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In vivo assessment of shoulder stability in dynamic rehabilitation exercises: A scoping review

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ABSTRACT

Background: The shoulder complex, which has the highest prevalence of instability, is currently, the subject of considerable debate regarding the methodologies used to assess shoulder stability during dynamic exercises.
Research question: The primary aim is to summarize evidence on various methodologies used to evaluate shoulder stability during dynamic exercises.
Methods: This scoping review included cross-sectional studies focusing on various evaluation techniques to assess shoulder forces, kinetics, and stability during dynamic movements. In analyzing each study, the selected data included population profile, sample size, exercise type, and evaluation methodology used.
Results: Twenty-seven studies with a total of 1187 subjects were included. Among the studies, various dynamic exercises were evaluated, including throwing exercises, movements with dumbbells or elastic bands, push-ups, and functional tasks. Most evaluation techniques were combined, with eleven studies using surface electromyography; seven used dynamometers to obtain direct strength measurements; two used six-force axis sensors; one utilized force platforms; and one was focused on the loss of speed using linear velocity transducers. Furthermore, motion capture systems such as high-speed cameras were used in fourteen studies. In conclusion, surface electromyography and high-speed cameras are the primary techniques for measuring muscle activity and kinetic and kinematic data. However, they do not directly measure glenohumeral stability, meaning further research is needed to develop reliable methodologies for this purpose.
Significance: This study holds significant relevance in the field of shoulder instability and has clear clinical implications, as it establishes the primary tools for estimating glenohumeral stability, which could enable patient stratification and the design of optimal intervention programs based on these measurements.

1. Introduction

The glenohumeral joint exhibits the greatest mobility of any joint in the body, which, combined with its complex anatomy, results in the highest prevalence of dislocation [1]. Shoulder stability is provided by the synergy of static and dynamic factors such as ligaments, labrum, and periarticular muscles [2].

Current evidence supports reaching a consensus on an active management approach to glenohumeral instability, which should be grounded in conservative treatment incorporating patient education and exercise, to manage pain, feelings of instability, and functional deficits [3,4]. Some authors have emphasized the importance of determining optimal load progression in exercise programs [5,6], and the subsequent need to measure functional and biomechanical parameters directly and indirectly related to instability during movement [7]. This necessitates a more rigorous and comprehensive evaluation of all relevant structures using a range of assessment methodologies.

Self-reported questionnaires are generally among the most utilized tools to assess shoulder dysfunctions. This measuring tool typically accompanies a physical examination based on functional tests, as the absence of an internationally agreed classification necessitates using this evaluation to stratify patients with glenohumeral instability [8]. However, these measurements lack objectivity and cannot be precisely replicated.

Regarding more objective measurements, imaging techniques serve as the preferred modality in clinical settings. Radiography is typically the first-line imaging technique when initial medical evaluation is required.

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However, more detailed imaging modalities that capture soft tissues, such as computed tomography or magnetic resonance imaging, are often required [9].

Although imaging techniques provide the most objective option, their use for follow-up assessment incurs significant economic costs. Furthermore, they do not allow functional evaluation during movement. Given the importance of dynamic stabilizers in monitoring patients with shoulder disorders and developing preventive strategies for asymptomatic individuals, and recognizing that their evaluation should occur during motion, various tools have been developed in recent years to objectively analyze these structures [10].

In-vivo shoulder assessment during motion or dynamic exercises focuses on assessing kinetics, muscle activity, and strength [11].

Three-dimensional motion capture systems are among the technologies used to record kinetic and kinematic data, as they enable movement tracking through reflective markers [12]. However, the choice of sampling rate can significantly affect measurements, meaning establishing a consensus is necessary to prevent these discrepancies [13].

Electromyography has been preferred for recording muscle activity as it generates an activation pattern diagram that can also serve as a feedback system to improve motor control [14]. However, the decision to opt for surface or fine wire electromyography depends on the muscle, as fine wire is necessary for deeper muscles overlaid by others [15].

Regarding muscle strength, the handheld dynamometer is the most commonly used technology; however, despite its good correlation with the isokinetic dynamometer, it only allows force evaluation under isometric conditions [16]. That is why various technologies like force plates, force sensors, and linear velocity transducers have been developed in recent years to enhance force assessment during motion [17].

Some reviews have previously been published assessing glenohumeral stability, but they have focused on biomechanical prediction models [18] or cadaveric specimens [19]. In addition, reviews based on in-vivo assessments highlight isometric contractions as the primary outcome [20]. Studies directly assessing stability through kinetic and strength parameters during dynamic exercises (commonly used in sports practice, work activity, or rehabilitation) therefore remain lacking.

These facts highlight the need to conduct a scoping review to offer a broad perspective on the various methods available in the scientific literature within this field, identify key parameters related to shoulder stability assessment to clarify current knowledge before developing systematic reviews on more specific topics, and identify knowledge gaps to address in future original research. For these reasons, this study aims to review in vivo evaluation methodologies applied to estimate forces, kinetics, and shoulder stability during dynamic exercises.

2. Material and methods

This scoping review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) Extension for Scoping Reviews (PRISMA-ScR) guidelines.

2.1. Information sources and search strategy

To carry out this scoping review, two reviewers (L. R. P. and A. I. C. V.) conducted a literature search from inception to March 2023 using the Pubmed, Scopus, Embase, and PEDro databases. The following combinations of terms were used: "Shoulder (Title) AND Load (Title)"; "Shoulder (Title) AND Biomechanics (Title)"; "Shoulder (Title) AND Kinetic (Title)"; "Shoulder (Title) AND Motor control (Title)"; "Shoulder (Title) AND Stability (Title); "Shoulder (Title) AND Force (Title)".

The need for multiple searches is justified because terms such as shoulder evaluation, assessment, and management cover a broad range of concepts. Following recommendations for biomedical reviews [21], four databases were explored. Due to variations in each database's search functionalities, it was necessary to use multiple simple searches rather than complex queries.

The studies identified in the search conducted were selected after three stages: in the first stage, the duplicated articles were identified and removed; in the second stage, titles and abstracts were analyzed; and in the third stage, the full text of the shortlisted articles was evaluated by two independent researchers (L. R. P. and A. I. C. V.).

2.2. Eligibility criteria

All studies that met the following inclusion criteria were selected:

a. Cross-sectional studies published in scientific journals.
b. Focused on assessing the stability of the glenohumeral joint in vivo using objective measurements.
c. During active and dynamic exercises.
d. Available in English or Spanish language.

The following studies were excluded from the review:

a. Studies with a sample size smaller than twenty participants.
b. Studies that included subjects with spinal cord injury or another neurological disease that implies the use of a wheelchair.
c. Conference proceedings or book chapters.

2.3. Data extraction

Data extraction was conducted by two reviewers (L. R. P. and A. I. C. V.) independently. A systematic extraction form was used for each article to collect the following data: (1) population profile (health condition, sample size, age, and sex of participants); (2) evaluation system (details of the devices used); (3) dynamic exercises evaluated; (4) reliability data.

2.4. Study quality assessment

Current scoping review guidelines indicate that a quality analysis is unnecessary due to the absence of a standardized tool for methodological assessment [22,23]. Therefore, this review emphasizes the various devices used for an in vivo shoulder assessment rather than the magnitude of the results obtained.

3. Results

A total of 2436 records were identified in the mentioned databases. After removing duplicates, 1398 references remained. After reviewing titles and abstracts, 750 were identified as potentially eligible, leading to a full-text assessment of each. After analyzing the fulfillment of the eligibility criteria, 27 studies were finally selected for inclusion in the current review (Figure A.1).

In total, 1187 subjects were included in the analyzed studies. Of these, 649 were athletes involved in throwing sports, weightlifting, and CrossFit; 173 were military personnel; 93 had jobs with repetitive tasks involving hands; 76 had health problems related to the shoulder and/or neck; and 196 were healthy volunteers.

As for the evaluation methodologies, various assessment types were identified, including electromyography, force sensors, three-dimensional motion capture systems, force plates, dynamometers, and linear velocity transducers. Table 1. shows the measurement methodology and dynamic exercises used to record the objective outcome variable. Figure A.2. visually shows the distribution of these methodologies for each dynamic exercise used.

3.1. In vivo evaluation methodologies

3.1.1. Electromyography

Eleven studies used surface electromyography to obtain shoulder muscle activation patterns. Seven of them were performed in healthy volunteers [24-30], one was carried out in people with neck or shoulder problems [31], and three opted for a case-control methodology, including in the group of cases patients with subacromial impingement syndrome or anterior shoulder instability [32-34].

Regarding reliability, electromyography demonstrated intra-class correlation coefficients ranging from 0.69 (teres major) to 0.996 (lower trapezius) [24,28,30].

3.1.2. Force sensors and force plates

Three studies assessed strength using different systems. Two of them used six-axis force sensors to evaluate functional tasks: one was performed in symptomatic and asymptomatic manual laborers [25], and the other in professional violinists [26]. Moreover, one study used a force plate to assess a push-up task in navy personnel [35].

Concerning reliability, force plates demonstrated intra-class correlation coefficients ranging from 0.91 to 0.96 [35], while no data was available for force sensors.

3.1.3. Three-dimensions motion capture systems

Most of the studies utilized three-dimensional motion capture systems to record kinematic data. In nine of these studies motion capture was the only assessment technology used [36–44]. The other five projects combine cameras with other systems: three of them incorporated strength measurements using dynamometers [45-47], and two combined electromyography data [24,25].

With regard to reliability, intra-class correlation coefficients range from 0.71 to 0.99 [25,40,47].

3.1.4. Handheld and isokinetic dynamometers

Seven studies used dynamometers to measure strength outcomes. Only one of them used a handheld dynamometer [45], while the other six studies used isokinetic dynamometers [31,46-48,35,49]. Nevertheless, most of them opted for combining dynamometers with other technologies, and only two of them focused solely on these strength measurements [48,49].

Concerning reliability, no data was available for handheld dynamometers, while several studies reported isokinetic dynamometer values ranging from 0.86 to 0.99 [46,48].

3.1.5. Linear velocity transducers

A single study employed linear velocity transducers to assess healthy volunteers during the concentric and eccentric phase of a shoulder press exercise. This tool demonstrated an intra-class correlation coefficient of 0.998, with a 95 % confidence interval ranging from 0.996 to 0.999 [50].

3.2. Type of exercises

Different types of dynamic exercises were assessed in the selected studies. Nine studies included throwing exercises based on the practice of baseball, with a focus on pitching fastballs [45,37–44]. Eight studies opted for dynamic exercises without load [24,31,46,32,48,33,49] or with elastic bands [28] focused on elevations, abductions, rotations, and scapular movements. Another exercise commonly applied for shoulder disorders was the bench press which was analyzed in two studies [36,50]. Moreover, lifting tasks commonly used to analyze shoulder stability were applied in three studies [25,27,29]. Puhs-ups are also widely used in shoulder rehabilitation, as shown in two studies [30,35]. The remaining three studies analyzed functional tasks, some of them related to the participants' professions [26,47,34].

4. Discussion

As far as the authors are aware, this is the first study to review in vivo assessment techniques used to estimate shoulder stability during dynamic exercises, encompassing healthy subjects as well as various phenotypes and pathologies. The main finding of this review is that most studies used an indirect method to obtain data on kinematic or kinetic variables due to the lack of technologies capable of directly measuring glenohumeral stability.

4.1. Electromyography

Most of the studies included in this review used electromyography to obtain data on muscle activity and used it as an indirect measure of glenohumeral stability. This methodology has been widely used because of the strong relationship between glenohumeral stability and abnormal muscle activation patterns, as identified by Spanhove et al. [51] in their systematic review.

Electromyography includes various procedures. All studies chosen used bipolar surface electrodes. However, four research groups opted to add intramuscular fine-wire electrodes to record data from deep muscles [25,50,40,29]. This aligns with Berckmans et al. [52], who highlighted the need to combine surface and intramuscular electromyography to obtain precise data on the three-dimensional kinematics of the scapula.

Regarding data analysis, there are various methods to process electromyography signals, such as integration and conversion to root mean square [24,31,28,34], full-wave rectified and low-pass filtered [25,26,32,29], and common mode rejection ratio [27,33]. This underscores the need for data post-processing to remove noise and ensure quality signals that correspond to actual muscle activity, as described by Chowdhury et al. [53] in their review.

Despite being an indirect method for assessing stability, electromyography has been widely used for this purpose due to its key advantages: it is a non-invasive procedure, enabling consistent identification of the relationship between muscle fatigue and shoulder stability to be established, as highlighted by Kallenberg et al. [54]. Reliability has been shown to be acceptable [24,28,30], consistent with previous studies that analyzed surface electromyography reliability in periarticular shoulder muscles, which reported superior results for absolute data compared to normalized data [55].

4.2. Force sensors and force plates

Force sensors are not widely used to analyze joint stability. Indeed, only two studies opted for this technology to assess glenohumeral instability [25,26]. However, new systems, such as force myography, are being developed in this field; these systems incorporate force sensors and use a non-invasive technique to detect changes in the stiffness of specific muscle groups, utilizing this data to decode the position or movement of the upper limb [56].

In these two articles, force sensors are placed on elements external to the subject, such as boxes [25] and violins[26]. This methodology allows the force exerted to be set without the influence of each subject's physical characteristics. This approach differs from direct measurements, in that it is less precise but avoids invasive techniques, thereby reducing the risk of tissue damage, as noted by Fleming et al. [57] in their review.

The use of force plates is becoming increasingly prevalent in shoulder evaluation [35], particularly for assessing glenohumeral stability and rotator cuff muscle forces to minimize injury risk. This method is typically applied during pushing and pulling tasks, as outlined by Urbanczyk et al. [58].

Although force platforms also serve as an indirect assessment method, their use is justified by their ability to measure force, kinematics, and even sensorimotor control, which often changes in individuals with glenohumeral instability. This makes this tool very useful both in terms of evaluation and proprioceptive rehabilitation, as highlighted by Edouard et al. [59]. Furthermore, force plates have demonstrated high reliability in the results identified in this review [35], consistent with findings reported by other authors [60].

4.3. Three-dimensions motion capture systems

3D motion capture systems operating at high speeds (> 100 Hz) were used to assess kinematic parameters, providing a valid tool for evaluating shoulder function across a complex spectrum [61]. Moreover, the tool is a reliable instrument, as demonstrated by the articles included in this review [25,40,47], consistent with other studies reporting moderate to excellent reliability [62].

All studies opted for the use of reflective markers to identify anatomical landmarks. However, there were differences in the number used, varying between two [24], five [45], fifteen [37,47], twenty-one [44], twenty-six [38,39,43], twenty-eight [46], thirty-four [25], and forty-one [41,42]. Moreover, the landmarks in which reflective markers were positioned were varied, with the acromion being the only anatomical reference that coincided in all the studies. This aligns with the Standardization and Terminology Committee of the International Society of Biomechanics' proposal for defining a joint coordinate system for the shoulder [63].

A consensus on sampling frequency has not been established. The most used frequencies were 240 Hz [36-39,43] and 250 Hz [45,46,41]. However, other sampling frequencies have also been used such as 100 Hz [24,25,47] or 300 Hz [40,42]. Despite the differences, they all meet the premise of applying a sampling frequency between 100 Hz and 500 Hz, as established by Bermejo et al. [64] in their review of methodological aspects for three-dimensional kinematic analysis.

4.4. Handheld and isokinetic dynamometers

Taking as a reference the close relationship between strength and muscle activation patterns in relation to glenohumeral instability [65], measuring muscle strength is presented as an estimator of shoulder stability during exercise. Various tools have been developed for this purpose, with the isokinetic dynamometer becoming the gold standard [66], due to its demonstrated reliability confirmed by the articles in this review [46,48], and other studies [67] that showed that moderate to excellent reliability depends on the movement analyzed and the dynamometer speed settings. Although not the most commonly used due to high costs, some researchers have demonstrated the strong validity and reliability of handheld dynamometers, as well as their greater cost-effectiveness compared to the isokinetic devices [68–70].

As for the most commonly assessed movements with isokinetic dynamometers in the shoulder, internal and external rotations clearly predominate in the articles included in this review [46,48,35,49]. This fact aligns with the direct relationship between the rotator muscles of the shoulder and their dynamic stability, as confirmed by Gombera et al. [71] in their systematic review. Other movements such as shoulder forward flexion have been evaluated [31]; however, this movement is also not a functional task, which is a primary limitation of using dynamometry.

4.5. Linear velocity transducers

Linear velocity transducers are currently being used to assess and monitor velocity loss during exercise. Only one article using this technology was included in this review [50], showing excellent reliability; however, the methodology employed in this study was previously validated by Orange et al. [72], confirming the reliability of this tool for monitoring upper limb training during a barbell bench press load.

4.6. Translation to clinical practice

It is well known that physiotherapists and medical doctors often encounter some barriers when implementing the latest scientific evidence into clinical practice; this review must therefore address this issue, as not all the methodologies analyzed offer the same applicability in clinical settings [73].

Electromyography, as one of the initial methodologies in biomechanical evaluations, allows for the straightforward assessment of surface muscles in clinical settings due to its non-invasive nature, feasibility for most patients, and its ability to be implemented both for evaluation and for training with feedback [74]. Likewise, force plates are increasingly used due to their portability, allowing installation in nearly all clinical settings, and their relatively low cost [75]. Similarly, linear velocity transducers are commercially available and are frequently used in both clinical and gym settings due to their ease of use [76]. Furthermore, handheld dynamometers are increasingly present in the clinical environment due to their small size, acceptable price, and validity and reliability [77]. Nevertheless, other tools analyzed in this review, such as motion capture systems and isokinetic dynamometers, have limited clinical application due to the need for large installation spaces, complexities in usage and data analysis, and high costs, which has led to their replacement by portable camera and dynamometer systems [78,79].

4.7. Limitations

The main limitation of this review is the difficulty in tracking literature due to the significant heterogeneity of terminology. This problem has been addressed by including broad terms in the search; however, some studies have probably not been identified. The absence of a quality assessment is also a significant limitation.

5. Conclusions

Different evaluation techniques are used to assess glenohumeral stability, although not all end up being applied to dynamic exercises. In this evaluation methodology, surface electromyography and high-speed cameras predominantly gather kinetic and kinematic data, alongside muscle activity, which can be inferred as an indirect measure of glenohumeral stability. Typically, these technologies are not used in isolation but are combined with other measurement tools that provide isometric or dynamic force data, like dynamometers, or pressure force data, such as sensors and force platforms. Linear velocity transducers are increasingly used to incorporate velocity loss data as an indicator of kinematic fatigue, which is also a predictor of glenohumeral instability.

The methodologies compiled in this review enable their application in a clinical setting; however, they do not provide a direct measure of glenohumeral stability. Research should therefore focus on developing precise and direct techniques that provide data on joint stability and apply to the clinical context.

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CRediT authorship contribution statement

Antonio Ignacio Cuesta-Vargas: Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Data curation, Conceptualization. **Laura Ramírez-Pérez:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Graham K. Kerr:** Writing – review & editing, Visualization, Validation, Supervision, Project administration, 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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Table 1
Table A.1. Characteristics of the included studies.

References	Population	Sample size	Type of exercise	Evaluation methodologies
Borms et al. [24]	Healthy people Age: 22.5 ± 1.33 Male: 15 (48.4 %)	N = 31	Bilateral upper limb elevation with shoulder external rotation into five variations: open hand, closed hand, dynamic bipedal squat, static unipedal squat and dynamic unipedal squat	EMG (1000 Hz): four bipolar surface electrodes placed over the serratus anterior and the three parts of the trapezius muscle on the dominant side. In addition, a reference electrode was placed over the ipsilateral clavicle. 3D motion capture system (100 Hz): two reflective markers applied 5 cm distal to the middle acromion and 5 cm proximal to the lateral humeral epicondyle.
Bullock et al. [45]	High school baseball pitchers Age: 16.3 ± 1.2 Male: 33 (100 %)	N = 33	First, isometric external and internal rotation; and second, throwing exercises: four fastballs, four breaking balls and four changeups to a catcher receiving throws at 18.4 m	Handheld dynamometer: placed on the proximal dorsal wrist surface for external rotation and volar surface for internal rotation. 3D motion capture system (250 Hz): four reflective markers placed on the trigonum spinae and inferior angle of each scapular. In addition, a reference marker was placed at L5.
Elert et al. [31]	Neck/shoulder problems (1 year) Age: no data Male: 0 (0 %)	N = 23	Dynamic maximum shoulder flexions with standardized contraction frequency	EMG (2000 Hz): three bipolar surface electrodes placed over the descending part of the trapezius, the anterior part of the deltoid, and the infraspinatus muscles. Isokinetic dynamometer: positioned according to the user manuals.
Franco-García et al. [36]	Healthy weightlifters Age: 21.4 ± 1.5 Male: 17 (63 %)	N = 27	Bench press exercise at maximum velocity among three intervals: 55–75 % RM, 75–85 % RM and 85–100 % RM, with different loads	3D motion capture system (240 Hz): participants placed their hands shoulder-width apart maintaining and equal separation from the barbell middle point. From that position data, velocity and acceleration data is calculated.
Friesen et al. [37]	High school softball pitchers Age: 16 ± 2 Male: 37 (100 %)	N = 37	Throwing exercises: fastballs for strikes (until 10 strikes) to a catcher located at 13.1 m	3D motion capture system (240 Hz): fourteen electromagnetic sensors affixed to body segments. In addition, a fifteenth sensor attached to a plexiglass stylus to identify joint positions and create local segment axes.
Goubault et al. [25]	Manual laborers Age: 30.9 ± 5.5 Male: 32 (100 %)	N = 32	Lifting task: moving an instrumented box from a table (73 cm) to a storage shelf adjusted at each participants' eye level	EMG (2000 Hz): surface electrodes placed over the deltoids (anterior, lateral, and posterior), biceps and triceps brachii, upper trapezius and pectoralis major. In addition, intramuscular electrodes were inserted into the infraspinatus, supraspinatus, and subscapularis muscles. 3D motion capture system (100 Hz): thirty-four reflective markers positioned on the trunk and the dominant side of participants. Force sensors: three six-axis force sensors on the lateral and anterior faces of the box.
Hernández -Belmonte et al. [50]	Healthy subjects with > 4 years of strength training Age: 22.1 ± 3.5 Male: 48 (100 %)	N = 48	Shoulder press exercise: concentric phase at maximal intended velocity and eccentric phase at a controlled mean propulsive velocity	Linear velocity transducer (1000 Hz): force transducer was located on the barbell.
Johnson et al. [46]	US special forces personnel Age: 27.6 ± 5.2 Male: 121 (100 %)	N = 121	Five movements: elevation, protraction, retraction, internal rotation, and external rotation. Five concentric repetitions for each exercise at 60 degrees per second.	3D motion capture system (250 Hz): twenty-eight reflective markers were placed bilaterally at the acromioclavicular joint, acromion, acromial angle, medial border and inferior angle of the scapula, epicondyles, styloid processes of the ulna and radius, caput of the second metacarpal, C7, T10, jugular notch and xiphoid process. Isokinetic dynamometer: positioned according to the user manuals.
Kok et al. [26]	Professional violinists Age: 29 Male: 4 (20 %)	N =20	Four playing conditions: open strings, first position, shifts and virtuosic.	EMG (1000 Hz): bipolar surface electrodes placed bilaterally over the sternocleidomastoid, upper trapezius, and anterior part of deltoid muscles. Force sensors: 6D mini force-sensor built into the violin chinrest.
Laudner et al. [38]	NCAA, Division I baseball pitchers Age: 20 ± 1.3 Male: 34 (100 %)	N = 34	Throwing exercises: five fastballs for strikes to a catcher located at 18.4 m	3D motion capture system (240 Hz): twenty-six reflective markers were placed bilaterally at radial and ulnar styloids, third metacarpal, superior lateral acromions, lateral humeral epicondyles, anterior and posterior hips, medial and lateral femoral epicondyles, medial and lateral malleoli, between second and third metatarsal heads and the calcaneus.

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Table 1 (*continued*)

References	Population	Sample size	Type of exercise	Evaluation methodologies
Laudner et al. [39]	NCAA, Division I baseball pitchers Age: 19.4 ± 1.2 Male: 55 (100 %)	N = 55	Throwing exercises: three fastballs thrown for strikes at 18.4 m	3D motion capture system (240 Hz): twenty-six reflective markers were placed bilaterally at radial and ulnar styloids, third metacarpal, superior lateral acromions, lateral humeral epicondyles, anterior and posterior hips, medial and lateral femoral epicondyles, medial and lateral malleoli, between second and third metatarsal heads and the calcaneus.
Lin et al. [40]	Elite baseball throwers Age: 23.6 ± 0.5 Male: 57 (100 %)	N = 57	Throwing exercises: ten overhand fastballs with maximal effort from the pitching mound toward a catcher positioned at the home plate.	3D motion capture system (300 Hz): reflective markers placed on joint centers of knee, pelvic, trunk and shoulder.
Murgia et al. [47]	Healthy young and older adults Age: 42.4 ± 18.6 Male: 9 (45 %)	N = 20	Functional tasks: reaching to the ipsilateral and the contralateral side; and hair-combing in three directions (left, middle and right side)	3D motion capture system (100 Hz): eleven virtual markers, four markers and four rigid bodies were located on suprasternal notch, xiphoid process, T10, left and right anterior iliac spine, left and right posterior superior iliac spine, ulnar styloid, radial styloid, lateral epicondyle, medial epycondile, left and right acromion, C7, chest, back, lower arm, upper arm, and right hand. Isokinetic dynamometer: positioned according to the user manuals.
References	**Population**	**Sample size**	**Type of exercise**	**Evaluation methodologies**
Nascimiento et al. [27]	Weight trained for > 6 months Age: 20.9 ± 1.8 Male: 20 (100 %)	N = 20	Lifting exercises: bench press and horizontal fly on stable (bench) and unstable (proprioceptive disc) surfaces	EMG (2000 Hz): bipolar surface electrodes were placed on biceps brachii, anterior and posterior deltoid, triceps brachii, clavicular fibers of pectoralis major, serratus anterior, and upper, middle and lower trapezius on the dominant side.
Nicholson et al. [41]	Baseball pitchers Age: no data Male: 70 (100 %)	N = 70	Throwing exercises: fastballs, breaking balls and changeups to a catcher positioned at 18.4 m	3D motion capture system (250 Hz): forty-one retroreflective markers were placed on anatomic landmarks following the recommendations of the PitchTrack Model.
Oliver et al. [28]	Healthy college students Age: 22.9 ± 3.4 Gender: no data	N = 26	Resistance-band exercises: “Y, I and T position”. In addition, airplane external and internal rotation, lunge with “W position”, get up with “hand to the ceiling” and single-leg balance with scapula protaction/retraction.	EMG (1000 Hz): bipolar surface electrodes placed over the latissimus dorsi, lower trapezius, upper trapezius and serratus anterior on the dominant side.
Ortega-Cebrián et al. [32]	SIS patients and healthy subjects Age: 27.2 ± 1.9 Male: no data	N = 68	Three movements: flexion scaption and abduction. Each movement was performed three times at different speeds: slow, medium, and fast.	EMG (2000 Hz): bipolar surface electrodes were placed on upper and lower trapezius, serratus anterior, anterior, medial and posterior deltoid, and pectoralis major. In addition, indwelling electrodes were placed on supra/infraspinatus and subscapularis.
Oyama et al. [42]	High school baseball pitchers Age: 15.5 ± 1.2 Male: 72 (100 %)		Throwing exercises: fastballs aiming at an “X” marked at the center of the strike zone at 18.4 m	3D motion capture system (300 Hz): forty reflective markers were placed on chin, sternal notch, C7, xyphoid process, T8, third metacarpal on dominant side, radial and ulnar styloids, medial and lateral humeral/femoral epycondiles, acromion, anterior and posterior superior iliac spine, greater trochanter, anterior thigh, anterior shank, medial/lateral malleolus, fifth metatarsal styloid, first metatarsal head, and front, right and left side of the head.
References	**Population**	**Sample size**	**Type of exercise**	**Evaluation methodologies**
Pogetti et al. [48]	Handball / baseball / softball athletes Age: 21.6 ± 0.4 Male: 43 (78.2 %)	N = 55	Two movements: internal and external rotation at three velocities (90°/s, 180°/s and 240°/s). Five maximal repetitions of each movement.	Isokinetic dynamometer: positioned according to the user manuals.
Poploski et al. [35]	US marines Age: 26.2 ± 0.4 Male: 52 (100 %)	N = 52	Two movements: internal and external rotation at maximal strength. Push-up task: pushing explosively and completely off the force plates.	Isokinetic dynamometer: positioned according to the user manuals. Force plate: each hand placed on a separate force place at approximately chest level.
Post et al. [43]	NCAA Division I baseball pitchers Age: 19.5 ± 1.2 Male: 67 (100 %)	N = 67	Throwing exercises: five fastballs to the strike zone at 18.4 m	3D motion capture system (240 Hz): twenty-six reflective markers were placed on bilaterally at the lateral tip of the acromions, lateral humeral/femoral epycondiles, anterior superior iliac spines, base of the sacrum, medial and lateral malleolus, calcaneus, radial and ulnar styloids, third metacarpal on dominant side, between second and third metatarsal heads, and top, right, and left side of the head.
Rajaratnam et al. [33]	ASI patients and healthy subjects Age: 25.2 ± 2.4 Male: 41 (93.2 %)	N = 44	Two movements: abduction and flexion. Each movement was performed nine times.	EMG (1800 Hz): bipolar surface electrodes were placed on the posterior deltoid, bilateral upper trapezius, and biceps brachii. In addition, intramuscular fine wires were inserted into the infraspinatus, supraspinatus and teres major.
Ramappa et al. [44]	Professional and youth pitchers Age: no data Male: 52 (100 %)	N = 52	Throwing exercises: full pitch cycle from preparation to final maximum shoulder internal rotation.	3D motion capture system: twenty-one bony landmarks were hand digitalized from 50 ms before the ball left the glove to 500 ms after the ball was released.
References	**Population**	**Sample size**	**Type of exercise**	**Evaluation methodologies**

(*continued on next page*)

Table 1 (*continued*)

References	Population	Sample size	Type of exercise	Evaluation methodologies
Szeto et al.[34]	Office workers Age: 34.8 ± 4.3 Female: 41 (100 %)	N = 41	Three screen-based typing: "normal" at normal speed and force, "faster" with a 20 % increase in speed, and "harder" with a 20 % increase in force.	EMG (1000 Hz): bipolar surface electrodes were placed bilaterally on cervical erector spinae, upper and lower trapezius, and anterior deltoids.
Torres-Banduc et al. [49]	CrossFit training participants Age: 24.1 ± 0.4 Male: 22 (100 %)	N = 22	Three movements: external diagonal, internal rotation, and external rotation.	Isokinetic dynamometer: positioned according to the user manuals.
Turpin et al. [29]	Healthy subjects Age: 24.0 ± 3.6 Male: 16 (53.3 %)	N = 30	Lifting-lowering task: moving a 6, 12 or 18 kg box from one shelf to another (three different heights, adjusted to the hip, shoulder and eye levels). Three trials were performed for each height, weight, and direction condition.	EMG (1000 Hz): bipolar surface electrodes were placed over the anterior, middle, and posterior deltoid, long heads of the biceps brachii and triceps brachii, superior and lower trapezius, serratus anterior, sternal portion of pectoralis major and latissimus dorsi. In addition, intramuscular fine-wire electrodes were inserted into the infraspinatus, supraspinatus, and lower subscapularis.
Vaseghi et al. [30]	Healthy subjects Age: 23.5 Male: 17 (56.7 %)	N = 30	Push-up task: (1) without external load, (2) with external load of 2 % of BW, (3) with external load of 4 % of BW, (4) with the dominant hand on the center of a wobble board and the other on a stable surface, (5) with the dominant hand on a medicine ball located on the center of a wobble board and the other on a stable surface	EMG (1000 Hz): bipolar surface electrodes were placed bilaterally on upper and lower trapezius, serratus anterior, long head of the biceps brachii, posterior deltoid and teres major.

ASI: Anterior Shoulder Instability; BW: Body Weight; EMG: Electromyography; NCAA: National Collegiate Athletic Association; SIS: Shoulder Impingement Syndrome; US: United States

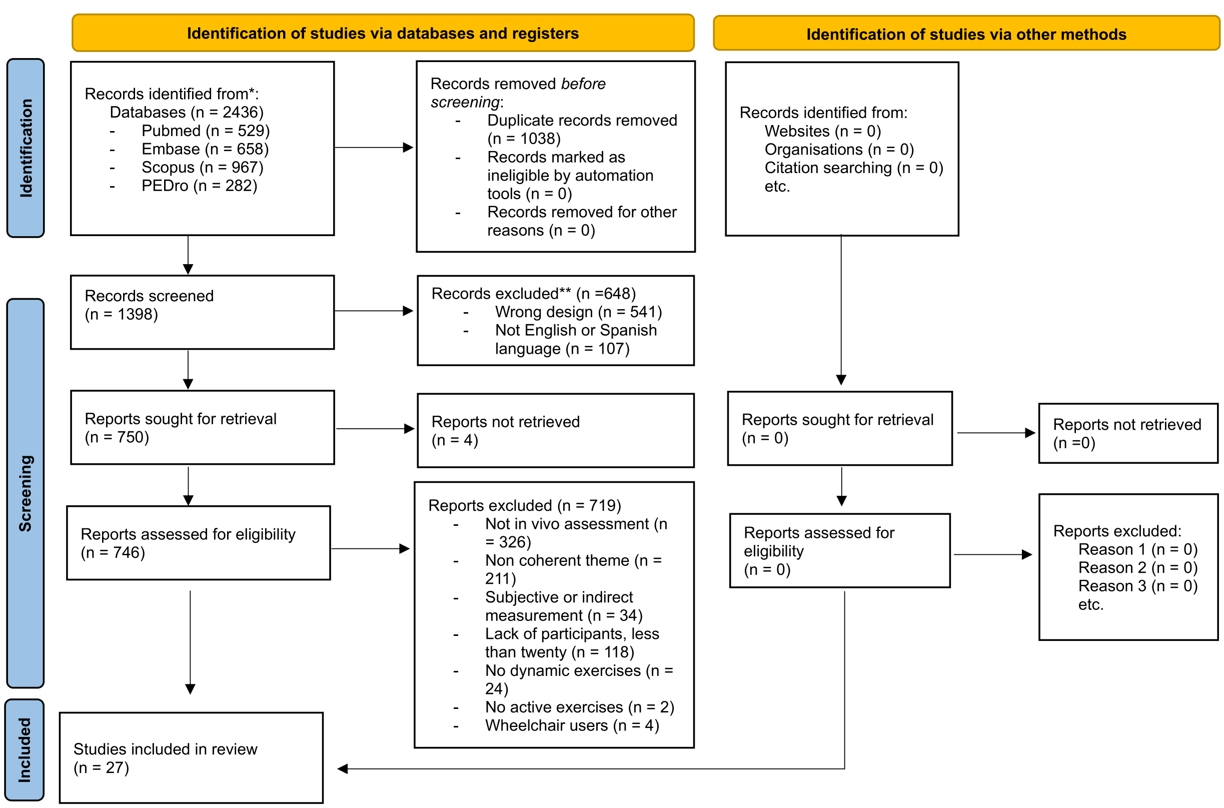
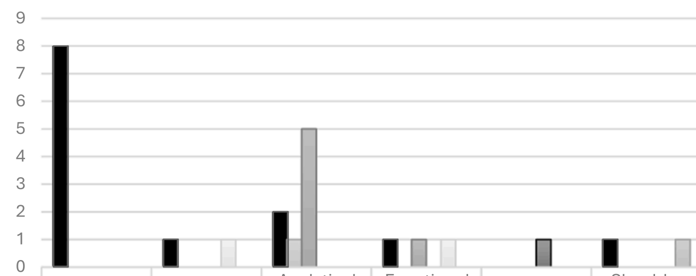


Fig. A.1. Figure A.1. Selection of studies. PRISMA 2020 flow diagram.



	Throwing	Lifting tasks	Analytical movements	Functional tasks	Push-ups	Shoulder press
3D motion capture system	8	1	2	1	0	1
Handheld dynamometer	0	0	1	0	0	0
Isokinetic dynamometer	0	0	5	1	0	0
Force plates	0	0	0	0	1	0
Force sensors	0	1	0	1	0	0
Linear velocity transducers	0	0	0	0	0	1

Fig. A.2. Figure A.2. Distribution of the evaluation methodologies applied per each type of exercise.

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