgically or evaluated before surgical treatment. The average of mean ages of the patients reported by the studies was 26.8 years, including 71 males and 15 females. One study did not report on the mean ages (Hung & Darling, 2014) and another study did not report on the sex of the participants (Peltz et al., 2015).

This review comprised different types of motion capture systems: reflective markers with cameras, electromagnetic tracking systems, computerized tomography, and dynamic fluoroscopy. The variables analyzed included movement time, range of motion, acceleration, glenohumeral translation (displacement of the humeral head in relation to glenoid center), glenohumeral, humerothoracic and scapulothoracic

Table 1
Risk of bias based on MINORS criteria.

	COMPARATIVE STUDIES											TOTAL	
	A CLEARLY STATED AIM	INCLUSION OF CONSECUTIVE PATIENTS	PROSPECTIVE COLLECTION OF DATA	ENDPOINT APPROPRIATE TO STUDY AIM	UNBIASED ASSESSMENT OF THE STUDY ENDPOINTS	FOLLOW-UP PERIOD APPROPRIATE	LOSS TO FOLLOW UP LESS THAN 5 %	PROSPECTIVE CALCULATION OF THE STUDY SIZE	AN ADEQUATE CONTROL GROUP	CONTEMPORARY GROUPS	BASELINE EQUIVALENCE OF GROUPS		ADEQUATE STATISTICAL ANALYSES
Arzi et al. 2014	2	1	1	2	0	1.5	2	0	2	0	1.5	2	15
Dellabiancia et al. 2017	1	1	2	2	0.5	1	1	0	N/A	N/A	N/A	N/A	8.5
Hung & Darling 2014	2	0	2	1.5	0.5	1	1	0	1.5	1	1	1.5	13
Kim et al. 2017	2	0	2	1.5	0.5	1.5	1	0	1	2	1.5	1.5	14.5
Lädemann et al. 2016	2	1	2	2	1	2	2	0	N/A	N/A	N/A	N/A	12
Marchi, Blana & Chadwick 2014	2	0	2	1.5	1	1.5	1	0	1	1	0.5	2	13.5
Matias & Pascoal 2006	1.5	0	1.5	2	1	1	1	0	N/A	N/A	N/A	N/A	8
Peltz et al. 2015	2	0.5	2	2	0.5	1.5	1.5	0	1.5	2	1.5	2	17
Ernstbrunner et al. 2022	2	0.5	1.5	1.5	1	1	0	0	1	2	1	1	12.5

N/A: Not applicable for non-comparative studies.

Table 2
Summary data of each study.

Author, year	Study Design	Population description	Main Group	Control Group	Type of Instability	Motion Capture	Task	Biomechanical Variables	Main Findings for the Shoulder Instability Group in Comparison with the Control Group
Dellabiancia et al. 2017	Cross-sectional	12 patients with traumatic anterior instability waiting for arthroscopic shoulder stabilization. Mean age: 26 years (range: 18–32) Males 8/Females 4	1. Shoulder instability patients with brace 2. Shoulder instability patients without brace	Contralateral limb	Anterior	Reflective markers. 8 cameras. Vicon motion capture system (Vicon Motion Systems Inc., Denver, CO, USA)	1. Shoulder abduction–adduction. 2. IR-ER with the arm adducted and the elbow in 90° of flexion.	1. GH translation 2. GH ROM 3. ST ROM	<i>GH translation:</i> –Higher variability for glenohumeral head translation in abduction–adduction movements. <i>GH ROM:</i> –Lower external rotation ROM ($p = 0.0022$). –No significant differences for internal rotation, abduction and adduction. <i>ST ROM:</i> –No significant differences reported.
Ladermann et al. 2016	Cohort	11 patients with shoulder instability assessed preoperatively and 1 year postoperatively. Mean age: 26.6 years (range, 17–44) Males 10/Females 1	Shoulder instability patients (pre- and post-operatively)	Contralateral limb	Anterior	Motion capture and CT. Reflective markers. 24 cameras. Vicon MX T-Series motion capture system (Vicon, Oxford Metrics, UK)	1. IR-ER at 90° abduction and elbow flexed 90°. 2. IR-ER with shoulder adducted. 3. Forward flexion of the arm. 4. Shoulder abduction with thumbs down.	5. GH ROM 6. Humeral motion relative to thorax 7. 3. GH translation	<i>GH ROM:</i> –Significantly lower ROM for flexion, abduction and IR ($p < 0.05$). – No significant difference for ER. <i>Humeral motion relative to thorax:</i> – Significantly lower ROM for flexion and IR at 90° abduction ($p < 0.05$) <i>GH translation:</i> –Increased anterior translation for flexion and abduction ($p < 0.001$).
Arzi et al. 2014	Case-control (retrospective)	13 patients with Recurrent Anterior Shoulder Instability treated surgically and 11 patients with Recurrent Anterior Shoulder Instability treated non-surgically. Non-surgical group: Mean age: 26.1 ± 8.0	1. Non-operated patients (Recurrent anterior instability). Post-surgery patients	Healthy controls	Anterior	Reflective markers. 3 cameras (ProReflex MCU240, Qualysis, Gothenburg, Sweden)	Reaching movements with arm fully extended.	3. Movement time 4. Movement amplitude (m) 5. Duration of the arm acceleration phase 6. Movement time similarity index 7. Number of peaks	–Patients with shoulder instability presented stereotypical motion closer to maximal smoothness than healthy controls.

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Table 2 (continued)

Author, year	Study Design	Population description	Main Group	Control Group	Type of Instability	Motion Capture	Task	Biomechanical Variables	Main Findings for the Shoulder Instability Group in Comparison with the Control Group
Hung & Darling 2014	Cross-sectional	years. Males 8/ Females 3 10 individuals with a history of anterior GHJ dislocation. Age: 19–37 years. Males 7/Females 3	Shoulder instability patients	Healthy controls	Anterior	Electromagnetic tracking system (Ascension Technology Corp, Burlington, Vermont)	1. Arm abduction 2. Reaching task	1. For the abduction task: ST orientation changes from 45° to 90° and 90° to 135° abduction 2. For 3D reaching task: ST orientation changes from the low to middle targets and from the middle to top targets	<i>ST orientation:</i> –No significant differences from controls for any task ($p > 0.05$)
Kim et al. 2017	Cross-sectional	10 male subjects with a history of primary anterior GHJ dislocation. Mean age: 23.4 ± 8.8 years (Range: 17–35)	Shoulder instability patients	Contralateral limb	Anterior	CT and fluoroscopic images	1. Arm abduction 2. IR-ER with the shoulder abducted to 90° and elbow in 90° of flexion. 3. Apprehension test in a sitting position	GH translation: superior/inferior and anterior/posterior	<i>GH translation:</i> –No significant difference for superior-inferior translation of humeral head. –Increased anterior translation of humeral head by 2.29 mm in the starting position ($p = 0.0089$). –No significant difference for humeral head translation for internal-external rotation and apprehension test.
Marchi, Blana & Chadwick 2014	Cross-sectional	6 male patients with shoulder dislocation. Mean age: 27 ± 7 years.	Shoulder instability patients	Healthy controls	Not specified (previous dislocation injury)	Reflective markers. CODA motion analysis system (Codamotion, Charnwood Dynamics, UK)	Hand-positioning tasks against external forces applied in six directions	1. Scapular ROM 2. GH stability	<i>Scapular ROM:</i> –Lower scapular elevation and higher posterior tilt, without significant differences regarding protraction ($p < 0.05$). <i>GH stability:</i> –Significantly lower than controls. Lower with the hand pushing away from the body and medially ($p < 0.05$).
Matias & Pascoal 2006	Cross-sectional	6 subjects with GH instability (anterior or multidirectional). Mean age: 37 ± 8.5 years. Males 3/Females 3	Shoulder instability patients	Estimations from linear regression model	3 subjects were classified with anterior instability and 2 subjects with multidirectional	Electromagnetic tracking device (“Flock of Birds System”, Ascension Technology Hardware,	Arm elevation	Thoracic, scapular and humeral rotations.	<i>Scapular orientation:</i> –Increased anterior scapular tilt (or delayed posterior tilt) ($p < 0.05$ for 5 subjects).

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Table 2 (continued)

Author, year	Study Design	Population description	Main Group	Control Group	Type of Instability	Motion Capture	Task	Biomechanical Variables	Main Findings for the Shoulder Instability Group in Comparison with the Control Group
					instability, 1 with postero-inferior.	MotionMonitor Software)			–Excessive protraction (or delayed retraction) (p < 0.05 for 3 subjects). –No significant differences were found in scapular upward rotation.
Peltz et al. 2015	Cohort	11 subjects with anterior GHJ instability. Mean age: 20.5 ± 4.9 years (Range: 16–29)	Shoulder instability patients pre- and post-operatively	Healthy controls	Anterior	Pulsed x-ray generators (CPX 3100CV; EMD Technologies) coupled to two 40-cm image intensifiers (AI5765HVP; Shimadzu) attached to synchronized high-speed video cameras (Phantom v9.1; Vision Research)	1.Apprehension test 2. Abduction, elevation, IR-ER at 90° of abduction.	1. GHJ motion 2. Active shoulder ROM	<i>GHJ motion during Apprehension test:</i> –Humeral head located significantly more anteriorly on the glenoid (7.9 % of glenoid width; 2.1 mm, p = 0.03). <i>Active shoulder ROM:</i> –ER ROM significantly lower (p < 0.01) – No significant differences were found for abduction, elevation and IR ROM.
Ernstbrunner et al. 2022	Cross-sectional	20 patients with recurrent anterior shoulder instability. Mean age: 28 years (Range: 19–49). Males 19/ Females 1	Shoulder instability patients	Healthy controls	Anterior	Open CT	Six static configurations that included: neutral and ER, lift off (touching one's back), 90° abduction, 90° flexion, maximum flexion and 90° abduction with 30° ER.	1. GH ROM 2. ST ROM 3. Scapulohumeral rhythm 4. GH translation	<i>GH ROM:</i> –Decreased GH abduction for shoulder abduction at 90° (mean difference: 13.3°, p = 0.038). –Increased GH abduction for shoulder abduction at 90° and ER (mean difference: 5°, p = 0.042). <i>ST ROM:</i> –Increased upward scapular rotation for shoulder abduction at 90° (mean difference: 13.3°, p = 0.038). –Decreased upward scapular rotation for shoulder abduction at 90° and ER (mean difference: 5°, p = 0.042). <i>Scapulohumeral rhythm:</i> –Reduced for shoulder abduction at 90° (p =

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Table 2 (continued)

Author, year	Study Design	Population description	Main Group	Control Group	Type of Instability	Motion Capture	Task	Biomechanical Variables	Main Findings for the Shoulder Instability Group in Comparison with the Control Group
									0.011). –Increased for shoulder abduction at 90° and ER (p = 0.017).
									GH translation: –No significant differences in humeral head anterior/posterior translation.

GHJ: glenohumeral joint; CT: computed tomography; IR: internal rotation; ER: external rotation; GH: glenohumeral; ST: scapulothoracic; ROM: range of motion.

peak angles, scapular translations, scapulohumeral rhythm (ratio between glenohumeral joint angle and scapulothoracic joint angle during arm elevation), humeral head contact center at glenoid and movement smoothness (the evolution of the movement over time) parameterization surrogates.

3.4.3. Controls

Five studies used healthy asymptomatic subjects as a control group (Arzi et al., 2014; Ernstbrunner et al., 2022; Hung & Darling, 2014; Marchi et al., 2014; Peltz et al., 2015). Meanwhile, three studies used the contralateral limb as the control group (Dellabiancia et al., 2017; Kim et al., 2017; Lädermann et al., 2016) and one study didn't use any control group (Matias & Pascoal, 2006).

3.5. Outcomes for qualitative review

The studies reported data on kinematics (Table 2). The methodology used and parameters analyzed in these nine studies were heterogeneous. Each utilized active movements without weight-bearing.

Ernstbrunner et al. found a significant difference for scapulothoracic and glenohumeral kinematics in patients with shoulder instability compared to healthy joints. Analyzing shoulder angles based on CT measurements, the authors reported that, at 90° of shoulder abduction, the glenohumeral joint angle had a mean decrease of 13.3° compared to controls, with a similar reciprocal increase of 13.3° in scapulothoracic angle, while in the abduction-external rotation position, a 5° increase glenohumeral joint angle was observed for unstable shoulders, with a reciprocal decrease in scapulothoracic upward rotation angle. At the same time, the scapulohumeral rhythm was reduced at 90° of shoulder abduction (control group: 3.7 ± 1.4, instability group: 2.1 ± 1.2, p = 0.011) and increased in the abduction-external rotation position (control group: 1.1 ± 0.2, instability group: 1.5 ± 0.7, p = 0.017) (Ernstbrunner et al., 2022).

Matias & Pascoal also analyzed the scapulohumeral rhythm, having observed an excessive scapular protraction (or a delay in the retraction, p < 0.05 for 3 subjects) and a more anteriorly tilted position (or a delay in posterior tilt, p < 0.05 for 5 subjects) as the arm was elevated for patients with unstable shoulders. The authors reported that, from a visual analysis of the graphs, a general pattern of motion was identified. Specifically, approaching 90° of arm elevation, the thorax showed a slight extension and contra-lateral rotation, while scapular movements were more expressive, where protraction initially followed arm elevation to change to retraction near 90° (Matias & Pascoal, 2006).

Concerning scapular orientation, Hung & Darling found similar findings for subjects with both healthy and unstable shoulders for shoulder abduction and functional reaching activities (Hung & Darling, 2014). Marchi, Blana & Chadwick detected lower scapular elevation and higher posterior tilt in unstable shoulders during hand-positioning tasks against external forces applied in six directions, without significant differences regarding protraction (Marchi et al., 2014).

Regarding humeral head translation in the superior-inferior axis, patients with shoulder instability demonstrated a lower superior translation by about one-sixth of glenoid diameter at 90° shoulder flexion compared to controls, while antero-posterior translation was not significantly different according to Ernstbrunner et al. (Ernstbrunner et al., 2022). Dellabiancia et al. reported a lower variability for glenohumeral translation observed in the values measured for healthy contralateral limbs compared with unstable shoulders in abduction-adduction movements (Dellabiancia et al., 2017). In contrast, in Lädermann's study, unstable shoulders demonstrated a higher anterior glenohumeral translation compared to normal shoulders, especially for flexion (normal shoulders: 1.1 ± 2.1 mm, unstable shoulders: 5.1 ± 2.0 mm, p < 0.05) and abduction movements (normal: 2.0 ± 3.0 mm, unstable: 6.0 ± 1.9 mm, p < 0.05) (Lädermann et al., 2016). In Kim's study, when analyzing scapular plane abduction, there was a significant difference in anterior-posterior humeral head translation between

healthy and dislocated shoulders of 2.9 mm for the initial position ($p = 0.0089$), with the humeral head of the unstable shoulder being at a more anterior position than in controls, which reduced to a minimal and non-significant difference of 1 mm average with increasing abduction angles ($p = 0.785$), and the authors suggest a not relevant alteration of glenohumeral position according to this data (Kim et al., 2017). Peltz et al. analyzed glenohumeral position during the apprehension test, detecting humeral head to be positioned 2.1 mm more anteriorly on the glenoid in previously injured shoulders than in healthy controls ($p = 0.03$) (Peltz et al., 2015).

Dellabiancia et al. compared kinematic data of shoulder instability patients with and without a brace developed for patients with recurrent shoulder dislocation (S2 Shoulder Stabilizer® – Dual Sanitaly S.p.A., Torino, Italy) and the contralateral healthy limb during abduction and adduction movements in the coronal plane and internal and external rotation in the axial plane. Relevant data for this current review, comparing only unstable shoulders with healthy limbs and not considering the results obtained with the immobilizer, is that during internal-external rotation movements, unstable shoulders had a lower external rotation (ER) excursion than stable joints (joint excursion – humerus orientation relative to the chest – for ER: unstable shoulders: $46 \pm 18.2^\circ$, normal shoulders: $61 \pm 16.8^\circ$, $p = 0.0022$) (Dellabiancia et al., 2017). The same finding was reported by Peltz et al., having not found significant differences for other movements analyzed (active ER ROM assessed with a goniometer: unstable shoulders: $87 \pm 8^\circ$, normal shoulders: $112 \pm 9^\circ$, $p < 0.01$) (Peltz et al., 2015). In contrast, Ladermann et al. found no significant difference for external rotation ROM (ER ROM for humerus motion relative to thorax in unstable shoulders: $23.5 \pm 17^\circ$, normal shoulders: $26.4 \pm 15.2^\circ$, $p > 0.05$; ER ROM for glenohumeral motion in unstable shoulders: $30.9 \pm 18.5^\circ$, normal shoulders: $35.8 \pm 17.9^\circ$, $p > 0.05$), but detected a significantly lower ROM for flexion (ROM for humerus motion relative to thorax in unstable shoulders: $156.6 \pm 5.8^\circ$, normal shoulders: $161.1 \pm 8.6^\circ$, $p < 0.05$; ROM for glenohumeral motion in unstable shoulders: $104.4 \pm 11.2^\circ$, normal shoulders: $118.2 \pm 11^\circ$, $p < 0.05$), abduction in the scapular plane (ROM for humerus motion relative to thorax in unstable shoulders: $145.8 \pm 18.9^\circ$, normal shoulders: $151.4 \pm 16.7^\circ$, $p > 0.05$; ROM for glenohumeral motion in unstable shoulders: $95.5 \pm 15.1^\circ$, normal shoulders: $109.2 \pm 13.9^\circ$, $p < 0.05$) and internal rotation for the ASI shoulders (ROM for humerus motion relative to thorax in unstable shoulders: $60.8 \pm 15.9^\circ$, normal shoulders: $55.8 \pm 19.8^\circ$, $p > 0.05$; ROM for glenohumeral motion in unstable shoulders: $32.9 \pm 14.9^\circ$, normal shoulders: $38.9 \pm 21.7^\circ$, $p < 0.05$) (Lädermann et al., 2016).

Arzi et al. evaluated the smoothness of movements in unstable shoulders. Smoothness of movement describes the evolution of the movement over time, indicating how close individuals were to scores defined by a maximal smoothness model, which was calculated according to several parameters that originate in a minimum jerk description. Jerk is mathematically defined as the rate of change of acceleration (Flash & Hogan, 1985). The authors observed that patients with shoulder instability moved stereotypically, meaning that their movement patterns followed closely the maximal smoothness model, even more than healthy controls, and it was more evident in slower motion than in faster speeds of movement (Arzi et al., 2014).

3.6. Outcomes for quantitative meta-Analysis

Two studies reported similar methodologies, including comparable motion analysis equipment, similar tasks, study design, population and outcome variables and were included in the meta-analysis. Studies that were not pooled were deemed inappropriate for meta-analysis due to significant methodological differences that would impair interpretation. Standardized mean difference between the anterior shoulder instability group and the contralateral shoulder was assessed in all pooled studies. No additional analyses, such as subgroup or meta-regression, were conducted.

Scapular anterior tilt data was available for 23 shoulders with anterior instability and 23 contralateral shoulders during active shoulder abduction. There was no statistically significant difference for peak scapular anterior tilt angle in the pooled analysis (Fig. 2). Standardized mean difference was 0.04 (95 % CI: $-1.22, 1.29$).

Scapular upward rotation data was available for 23 anterior instability shoulders and 23 contralateral shoulders during shoulder abduction. There was no statistically significant difference for peak upward rotation angle in the pooled analysis (Fig. 3). Standardized mean difference was 0.29 (95 % CI: $-0.29, 0.87$).

Glenohumeral peak angle in the coronal plane (shoulder abduction) was available for 23 anterior instability shoulders and 23 contralateral shoulders during active shoulder abduction. There was statistically significant difference for this outcome in the pooled analysis (Fig. 4), indicating that the control group has greater glenohumeral (GH) motion compared to instability group. Standardized mean difference was -0.78 (95 % CI: $-1.38, -0.18$).

Glenohumeral peak internal rotation angle was available for 23 anterior instability shoulders and 23 contralateral shoulders. The task analyzed was active maximum internal rotation when the arm was adducted and the elbow in 90° of flexion. There was no statistically significant difference for this outcome in the pooled analysis (Fig. 5). Standardized mean difference was -0.18 (95 % CI: $-0.77, 0.53$).

Glenohumeral peak external rotation angle was available for 23 anterior instability shoulders and 23 contralateral shoulders. The task analyzed was active maximum external rotation when the arm was adducted and the elbow in 90° of flexion. There was no statistically significant difference for this outcome in the pooled analysis (Fig. 6). Standardized mean difference was -0.60 (95 % CI: $-1.20, -0.01$).

Scapulohumeral Rhythm in the coronal plane was available for 23 anterior instability shoulders and 23 contralateral shoulders during active shoulder abduction. There was statistically significant difference for this outcome in the pooled analysis (Fig. 7), indicating that the instability group showed a greater scapulohumeral rhythm. Standardized mean difference was 1.38 (95 % CI: $0.21, 2.56$).

3.7. Risk of bias across studies included in the meta-analysis

Evidence of low heterogeneity was observed across studies for the scapular upward rotation ($I^2: 0\%$), glenohumeral peak angle on the coronal plane ($I^2: 0\%$), glenohumeral peak internal rotation angle ($I^2: 0\%$), and glenohumeral peak external rotation angle ($I^2: 0\%$).

Evidence of moderate/substantial heterogeneity was observed across studies for scapulothoracic rhythm ($I^2: 68\%$), and substantial/considerable heterogeneity for scapular anterior tilt data ($I^2: 79\%$).

4. Discussion

The meta-analysis results indicate increased scapulohumeral rhythm, suggesting a relatively greater contribution of motion at the glenohumeral joint compared with the scapulothoracic joint for arm abduction, and reduced glenohumeral peak angles for unstable shoulders.

The glenohumeral peak angle in the coronal plane was higher for controls, indicating that healthy shoulders have greater glenohumeral motion than unstable shoulders for abduction. For glenohumeral peak external rotation angle, there was a trend towards more external rotation for healthy shoulders than the instability group, as the confidence interval did not cross zero and p was 0.05. These motion alterations could be related to fear, pain, apprehension, and poor neuromuscular control during the tasks. Additionally, the meta-analysis demonstrated that the instability group showed a greater scapulohumeral rhythm in the coronal plane, which means a relatively greater contribution of motion at the glenohumeral joint compared with the scapulothoracic joint for arm abduction. An altered scapulohumeral rhythm may be indicative of impaired neuromuscular control or biomechanical changes due to instability. Contrasting these findings, the results of the studies

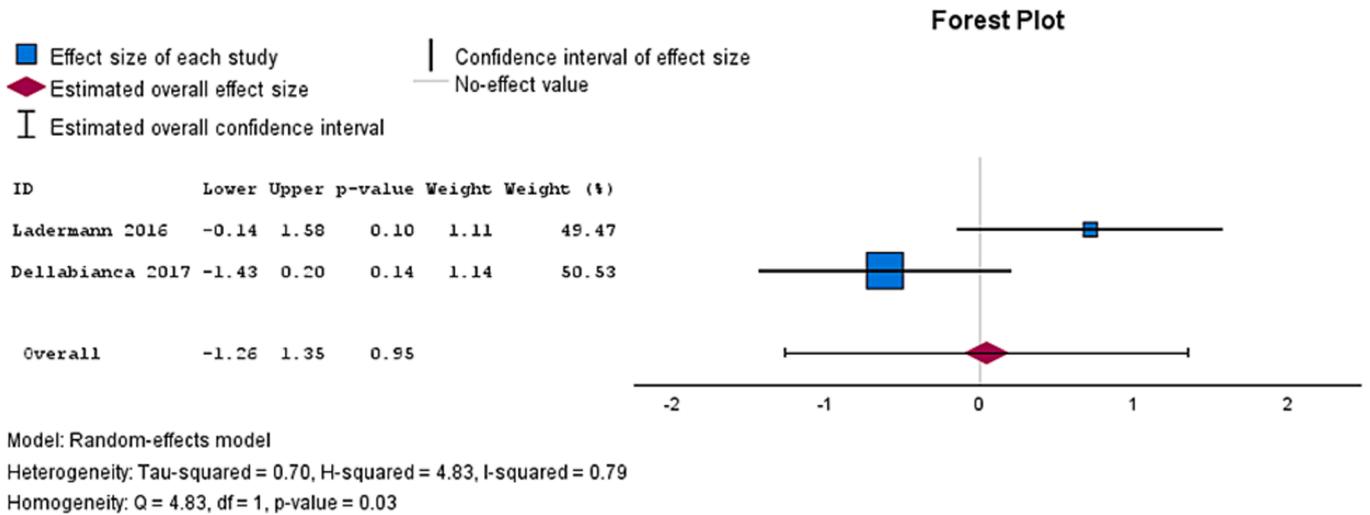


Fig. 2. Peak Scapular Anterior Tilt Angle: standardized mean differences between shoulder instability and control group.

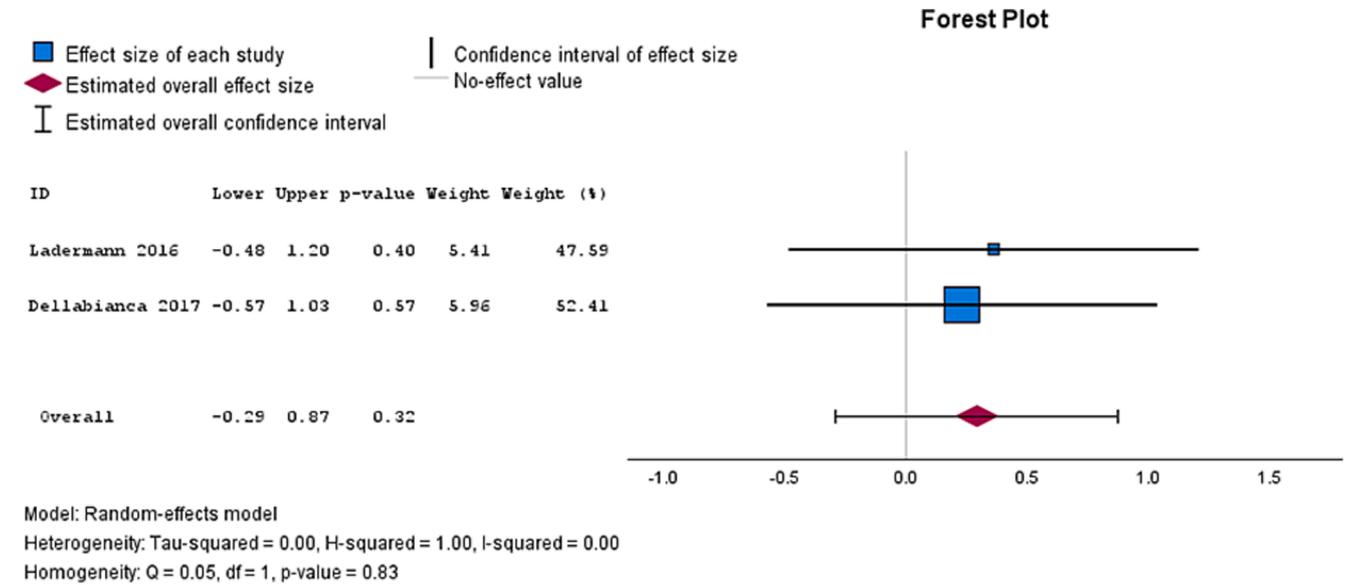


Fig. 3. Upward Rotation: standardized mean differences between shoulder instability and control group.

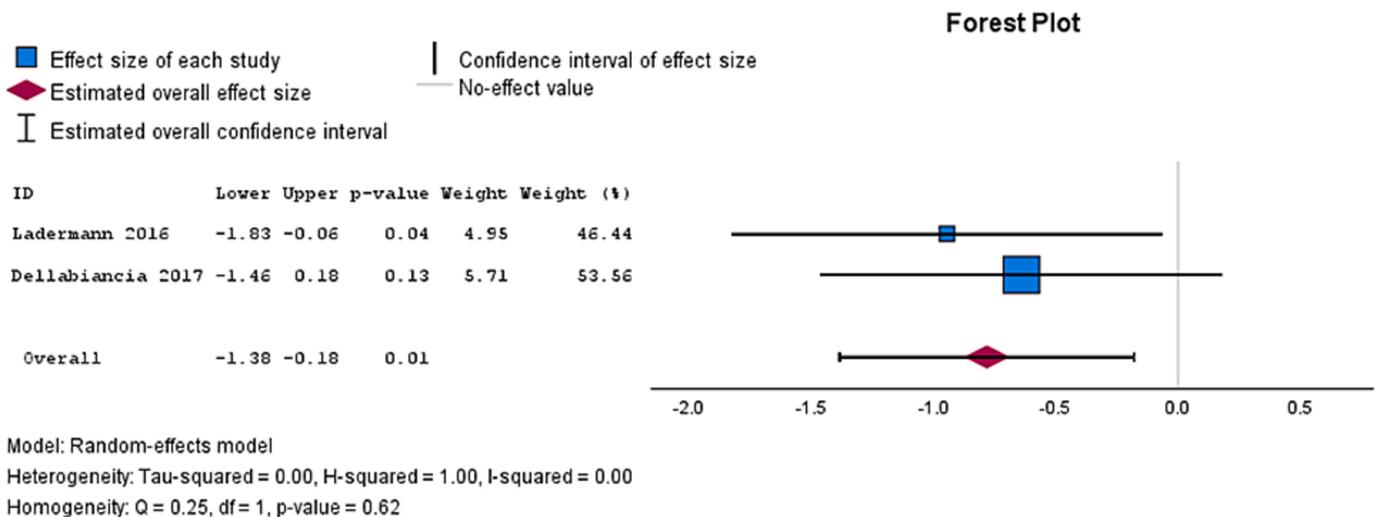


Fig. 4. Glenohumeral peak angle on the coronal plane (shoulder abduction): standardized mean differences between shoulder instability and control group.

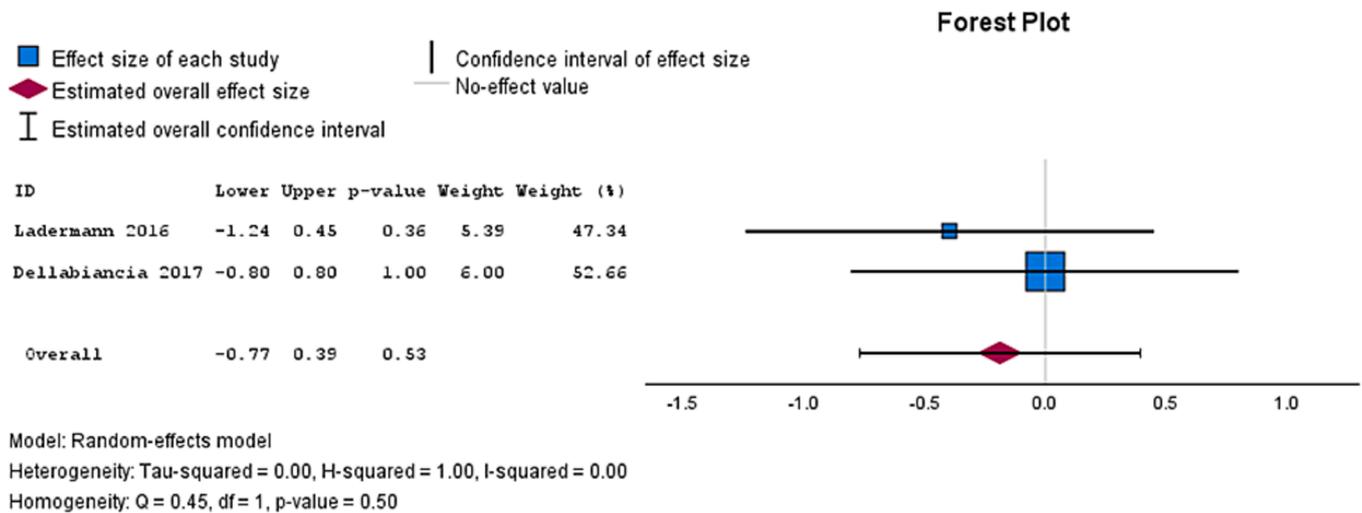


Fig. 5. Glenohumeral peak internal rotation angle: standardized mean differences between shoulder instability and control group.

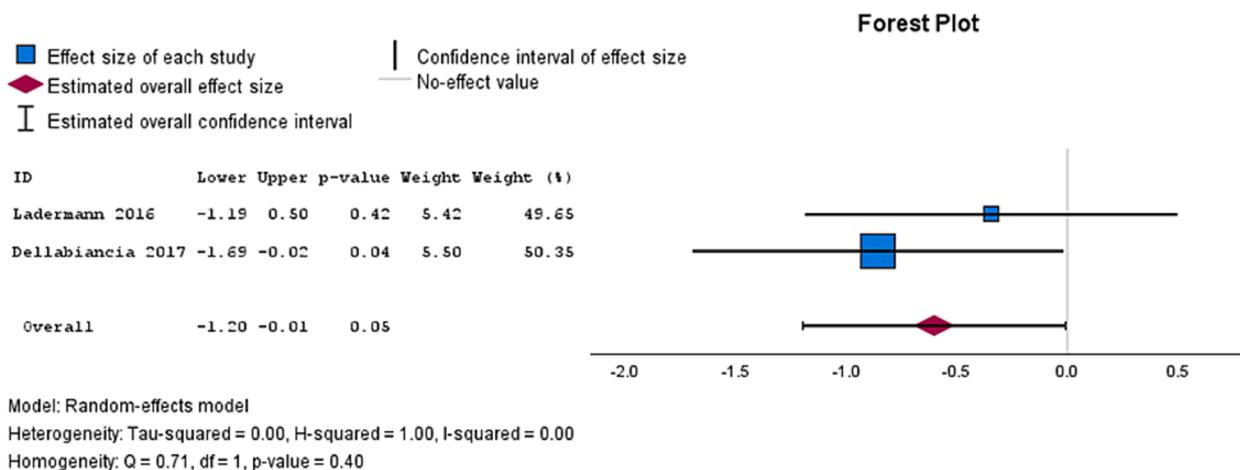


Fig. 6. Glenohumeral peak external rotation angle: Standardized mean differences between shoulder instability and control group.

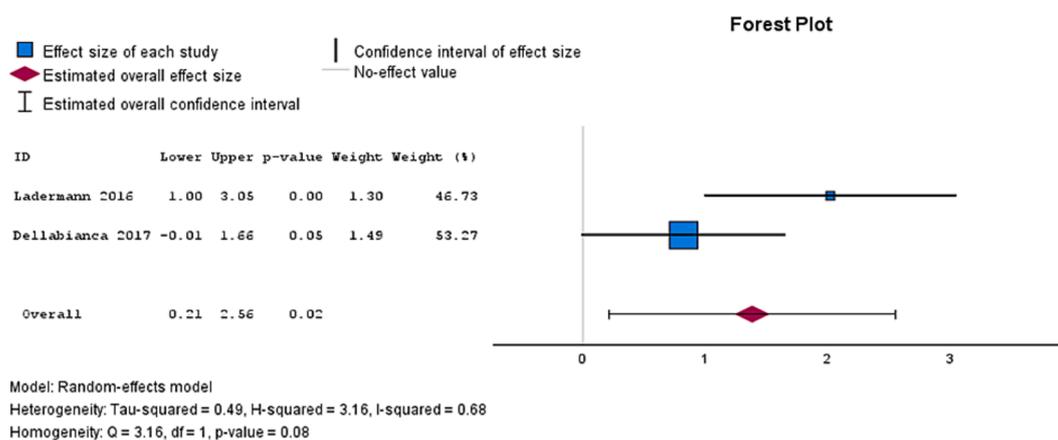


Fig. 7. Scapulohumeral Rhythm: Standardized mean differences between shoulder instability and control group.

included in the qualitative analysis present a more complex picture. Among the nine studies evaluated, six analyzed the scapulohumeral rhythm or scapular orientation (Dellabiancia et al., 2017; Ernstbrunner et al., 2022; Hung & Darling, 2014; Kim et al., 2017; Marchi et al., 2014; Matias & Pascoal, 2006). Ernstbrunner et al., analyzing six static shoulder positions, found a significant difference for scapulothoracic

and glenohumeral kinematics in patients with shoulder instability compared to healthy controls. They found a reduced scapulohumeral rhythm with a greater scapular upward rotation in 90° of shoulder abduction, which may be related to a compensation for reduced glenohumeral motion in this position, and an increased scapulohumeral rhythm with less scapular upward rotation in the abduction-external

rotation position, meaning that the global shoulder function relied more on glenohumeral movement in this position (Ernstbrunner et al., 2022). Another study that evaluated the scapulohumeral rhythm was from Matias & Pascoal, which detected an excessive protraction and a more anteriorly tilted position of the scapula as the arm was elevated for patients with unstable shoulders, which could be due to poor muscle control (Matias & Pascoal, 2006). However, Matias & Pascoal did not find any differences in the scapulohumeral rhythm throughout the coronal plane (glenohumeral abduction and scapular upward rotation). Hung & Darling did not find differences in scapular orientation between healthy and unstable shoulders, suggesting little impact of anterior shoulder instability on scapular orientation during 3D reaching tasks (Hung & Darling, 2014). These studies were unable to be included in the meta-analysis due to insufficient comparison groups (Matias & Pascoal), drastically different methodology and testing protocols (Ernstbrunner et al.), or SHR outcomes being reported for only a single, customized task not common to other studies (Hung et al.).

We expected that patients with ASI would present a greater anterior translation of the humeral head in the glenoid, especially in the abduction-external rotation position of the shoulder—the critical apprehension position. Five studies assessed humeral translation and despite the existence of a trend towards an anterior translation, results were contradictory and showed minimal to non-significant differences between ASI and healthy shoulders (Dellabiancia et al., 2017; Ernstbrunner et al., 2022; Kim et al., 2017; Lädermann et al., 2016; Peltz et al., 2015). The conflicting findings in these studies could be attributed to the limited sensitivity of the motion analysis methods used. These methods may have difficulty detecting subtle yet clinically significant movements of the humeral head within the glenoid.

Three studies analyzed the range of motion during active movements. Dellabiancia et al. and Peltz et al. found a reduced ROM for active shoulder external rotation (Dellabiancia et al., 2017; Peltz et al., 2015), while Lädermann et al. detected a lower ROM for flexion, abduction in the scapular plane and internal rotation for the ASI shoulders (Lädermann et al., 2016). These alterations in the active ROM could be related to pain or apprehension during the tasks.

One study found that ASI shoulders exhibited greater smoothness compared to normal shoulders. ASI patients appeared to employ a feedforward mode of control characterized by shorter movement times and less movement fragmentation. This suggests that their movements were preplanned for the entire path, thereby minimizing reliance on feedback-based corrections. Consequently, the unstable shoulders of ASI patients may move more “safely”. However, these preplanned movements may indicate a less adaptive response to unexpected changes in movement conditions. As a result, these patients could potentially benefit from a rehabilitation protocol emphasizing neuromuscular control, specifically transitioning from a feedforward to a feedback-based mode of control (Arzi et al., 2014).

The topic of motion analysis and shoulder instability is a critical area of research with significant clinical repercussions. Despite the considerable research efforts we noticed a lack of standardization in the design and execution of studies examining this subject, preventing quantitative comparisons and also qualitative comparisons in many cases. As mentioned, 3D kinematic analysis can be performed with various motion tracking techniques, such as marker-based (highly accurate but costly and preparation-intensive), markerless (less precise but non-invasive and improving with 3D imaging), and IMUs (portable but less accurate). Differences in accuracy and setup affect comparisons, as more precise systems detect subtler kinematic changes. Based on the evaluation of the majority of the studies, standardizing shoulder motion analysis will be highly beneficial for future research. The reporting of shoulder motion, including separate reports of the GH joint, ST joint and humeral elevation (relative to the ground and thorax), across the three anatomical planes of motion. We recommend that forward flexion and shoulder abduction in the scapular plane must be included during the analysis. Additionally, using a metronome is an important tool that may

help reduce inconsistency during task execution. Performing the movements while standing is another recommendation supported by most of the studies included in this review. The use of dumbbells for tasks remains a contentious issue and could be a topic of debate for future research. Additionally, we suggest standardization of the choice of the motion capture system employed, giving preference for the passive marker systems.

A significant advantage of utilizing passive marker systems, for example, is the small size, separation, and extremely light weight of the markers. Due to this reason, passive optical motion tracking systems are widely employed in developmental studies (van Schaik & Dominici, 2020). Regarding the electromagnetic 3D motion analysis, the position and orientation of sensors on the body are determined by electromagnetic systems through time-of-flight calculations. This involves computing the time taken for electromagnetic waves to travel from the transmitter to the sensors. However, electromagnetic systems are typically less accurate and have a lower sample frequency than optical systems, as noted by Van Der Kruk and Reijne in 2018 (van der Kruk & Reijne, 2018).

Standardization should also be improved in the selection process of study participants. Shoulder instability is a complex condition that can arise from various underlying factors, including trauma, repetitive overhead activity, and connective tissue disorders (DeFroda et al., 2021; Domos et al., 2018; Kibler & Sciascia, 2016). However, not all studies clearly define the specific population being studied, leading to potential confounding variables that may impact the results obtained. The approach for the ASI was an additional concern. As previously mentioned, ASI is a complex condition that can range from cases with little or no bone loss and few episodes of shoulder instability, resulting in minimal limitations in daily activities, to cases with significant bone loss and frequent shoulder dislocations, which can profoundly affect an individual's quality of life. This discrepancy between different clinical conditions and chronicity generates a significant distinction in how the shoulder movements are performed.

We need to emphasize the regular level of quality in almost half of the studies, with small sample sizes and some without a control group. This finding may be attributed to the difficulty in obtaining patients from specific groups, as well as the effort in obtaining instrumentation, technicians, and specific laboratories.

Furthermore, there is a demand for standardization in the measurement of motion and stability. Various motion analysis techniques, such as three-dimensional motion analysis and electromyography, were employed in the studies analyzed in this review. Nevertheless, the variation in measurement techniques, protocols, and analysis methods poses a challenge for accurately comparing the results across different studies. Four studies used optical measurement for motion analysis – three with passive markers (Arzi et al., 2014; Dellabiancia et al., 2017; Lädermann et al., 2016) and one with active markers (Marchi et al., 2014). Two studies used electromagnetic 3D motion analysis systems (Hung & Darling, 2014; Matias & Pascoal, 2006). The other 3 studies used CT scan associated or not with dynamic fluoroscopy or x-ray (Ernstbrunner et al., 2022; Kim et al., 2017; Peltz et al., 2015). Thus, several studies relied solely on static images for assessing shoulder kinematics, but it is urgent to acknowledge that shoulder biomechanics can differ significantly between static and dynamic tasks. The utilization of static images may not fully capture the dynamic and functional aspects of shoulder motion. The reliance on static measurements might oversimplify the assessment of ASI, potentially leading to an incomplete understanding of the dynamic challenges faced by individuals with this condition.

The lack of standardization can lead to inconsistencies and discrepancies in the results obtained, making it challenging to draw definitive conclusions and develop effective treatment approaches. The main relevance of our review is that, even with different motion-tracking devices, we could better understand how shoulder movement is affected in instability cases. The limited number of available studies

investigating biomechanics in shoulder instability patients resulted in a low-strength *meta-analysis*. Also, as mentioned previously, the lack of standardization across the studies evaluated in this qualitative review, as well as the limited samples in each study, made it difficult to achieve strong conclusions, with contradictory results among the studies. Additionally, one of the studies included in the systematic review (Matias & Pascoal, 2006) included not only patients with anterior shoulder instability (from the 6 patients evaluated in this study, three were classified with anterior instability and two with multidirectional type, and there was no consensus for the last patient), which could have somehow interfered with the final results.

5. Conclusion

This systematic review and *meta-analysis* enhance our understanding of shoulder motion in patients with anterior shoulder instability. The findings of the *meta-analysis* revealed increased scapulohumeral rhythm and reduced glenohumeral peak angles in unstable shoulders, while the qualitative review presented controversial results for scapulohumeral rhythm, scapular orientation, glenohumeral head translation, and active range of motion. Kinematic changes due to ASI may be related to pain, apprehension, functional changes from capsule and ligament pathoanatomy, impaired neuromuscular control or a combination of each during shoulder tasks. As treatment strategies may vary, it is essential to identify and quantify these variables to enhance the efficiency of interventions.

The review underscores challenges in the current research, highlighting methodological inconsistencies in motion analysis studies of shoulder instability. Standardized protocols for defining and assessing instability, selecting participants, and measuring motion and muscle activation could mitigate discrepancies, enhancing research quality. Future studies should prioritize such standardization to provide a more reliable foundation for clinical decision-making in managing anterior shoulder instability.

CRedit authorship contribution statement

Talissa Oliveira Generoso: Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Formal analysis, Data curation. **Vitor La Banca:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Felipe F. Gonzalez:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **João Artur Bonadiman:** Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Lucas Valerio Pallone:** Writing – review & editing. **Eliane C. Guadagnin:** Writing – review & editing, Validation, Supervision, Resources, Methodology, Investigation. **Grant E. Garrigues:** Writing – review & editing. **Jonathan A. Gustafson:** Writing – review & editing, Supervision, Project administration, Methodology. **Leonardo Metsavaht:** Writing – review & editing, Supervision, Resources, Project administration. **Gustavo Leporace:** Writing – review & editing, Validation, Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jbiomech.2025.112543>.

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