Biomechanical studies for glenoid based labral repairs with suture anchors do not use consistent testing methods. A critical systematic review

Erik Hohmann*
MBBS, FRCS, FRCS (Tr & Orth), MD, PhD
Faculty of Health Sciences, University of Pretoria, Pretoria, South Africa
Burjeel Hospital for Advanced Surgery, Department of Orthopaedic Surgery and Sports Medicine
ehohmann@hotmail.com

Vaida Glatt
PhD
University of Texas Health Science Center, San Antonio, Texas, USA
v.glatt@gmail.com

Kevin Tetsworth
MD, FRACS
Department of Orthopaedic Surgery, Royal Brisbane Hospital, Herston, Australia
Department of Surgery, School of Medicine, University of Queensland, Australia
Limb Reconstruction Centre, Macquarie University Hospital, Sydney, Australia
kevin.tetsworth@health.qld.gov.au

Nikolaos Paschos
MD
Department of Orthopaedic Surgery, Harvard Medical School
Massachusetts General Hospital
Boston, MA, USA
paschos.nikolaos@gmail.com

***Corresponding Author:**
Erik Hohmann
Medical School, University of Pretoria
Pretoria, South Africa
drerik@burjeelspecialty.com

Abstract

Purpose:

The purpose of this systematic review was to investigate variability in biomechanical testing protocols for laboratory-based studies using suture anchors for glenohumeral shoulder instability and SLAP lesion repair.

Methods:

A systematic reviewing of Medline, Embase, Scopus and Google Scholar using Covidence software was performed for all biomechanical studies investigating labral-based suture anchor repair for shoulder instability and SLAP lesions. Clinical studies, technical notes or surgical technique descriptions, or studies treating glenoid bone loss or capsulorraphy were excluded. Risk of bias (ROB) was assessed with the ROBINS-I tool. Study quality was assessed with the QUACS (Quality Appraisal for Cadaveric Studies). Heterogeneity was assessed with the I^2 statistic.

Results:

A total of 41 studies were included. ROB was serious and critical in 27 studies, moderate in 13, and low in one; six studies had high quality, 21 good quality, 10 moderate quality, 2 low quality, and 2 very low quality. 31 studies used and 22 studies included cyclic loading. Angle of anchor insertion was reported by 33 studies. The force vector for displacement varied. The most common directions were perpendicular to the glenoid (9), and antero-inferior or anterior (8). The most common outcome measures were load to failure (35), failure mode (23), and stiffness (21s). Other outcome measures included load at displacement, displacement at failure, tensile load at displacement, translation, energy absorbed, cycles to failure, contact pressure, and elongation.

Conclusion:

This systematic review demonstrated a clear lack of consistency in those cadaver studies that investigated biomechanical properties following surgical repair with suture anchors for shoulder instability and SLAP lesions. Testing methods between studies varied substantially with no universally applied standard for preloading, load to failure and cyclic loading protocols, insertion angles of suture

anchors, or direction of loading. To allow comparability between studies standardisation of testing protocols is strongly recommended.

Keywords:

Shoulder instability; laboratory studies; cadaveric studied; suture anchors; biomechanical properties; load to failure; systematic review

Clinical relevance

The demonstrated heterogeneity between testing protocols for basic science biomechanical studies makes between study comparisons difficult. Standardised testing protocols are recommended.

Introduction

Shoulder instability is common among young athletes, and most often occurs in the anterior direction. [1,2] The optimal treatment for traumatic anterior glenohumeral dislocations remains controversial. [3,4] However, the available evidence suggests that young active adults engaging in highly demanding physical activities benefit from primary surgery. [3-5] If surgery is indicated modern arthroscopic repairs include the use of suture anchors, and the results provide equivalent outcomes to open surgery. [6] Ideal insertion of suture anchors should be performed 2-3 mm from the glenoid rim at an angle of 45 degrees. [7] Superior labral anterior to posterior tears were first described by Andrews, [8] and the term SLAP lesion was later introduced by Snyder et al in 1990. [9] If symptomatic repair with suture anchors is performed it predictably results in and good to excellent outcomes in over 80% of patients. [10-12]

Over the past 30 years, numerous studies have reported on the influence of several biomechanical variables for suture anchors that are used to treat shoulder instability. [13-18] However, several authors have raised criticism that variation in testing methodology may not allow between study comparisons.

[19-22] In general, testing protocols for biomechanical studies should be standardized to allow for meaningful comparisons, [19,20] and this standardization would also help to reduce variability between research groups. [19,20] For example, Virk et al. performed a systematic review comparing biomechanical studies of disc repair devices and was unable to delineate common test parameters, concluding there was too much variation in testing methodology and reporting of results. [19] Furthermore, Steiner et al. reported that axial compressive testing in small animal fracture models can lead to measurement errors of up to 80%, and bending tests show a large dependency on loading direction. [21] Gedney reported that strain rates with wire tie tests are speed dependent, and increasing speeds from 2 in/min to 16 in/min resulted in a 7% increase in peak load and 200% decrease in elongation. [22] Finally, a recent systematic review investigated rotator cuff repair methods in cadaver models, and reported substantial variation for testing protocols with respect to scapular orientation, simulation of muscle activation, capsular status, and rotator cuff force. [23]

The purpose of this systematic review was to investigate variability in biomechanical testing protocols for laboratory-based studies using suture anchors for glenohumeral shoulder instability and SLAP lesion repair. It was hypothesized that studies used a variety of different biomechanical test protocols and variables, compromising the ability to compare between study results.

Methods

The methods described in the Cochrane Handbook were used to perform this systematic review. [24] The Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) guideline statements were used to report the results of this review. [25]

Eligibility Criteria

All biomechanical studies for shoulder instability using labrum-based and capsulo-labral repair techniques for both anterior and posterior shoulder instability, SLAP repair, and general laboratory-based biomechanical testing of shoulder suture anchors were included.

Clinical studies, technical notes, or descriptions of surgical techniques were excluded. Studies investigating treatment of glenoid bone loss or studies testing capsulorraphy techniques were also excluded. Conference proceedings or abstracts, expert opinions (level V), systematic reviews, meta-analyses, and review articles were also excluded.

Information Sources and Literature Search

The Covidence software program was utilized to assist screening all available studies. This software allows screening by title and abstract, applying inclusion and exclusion criteria. A systematic search utilizing Medline, Embase, Scopus, and Google Scholar databases was performed to identify all publications in the English and German literature from January 1970 through February 2021. The following search terms, its synonyms, and all possible combinations were utilized: “cadaveric”, “biomechanical”, “shoulder”, “glenohumeral” “instability”, “labrum repair”, “anchor”, “stabilization”. In addition, all references of the included articles were also reviewed for missing studies.

Data extraction and quality assessment

Two independent reviewers screened all titles and abstracts based on the criteria described. Each study was assessed as eligible by voting yes, maybe, or not eligible. All voting was blinded and all references that were deemed eligible were carried forward for full text review. Discrepancies between the reviewers (EH, NP) were discussed and resolved by consensus. Maybe votes were carried forward into full text screening. For studies that met the inclusion criteria, an electronic data extraction form was used to obtain the following information from each article: author, journal, and year of publication, conflicts of interest, sample size, testing and surgical protocols, and outcomes. The level of evidence (LOE) was extracted from the full text, and if no LOE was identified the LOE was established in line with recent guidelines. [26] Risk of bias was assessed using the ROBINS-I tool. [27] The ROBINS-I tool examines the following domains of bias: confounding, selection bias, bias in classification of interventions, bias due to deviations from intended interventions, bias due to missing data, bias related to measurement of outcome, and bias in the selection of the reported results. Each domain of bias is evaluated with one of the following responses: “yes”, “probably yes”, “probably no”, and “no”, with probable responses having similar implications as “yes” or “no” but are not absolute. The categories of judgement for each study are low, moderate, serious, and critical risk of bias. [27]

Methodological quality of the cadaveric studies was assessed with the QUACS scale. [28] The QUACS scale was initially constructed to assess quality of observational cadaveric studies and includes 13 items: basic information about sample, methods are described comprehensively, condition of the examined specimens is reported, education of researcher is stated, findings are observed by more than one researcher, results are presented thoroughly, statistical methods are adequate, details about consistency of findings are given, photographs are included, study is discussed within context of the current evidence, clinical implications are discussed, limitations are addressed. [28] If these individual items were present a ‘yes’ was scored. The sum of all scores was then converted into a percentage to harmonize the scoring system. [29] A score of >90% was then defined as high quality, a score of 80% as good quality, a score between 60-79% as moderate quality, a score between 40-50% as low quality and a score below 40% as very low quality. These scores were adapted from measurement of observer agreement. [31] It is recognized that this adoption may have resulted in observer bias. However, interobserver agreement was 0.93, reducing the likelihood of significant error.

Data Synthesis and Analysis

Heterogeneity within and between studies was assessed with the I^2 statistic. The I^2 statistic and publication bias were calculated using the Comprehensive Meta-Analysis software package (CMA), version 3 (Biostat Inc, Englewood, NJ, USA).

Results

Study selection and characteristics

The initial search was performed on February 1st, 2021 and identified a total of 3204 studies. Following removal of duplicates and abstracts, the full text versions of 1831 articles were appraised. 1729 of these articles were then excluded, and 102 full text articles were evaluated. After further detailed review, forty-one articles remained and were included in the qualitative synthesis (tables 1-3). [13-15,17,18,31-66] Of those studies, three described the general properties of suture anchors in shoulder instability using polyurethan foam [31-33] and one study used fresh frozen specimens. [35] Nine studies tested suture anchors for SLAP repairs, [13,14,35-41] and 28 studies [15,18,19,42-66] tested suture anchors for the treatment of Bankart lesions. The details of study selection are summarized in the PRISMA Flow Diagram in figure 1. Overall agreement between the two reviewers for final eligibility was excellent (kappa value 0.88, 95% CI 0.84-0.92). All 41 included studies were published in English between 1993 and 2020 [tables 1-3].

Risk of bias

The findings of the risk assessment for bias using the ROBINS-I tool are summarized in table 4. If the authors did not perform bone density measures for their specimens the risk of bias was considered serious, and 23 of the 28 studies using fresh frozen cadavers fulfilled this criteria. [13,14,34-39,41,45,46,49-54,57-59,62,64] This assessment was based on the study y Ambrose et al., who demonstrated that results of biomechanical studies lacked consistency and were associated with variability of bone mineral density. [67] Four studies had an overall critical risk of bias. [16,43-45] These studies were all performed in the 1990s and were downgraded to critical for bias in the classification of interventions. Twenty-three studies [13,14,34-41,45,48,49-54,57,58,61,62,64] did not measure bone density and were assessed as having a serious overall risk of bias, and 13 studies [17,31-33,49,55,56,59,60,63,65,66] had an overall moderate risk of bias. Only one study was assessed as low risk of bias. [17]

Study Quality

Utilizing the QUACS scale, two of the general shoulder instability articles [31,32] had high quality, one study moderate quality, [33] and one study low quality [table 5]. [34] For the treatment of SLAP lesions, one study had high quality, [14] six studies good quality, [13,35,36,37,39,40] and one study moderate quality. [38] Only three studies investigating suture anchors for shoulder instability had high quality. [59-61] Fifteen studies had good quality, [17,18,43,44,47,48,50-52,54-56,62,65,66] eight studies had moderate quality, [33,45,49,53,57,58,63,64] one study low quality, [15] and two studies [42,46] had very low quality. Overall, 27 of the 42 (64%) included studies had either good or high quality. The funnel plot for publication bias [Figure 2] appeared asymmetrical, and Eggers' test (Eggers intercept 3.894, standard error 0.782 [95% CI: 2.309-5.478], z-value 23.86, p=0.0001) suggested publication bias. Heterogeneity using the I^2 statistic was calculated to be 96.05; according to the Cochrane Handbook this suggests considerable heterogeneity. [24]

Testing Methods and Test Set-up

Testing methods varied substantially between studies and there was no consistency. However, there was consistency with regards to loading. All studies, with the exception of Uggen et al., [40] have used a materials testing machine for preload, load to failure, and cyclic loading. Thirty-one studies preloaded specimens prior to testing, but the loads varied between 1 to 25N. Load to failure loading rates ranged from 1 mm/sec to 5 mm per minute. The most common load to failure speed was 12.5 mm/sec but only 4 of the 41 studies used this speed. [32,33,56,62] Twenty-one studies [13,14,32,3539,40,43,45,46,48,49,54,55,58,59,63-66] included cycling loading, but the protocols varied between studies [tables 1-3]. There was no consistency for cycling loading protocols, and only four studies [17,55,,59,61] used the same protocol; three studies [55,59,61] used a previously published protocol. [17]

Sixteen studies reported the angle of suture anchor insertion, and 13 studies used a 45^{o} degree insertion angle while three studies used a 30^{o} degree insertion angle. The force vector of pull load varied between studies. In nine studies the force vector was directed perpendicular to the glenoid.[18,31,34,35,39,40,52,54,66] In eight studies the force vector was directed anterior or antero-inferior.[17,38,51,55,56,57,59,61] In eight studies the force vector was not reported.[32,33,41,42,45,50,62,64] Other studies used a force vector perpendicular to anchor insertion,[13,63] posterior direction,[14,36] vertical direction,[15,43] in line with anchor insertion,[46,48,53] in line with glenoid,[65] or various angles posterior direction[37,49] and three studies used humeral translations.[44,47,58]

Outcome Measures

Load to failure, mode of failure, and stiffness were the most commonly reported outcome measures. Thirty-five studies included load to failure[14,15,17,18,32-34,36-42,45-52,54-66] and this was the most commonly used outcome measure. Twenty-three studies reported failure mode.[13,17,32-35,37-39,48,49,51,53,55,56,59,66] Twenty-one studies reported stiffness as an outcome measure.[14,17,31,35,36-38,39,40,44,47,49-55,58,61,63,65] Other outcome measures included load at displacement, displacement at failure, tensile load at displacement, translation, energy absorbed, cycles to failure, contact pressure, and elongation (tables 1-3).

Discussion

The results of this systematic review established a clear lack of consistency between laboratory-based studies investigating biomechanical properties for surgical repair with suture anchors in shoulder instability and SLAP lesions. The testing methods varied substantially, with no universally applied standard for preloading, load to failure, and cyclic loading protocols. Similarly, the authors have used different insertion angles for suture anchor placement into the glenoid, resulting in considerable variability. In addition, only 38% of the studies described the insertion angles in their methods. The direction of loading is defined by the vector at which the anchors were loaded with regards to the orientation of the glenoid. The direction of loading of the anchors and constructs also varied highly, and ten different directions of load were used by the 41 studies included. Load to failure was the most commonly used outcome variable and was reported by 81% of the studies; mode of failure (56%) and stiffness (51%) were other commonly reported outcome measures. Uncommon outcome measures included load at displacement, displacement at failure, tensile load at displacement, translation, energy absorbed, cycles to failure, contact pressure, and elongation.

Cadaveric studies are important and indispensable tools to investigate surgical implants and techniques. However, to allow study comparability it is imperative that study design, methodology, and outcome measures are similar. The lack of widely accepted or universally followed standard protocols may not allow reliable and valid comparisons. Comparability is even more important when synthesizing qualitative and quantitative studies, and the variability in study methodology possibly prohibits comparison between seemingly uncombinable and incomparable studies. [68] In fact, it makes systematic reviews reliably unreliable, if the included studies use different study designs and testing protocols. [68] One could strongly argue that the clear lack of consistency with regards to testing methods, testing set-up, and outcome measures demonstrated by this systemic review could be viewed as a worst-case scenario. Classical test theory has proposed that the true score can only be obtained on repeated measurements. [69] As the result of the inability to validate individual studies by independent researchers, this lack of validation then creates doubts regarding the legitimacy of their study conclusions. Furthermore, although these studies may have internal consistency, they cannot be generalized or validated. Interestingly, the study quality of the included studies in this systematic review was good or high in 66%, and only one study (2%) had low quality. This suggests that the studies themselves do not suffer from major methodological issues, but the lack of standardisation of testing protocols simply does not allow comparisons or validation.

Risk of bias was high or critical in 27 of the 41 included studies in this review. The most common reason for the serious risk of bias assessment was the lack of bone density measures performed for the human cadaveric specimens used in the testing protocol. Twenty-three studies (57%) did not measure bone density, and the item ‘bias in selecting of participants’ was assessed by both reviewers as serious. It may of course be argued that bone density is not an important denominator, and has only minor influence on the study results both within and between studies. However, Ambrose et al. clearly demonstrated that interference screw fixation of tendons in bone specimens with a T-score of -2.5 (BMD 0.325 g/cm^2) had only 50% of the ultimate strength compared to normal bone density (0.50 g/cm^2). [67] This observation [67] therefore provides a very powerful argument that bone density assessment should be included in human cadaver studies, and supports the omission as a serious risk of bias. According to Cochrane, this proportion of high risk of bias alone is sufficient to affect the interpretation of results. [24]

Prior publications have previously reported inconsistent study design and testing methods. [19,23] Williamson et al. performed a systematic review of cadaveric methodology for studies involving rotator cuff repair and instability and also described considerable variability for scapula orientation, muscle activation strategies, and status of the joint capsule. [23] This heterogeneity of study protocols has affected other subspecialty areas as well, and when Virk et al. compared biomechanical studies of disc repair devices they also could not identify any common features across models. [19] They concluded that direct comparison of results from preclinical models is not possible, and called for greater standardisation of biomechanical models. [19] Although testing methodologies for biomechanical studies have evolved over the past 50 years standard testing protocols have not been developed, making comparisons between experiments difficult and conclusions about in vivo performance challenging. [70]

It seems obvious that biomechanical studies suffer from lack of comparability. The reasons are mainly related to the large variance between study protocols which reduces external but also internal validity, as the individual study results cannot be confirmed nor refuted by other authors. To maintain a high standard of science and enable researchers and clinicians to compare studies, it seems imperative to develop standardized protocols for basic biomechanical cadaver studies. For pharmacological studies this has already been implemented and is governed by legislation. For example, the Federal Drug Administration [FDA] has clear guidelines for comparability protocols for human drugs and biologics, and there is no compelling reason why the orthopaedic community cannot develop similar protocols. [71] Paschos et al. have previously provided some guidance in this regard, and suggested that study methodology should be reproducible, validated and based on already established models. [72] One potential solution to achieve study validity is to require previously described protocols with supporting references. [72] However, this approach still allows variability rather than standardisation.

Limitations

One of the limitations of this systematic review is the lack of validated quality assessment tools. The tools used to assess study quality was the QUACS scale. The QUACS scale has an ICC of 0.87, with a strong association between expert rating and the means of the QUACS scale. [28] Wilke et al. developed this scoring system, defining high, good, moderate, and low quality, and these definitions themselves may have caused observer bias. [28] In addition, the limitations of this systematic review also reflect the limitations of the included studies. Risk of bias was high for 23 studies, and this assessment was primarily based on the lack of bone density assessment. This criterion was developed by the authors, and it is possible that this definition has itself resulted in bias.

Conclusion

This systematic review demonstrated a clear lack of consistency in those cadaver studies that investigated biomechanical properties following surgical repair with suture anchors for shoulder instability and SLAP lesions. The testing methods between studies varied substantially with no universally applied standard for preloading, load to failure and cyclic loading protocols, insertion angles of suture anchors, or direction of loading. In order to allow comparability between studies standardisation of testing protocols is strongly recommended.

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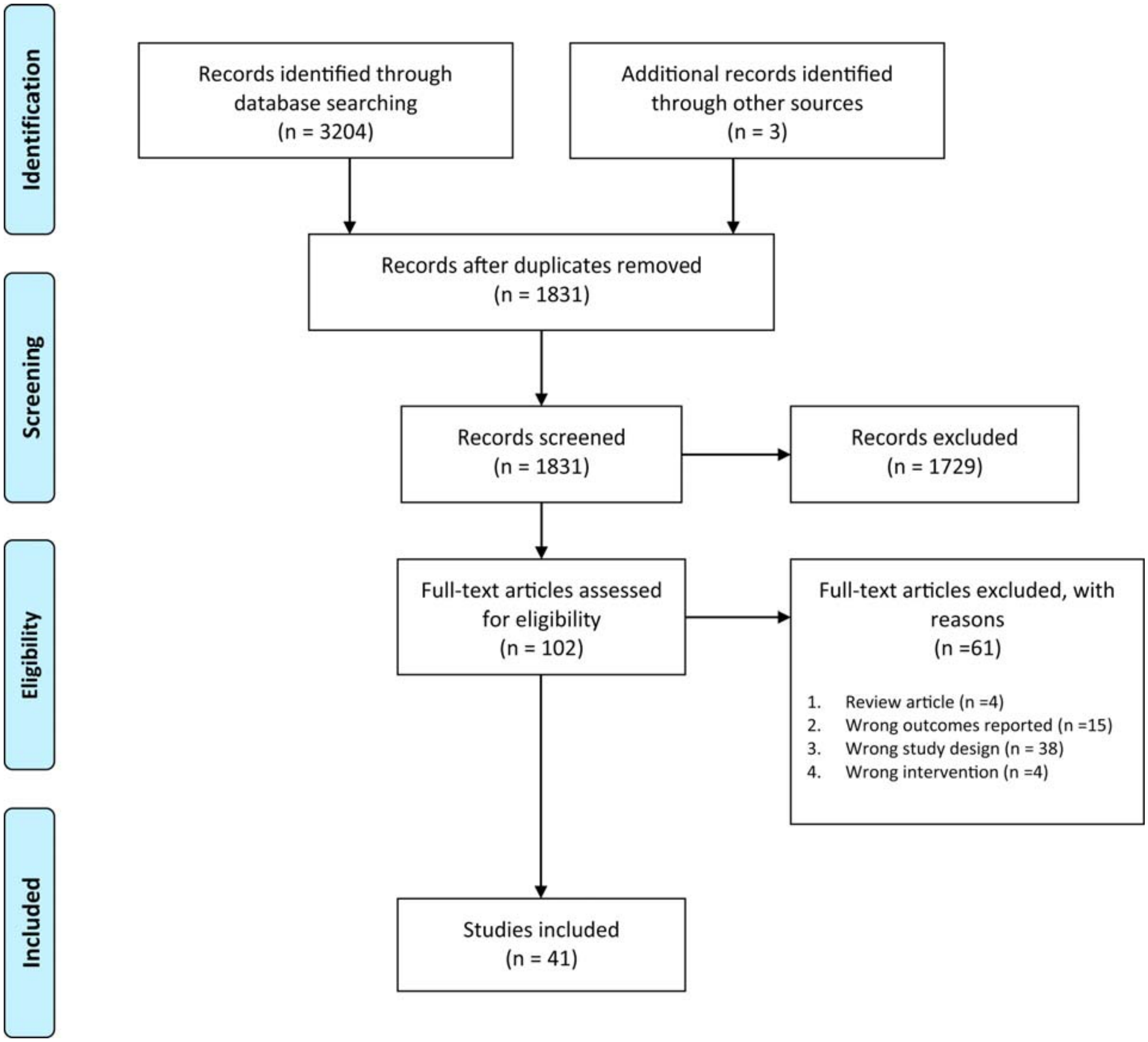

Figure 1:

The initial search identified a total of 3207 studies; 1831 records were screened, 102 full text articles assessed for eligibility and 41 studies were included in the qualitative synthesis.

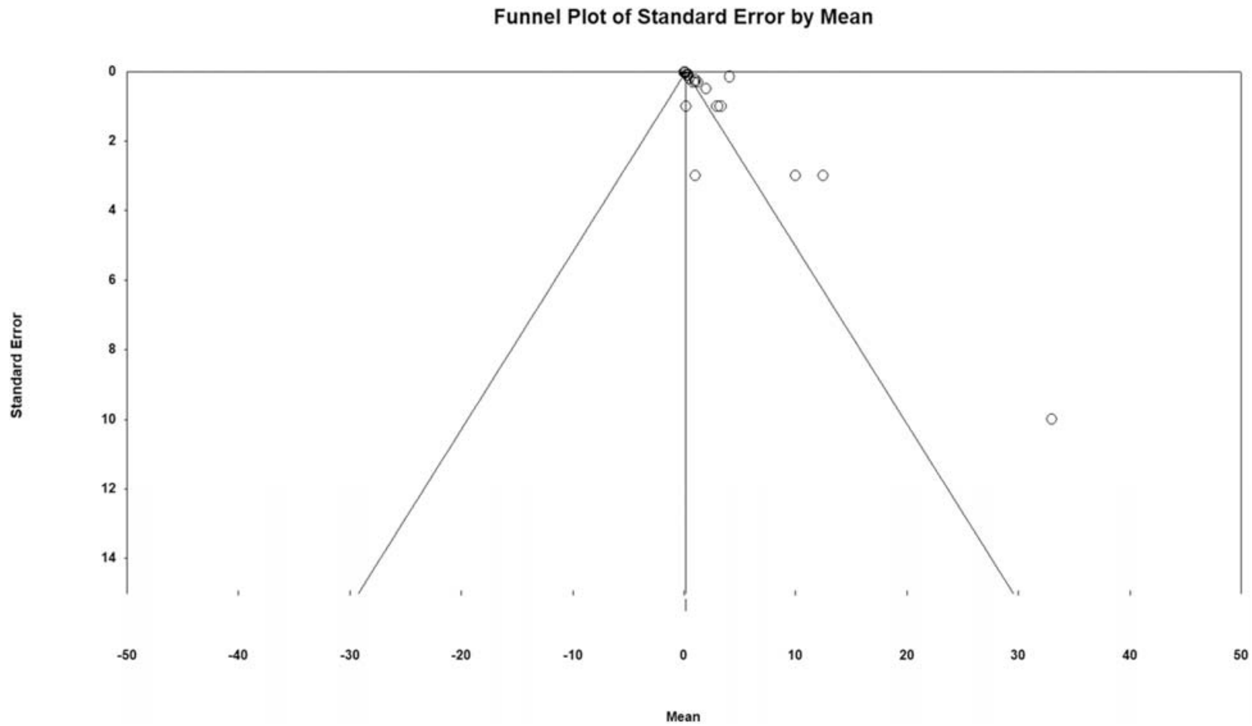

Figure 2: The funnel plot for publication bias is asymmetrical. Eggers' test (Eggers intercept 3.894, standard error 0.782 [95% CI: 2.309-5.478], z-value 23.86, p=0.0001) suggested publication bias.

Table 1: Studies included in the qualitative assessment investigating general shoulder instability suture anchor repairs

Author	Devices	Specimens	Number	Testing Method	Test Set-Up	Outcome Measures
Leedle (2005) San Antonio USA	GII Mitek, Knotless Mitek, Panalok	Fresh Frozen Human	N=15	MTS Instron Preload: not mentioned Load to failure @ 3.3 mm/sec	Anchor insertion angles unknown Vector perpendicular to glenoid	Load to Failure Failure mode
Denard (2009) Munich Germany	Corkscrew, Swivelock	Polyurethan foam blocks	N=104	MTS Instron Preloading 5 N 1mm/sec Load to failure 1 mm/sec	Anchor insertion perpendicular to glenoid Vector perpendicular to glenoid	Stiffness. Load at 3 mm displacement Displacement at failure
Barber (2016) Plano USA	All suture anchors	Polyurethan foam blocks, porcine bone	N=130	MTS Instron Preload 10N, 200 cycles 10-100N, 0.5 Hz Load to failure @ 12.5 mm/sec	Anchor insertion angle unknown Vector unknown	Load to Failure Failure Mode Displacement
Godry (2020) Düsseldorf Germany	Y-Knot All Suture Anchor Self-made-anchor	Polyurethan foam blocks	N=17	MTS Instron Pretension 10N Load to failure 12.5 mm/sec	Anchor insertion angle unknown Vector unknown	Load to failure Failure Mode

Table 2: Studies included in the qualitative assessment investigating SLAP lesion suture anchor repairs

Author	Devices	Specimens	Number	Testing Method	Test Set-Up	Outcome Measures	Other Measures
Di Raimondo (2004) New York USA	Corkscrew, Suretac	Fresh Frozen Human	N=21	MTS Bionix Preload 10N Incremental tensile load of 10N load to 200 N @10N/sec Relaxation between increments to baseline for 20 sec	Anchor placement 45^0 to glenoid surface Vector perpendicular to anchor	Failure mode Separation of 2 mm or until ultimate failure	Displacement: surface markers, optical measures Camera 20Hz
Domb (2007) New York USA	Bio-SutureTak	Fresh Frozen Human	N=21	MTS brand not mentioned Preload 10N Incremental tensile load of 10N load to 200 N @10N/sec Relaxation between increments to baseline for 20 sec	Anchor placement 45^0 to glenoid surface Vector perpendicular to glenoid	Failure mode Stiffness Separation of 2 mm or until ultimate failure	Displacement: surface markers, optical measures Camera 20Hz
Morgan (2008) Charlotte USA	Bio SutureTak	Fresh Frozen Human	N=16	MTS Bionix Preload 10 N Load to failure 25mm/min	Anchor placement 45^0 to glenoid surface Vector posterior direction	Load to failure Stiffness Repair failure (2 mm displacement)	
Yoo (2008) Seoul South Korea	Mini Revo	Fresh Frozen Human	N=15	MTS Instron Preload 10N Increment at 10N rate 10N/sec to 200 N or failure	Anchor placement 45^0 to glenoid surface Vector 20^0 posterior to vertical glenoid axis	Load to failure Failure mode Stiffness Tensile load @ 2 mm displacement	Reflective marker Video analysis Camera 50Hz
Baldini (2009) Denver USA	BioZip	Fresh Frozen Human	N=20	MTS Instron Load to failure @ 0.833 mm/sec	Anchor placement 45^0 to glenoid surface Vector anterior direction	Load to failure Failure mode Stiffness	
Sileo (2009) New York USA	Lupine, Bioknotless Mitek	Fresh Frozen Human	N=10	MTS Systems Eden Prairie Preload 10N, 25 cycles 10-20N 25 cycles with 10N increments until failure at 1Hz	Anchor placement 45^0 to glenoid surface Vector perpendicular to glenoid	Load to failure Failure mode Repair failure (displacement 2mm)	
Uggen (2009) Los Angeles USA	Bio Pushlock, Bio-SutureTak	Fresh Frozen Human	N=12	Custom Made Manual System Preconditioned 10 cycles 2.2 Nm Load to failure preconditioned 10 cycles 0-1 mm @20 mm/min then loaded until failure with 20 mm/min	Anchor placement 45^0 to glenoid surface Vector perpendicular	Load to failure Stiffness AP, SI translation @ 15+20N Load @ 2 mm displacement Yield load Yield displacement, Displacement @ failure Energy absorbed @ failure ROM: external/internal rotation pre-post	
Grieshober (2019) Baltimore USA	Juggerknot	Fresh Frozen Human	N=10	MTS Bionix Load to failure @0.5 mm/sec	Curved versus straight guides Vector unknown	Load to failure	
Nolte (2020) Vail USA	Knotless FiberTak Q-Fix	Fresh Frozen Human	N=20	MTS Instron Preconditioned 5N 10 cycles 5-20N @1Hz Load to failure @1mm/sec	Anchor placement 45^0 to glenoid surface Vector 90^0 posterior to glenoid face	Load to failure Failure mode Stiffness Load to displacement @ 1+2mm	Video documentation

Table 3: Studies included in the qualitative assessment investigating Bankart lesion suture anchor repairs

Author	Devices	Specimens	Number	Testing Method	Test Set-Up	Outcome Measures	Other Measures
Hecker (1993) Boston USA	Acufex wedge/rod anchors	Fresh Frozen Human	N=20	MTS Instron Preload 1-2N Load to failure 1 mm/sec	Anchor entry unknown Vector vertical	Load to failure Failure mode	
Klein (1995) Pittsburgh USA	GII Mitek	Fresh Frozen Human	N=6	MTS Instron Not reported	Anchor entry unknown Vector unknown	Load to failure	
Wetzler (1996) Philadelphia USA	GII Mitek	Fresh Frozen Human	N=22	MTS Instron Cycling @2Hz Load unknown (stress ratio between minimum and maximum load 0.15)	Anchor entry unknown Vector vertical	Failure mode Cycles to failure	
Mohammed (1998) Sydney Australia	GII Mitek, Acufex T-Fix	Fresh Frozen Human	N=20	MTS Bionix Humeral head displacement @25mm/min	Anchor standard entry Insertion angles unknown Humeral head translation anterior	Failure mode Stiffness Peak Load Energy to peak load Elongation of capsulolabral complex	
Roth (1998) Newark USA	GII Mitek Statak 3.5	Fresh Frozen Human	N=22	MTS Instron Cycles @2Hz 30-350N Load lowered until 10% of anchors reached 50,000 cycles	Anchor standard entry, Insertion angles unknown Vector unknown	Load to failure	
Zumstein (2004) Zurich Switzerland	GII Mitek, Knotless Mitek,	Fresh Frozen Human	N=7	MTS Instron 25 cycles from 25-50N @20mm/min 25 cycles from 25-75N Increase by 25N per new cycle until failure	Anchor 30^0 angle Vector in line with anchor	Load to failure	
Mueller (2005) Munich Germany	Fastak, Panalok, Suretac	Fresh Frozen Human Bone density	N=28	MTS Instron Humeral Head displacement @20 mm/min	Anchor insertion angle unknown Humeral head translation anterior direction	Load to failure Stiffness Mean anterior translation @failure	
Provencher (2008) Chicago USA	Corkscrew	Fresh Frozen Human Bone density	N=14	MTS Systems Eden Prairie Preload 10N Load to failure 3mm/sec	Anchor insertion 40^0 to glenoid Vector 90^0 to glenoid	Load to failure Failure mode	
Nho (2010) Chicago USA	PEEK SutureTak, PEEK Pushlock	Fresh Frozen Human Bone density	N=30	MTS Systems Eden Prairie Preload 5N for 2 min 100 cycles @1Hz from 5-25N Load to failure 15mm/min	Anchor angle unknown Vector antero-inferior	Load to failure Failure mode Stiffness Ultimate load @ 2mm displacement Elongation amplitude at final cycle	Displacement: surface markers, optical measures Camera 48Hz
Sparks	BioFastak	Fresh Frozen	N=24	MTS Bionix	Anchor insertion 45^0 to glenoid	Load to failure	

(2010) Louisville USA	Bio Mini-Revo	Human Bone density		Preload 25N 25 cycles 25-50N @0.2 Hz 25N load increase every 25 cycles	Vector in line with anchor insertion	Failure mode	
Ranawat (2011) Ann Arbor USA	Bioknotless Mitek Bio-Suture Tak	Fresh Frozen Human	N=16	MTS Adelaide Testing Machine Preload 5N 100 cycles 20-80N @0.5 mm/sec Load to failure 1.25 mm/sec	Anchor insertion angle unknown Vector 30^0 angle to glenoid	Load to failure Failure mode Stiffness	
Gillis (2012) Baltimore USA	Bio SutureTak	Fresh Frozen Human	N=24	MTS brand not mentioned 22N compressive load Anterior-Posterior 10N load @0.1 mm/sec Load to failure 0.1 mm/sec	Anchor insertion angle unknown Vector unknown	Load to failure Anterior-posterior translation	Camera Motion System
Mazzocca (2012) Farmington USA	SutureTac, JuggerKnot	Fresh Frozen Human	N=12	MTS Systems Eden Prairie Preconditioning 10 cycle 1 Hz 0-1-N 10N preload Load to failure 3 mm/min	Anchor angle unknown Vector antero-inferior	Failure mode Load to failure Stiffness Load at 2 mm displacement Absorbed energy	
Kamath (2012) Chapel Hill USA	Mitek Lupine	Fresh Frozen Human	N=20	MTS Instron Preconditioning 10 cycles 1Hz 0-30N Reset to 10N preload Load to failure @0.33 mm/sec	Anchor insertion angle unknown Vector perpendicular to glenoid	Load to failure, Stiffness Displacement @ failure Load @ 2 mm displacement, Energy @ failure Energy @2mm displacement	
Dwyer (2013) Toronto Canada	Yknot, Bio Mini-Revo	Bovine tibia Fresh Frozen Human	N=8 N=8	MTS Instron Preload 10 N Load to failure 10 mm/min Displacement @ 50N	Anchor insertion angle unknown Vector in line with anchor	Failure mode Stiffness	
Lim (2013) Seoul Korea	BioSutureTak	Fresh Frozen Human	N=12	MTS Instron Preload 10N 500 cycles 10-60N @1Hz	Anchor insertion angle perpendicular Vector orthogonal to glenoid	Load to failure Stiffness Yield load	
Martetschlaeger (2013) Vail USA	Bio Pushlock	Fresh Frozen Human Bone density	N=18	MTS Instron Preload 5N for 2 min 100 cycles 5-25N at 1Hz Load to failure 5 mm/min	Anchor insertion angle unknown Vector antero-inferior	Load to failure Failure mode Stiffness Maximum load @ 2 mm displacement Energy	
Frank (2014) Chicago USA	BioRaptor	Fresh Frozen Human Bone density	N=30	MTS Systems Eden Prairie Preload 10N 250 cycles 10-60N @1Hz Load to failure 12.5 mm/sec	Anchor insertion angle unknown Vector 45^0 antero-inferior	Load to failure Failure mode	
Hanna (2015) DetroiUSA	Corkscrew	Fresh Frozen Human	N=20	MTS Systems Eden Prairie Preload 5N Load to failure 15mm/min	Anchor insertion angle unknown Vector antero-inferior	Load to failure Peak contact pressure Mean contact pressure Contact area	
McDonald	Bio	Fresh Frozen	N=12	MTS Systems Eden Prairie	Anchor insertion angle unknown	Load to failure	

(2016) Irvine USA	SutureTak	Human		Preconditioning with cyclic loading 1-2 mm for 10 cycles Load to failure 60 mm/min	Humeral head translation anterior	Stiffness Energy and deformation @ Yield load, Energy and deformation @ ultimate load	
Judson (2016) Farmington USA	Bio Suturtak	Fresh Frozen Human Bone density	N=22	MTS Systems Corp Preload 5N for 5 minutes Cyclic loading 100 cycles 5-25N @ 1Hz Load to failure @ 15 mm/min	Anchor insertion angle unknown Vector ant-inf 0^0 from the glenoid surface	Load to failure	Digital video tracking system Tracking markers on glenoid and capsule, manual caliper measures
Ericksson (2017) New Brunswick USA	Juggerknot, Bioraptor	Fresh Frozen Human Bone density	N=20	MTS Instron Preload 5 mm at 1N/sec 25 cycles 5-25N at 15 mm/min Load to failure at 15 mm/min	Anchor angle 45^0 Vector in line with anchor	Load to failure Load to 2 mm displacement	
Judson (2017) Farmington USA	Bio-SutureTak	Fresh Frozen Human	N=24	MTS Systems Corp Preload 5N for 5 minutes Cyclic loading 100 cycles 5-25N @ 1Hz Load to failure @ 15 mm/min	Anchor angle 135^0 Vector in line with glenoid antero-inferior	Load to failure Failure mode Stiffness Gap formation Displacement after 100 cycles	Digital video tracking system Tracking markers on glenoid and capsule, manual caliper measures
Kramer (2018) San Francisco USA	Juggerknot	Fresh Frozen Human	N=12	MTS Instron 5N Preload Load to failure 12.5 mm/sec	Anchor 45^0 to glenoid Vector unknown	Load to failure Stiffness	
Ntalos (2019) Hamburg Germany	Yknot, CrossFT	Fresh Frozen Human Bone density	N=10	MTS Systems Eden Prairie Preload 20N Cyclic loading from 50N increase by 0.05N at each cycle at 1 Hz until failure	Anchor angle unknown Vector perpendicular to anchor insertion	Load to failure Stiffness Number of cycles Gap Displacement	Video Analysis Frames/sec unknown
Ruder (2019) Charlotte USA	Suturefix Ultra Iconix 1 Q-Fix JuggerKnot	Fresh Frozen Human	N=28	MTS Systems Eden Prairie Preload 10N @1N/sec for 5 sec 200 cycles 10-60N @1 Hz Load to failure @ 33mm/s	Anchor insertion 30^0 relative to glenoid surface Vector unknown	Load to failure Failure mode Displacement @ 100+200 cycles	
Lacheta (2020) Vail USA	FiberTak	Fresh Frozen Human	N=30	MTS Instron Preconditioning with cyclic loading at 5-15N for 10 cycles Load to failure 5 mm/min	Anchor angle unknown Vector in line with glenoid	Load to failure Stiffness Strain @ 200 N	Surface markers Optical measures Video Analysis 1Hz
Gülecyüz (2020) Munich Germany	Pushlock	Fresh Frozen Human Bone density	N=7	MTS Zwick Preload 25N 25 cycles @20mm/min @25 N increased by 25 N every 25 cycles until failure	Anchor angle unknown Vector 90^0 to glenoid surface	Load to failure Failure mode Maximum displacement	

Table 4: Risk of Bias Assessment with the ROBINS-I tool

	Bias Due to Confounding	Bias in selecting of participants	Bias in classification of interventions	Bias due to deviations from intervention	Bias due to missing data	Bias in measurement of outcomes	Bias in selection of the reported result	Overall risk of bias
Leedle 2005	Low	Serious	Low	Moderate	Low	Moderate	Low	Serious
Denard 2009	Low	Low	Low	Low	Low	Moderate	Low	Moderate
Barber 2016	Low	Low	Low	Moderate	Low	Low	Low	Moderate
Godry 2020	Low	Low	Low	Moderate	Low	Low	Low	Moderate
Di Raimondo 2004	Low	Serious	Low	Moderate	Low	Moderate	Low	Serious
Domb 2007	Low	Serious	Low	Low	Low	Moderate	Low	Serious
Morgan 2008	Low	Serious	Low	Low	Low	Moderate	Low	Serious
Yoo 2008	Low	Serious	Low	Low	Low	Moderate	Low	Serious
Baldini 2009	Low	Serious	Low	Low	Low	Low	Low	Serious
Sileo 2009	Low	Serious	Low	Low	Low	Moderate	Low	Serious
Uggen 2009	Low	Serious	Low	Low	Low	Moderate	Low	Serious
Grieshober 2019	Low	Serious	Low	Serious	Low	Low	Low	Serious
Nolte 2020	Low	Serious	Low	Low	Low	Moderate	Low	Serious
Hecker 1993	Low	Low	Critical	Low	Low	Low	Low	Critical
Klein 1995	Moderate	Critical	Critical	Low	Low	Moderate	Low	Critical
Wetzler 1996	Low	Serious	Critical	Low	Low	Moderate	Low	Critical
Mohammed 1998	Low	Serious	Critical	Low	Moderate	Moderate	Low	Critical
Roth 1998	Low	Serious	Low	Moderate	Low	Moderate	Low	Serious
Zumstein 2004	Low	Serious	Low	Low	Low	Low	Low	Serious
Mueller 2005	Low	Low	Moderate	Moderate	Low	Moderate	Low	Moderate
Provencher 2008	Low	Low	Low	Low	Low	Low	Low	Low
Nho 2010	Low	Low	Low	Moderate	Low	Moderate	Low	Moderate
Sparks 2010	Low	Low	Low	Low	Low	Low	Low	Low
Ranawat 2011	Low	Serious	Low	Low	Low	Low	Low	Serious
Gillis 2012	Low	Serious	Moderate	Moderate	Low	Moderate	Low	Serious
Mazzocca 2012	Low	Serious	Moderate	Moderate	Low	Moderate	Low	Serious
Kamath 2012	Low	Serious	Moderate	Moderate	Low	Moderate	Low	Serious
Dwyer 2013	Moderate	Serious	Low	Moderate	Low	Moderate	Low	Serious
Lim 2013	Low	Serious	Low	Moderate	Low	Moderate	Low	Serious
Martetschlaeger 2013	Low	Low	Moderate	Moderate	Low	Moderate	Low	Moderate
Frank 2014	Low	Low	Low	Moderate	Low	Moderate	Low	Moderate
Hanna 2015	Low	Serious	Low	Moderate	Low	Moderate	Low	Serious

Mc Donald 2016	Low	Serious	Low	Moderate	Low	Moderate	Low	Serious
Judson 2016	Low	Low	Low	Moderate	Low	Moderate	Low	Moderate
Ericksson 2017	Low	Low	Moderate	Low	Low	Moderate	Low	Moderate
Judson 2017	Low	Serious	Moderate	Low	Low	Moderate	Low	Serious
Kramer 2018	Low	Serious	Low	Moderate	Low	Moderate	Low	Serious
Ntalos 2019	Low	Low	Moderate	Moderate	Low	Moderate	Low	Moderate
Ruder 2019	Low	Serious	Moderate	Low	Low	Moderate	Low	Serious
Laccheta 2020	Low	Low	Moderate	Moderate	Low	Moderate	Low	Moderate
Gülecyüz 2020	Low	Low	Moderate	Moderate	Low	Low	Low	Moderate

Table 5: Study quality of the included studies assessed with the QUACS scale

	Objective Stated	Basic Information about sample is included	Applied methods are described comprehensively	Study reports condition of the examined specimens	Education of dissecting researcher is stated	Findings are observed by more than one researcher	Results presented thoroughly and precise	Statistical methods appropriate	Details about consistency of findings are given	Photographs included	Study discussed within context of current evidence	Clinical implications are discussed	Limitations are addressed	Quality
Leedle 2005	yes	yes	no	no	no	no	yes	yes	yes	yes	no	yes	no	Low
Denard 2009	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	High
Barber 2016	yes	yes	yes	yes	no	yes	yes	yes	yes	yes	yes	yes	yes	High
Godry 2020	yes	yes	yes	no	no	yes	no	yes	no	yes	yes	no	yes	Moderate
Di Raimondo 2004	yes	yes	yes	no	no	yes	yes	yes	yes	yes	yes	no	yes	Good
Domb 2007	yes	yes	yes	no	no	yes	yes	yes	yes	yes	yes	yes	yes	Good
Morgan 2008	yes	yes	yes	no	no	yes	yes	yes	yes	no	yes	yes	yes	Good
Yoo 2008	yes	yes	yes	no	no	yes	yes	yes	yes	yes	yes	no	yes	Good
Baldini 2009	yes	yes	yes	no	no	yes	yes	no	yes	yes	yes	no	yes	Moderate
Sileo 2009	yes	yes	yes	no	no	yes	yes	yes	yes	yes	yes	no	yes	Good
Uggen 2009	yes	yes	yes	no	no	yes	yes	yes	yes	yes	yes	yes	yes	Good
Grieshober 2019	yes	yes	yes	no	yes	yes	yes	yes	yes	yes	yes	yes	yes	High
Nolte 2020														
Hecker 1993	yes	no	yes	no	no	yes	yes	yes	yes	no	yes	no	no	Low
Klein 1995	yes	no	yes	no	no	yes	yes	no	no	no	no	no	no	Very Low
Wetzler 1996	yes	yes	yes	no	no	yes	yes	yes	yes	yes	yes	yes	yes	Good
Mohammed 1998	yes	yes	yes	no	no	yes	yes	yes	yes	yes	yes	no	yes	Good
Roth 1998	yes	yes	yes	no	no	yes	yes	no	yes	no	no	yes	yes	Moderate
Zumstein 2004	yes	no	yes	no	no	yes	yes	no	no	no	no	no	yes	Very low
Mueller 2005	yes	yes	yes	no	no	yes	yes	yes	yes	yes	yes	yes	yes	Good
Provencher 2008	yes	yes	yes	no	no	yes	yes	yes	yes	yes	yes	yes	yes	Good
Nho 2010	yes	yes	yes	no	no	yes	yes	yes	yes	yes	yes	yes	yes	Good
Sparks 2010	yes	yes	yes	no	no	yes	yes	yes	yes	yes	yes	yes	yes	Good
Ranawat 2011	yes	no	yes	no	no	yes	yes	yes	yes	yes	yes	no	yes	Moderate
Gillis 2012	yes	yes	yes	no	no	yes	yes	yes	yes	yes	yes	yes	yes	Good
Mazzocca 2012	yes	yes	yes	no	no	yes	yes	yes	yes	yes	yes	yes	yes	Good
Kamath 2012	yes	yes	yes	no	no	yes	yes	yes	yes	yes	yes	no	yes	Good
Dwyer 2013	yes	no	yes	no	no	yes	yes	yes	yes	yes	yes	no	yes	Moderate
Lim 2013	yes	yes	yes	no	no	yes	yes	yes	yes	yes	yes	yes	yes	Good
Martetschlaeger 2013	yes	yes	yes	no	no	yes	yes	yes	yes	yes	yes	yes	yes	Good
Frank 2014	yes	yes	yes	no	no	yes	yes	yes	yes	yes	yes	yes	yes	Good
Hanna 2015	yes	no	yes	no	no	yes	yes	yes	yes	yes	yes	yes	no	Moderate
Mc Donald 2016	yes	yes	yes	no	no	yes	yes	yes	yes	yes	yes	no	yes	Moderate

Judson 2016	yes	yes	yes	yes	no	yes	yes	yes	yes	yes	yes	yes	yes	High
Ericksson 2017	yes	yes	yes	yes	no	yes	yes	yes	yes	yes	yes	yes	yes	High
Judson 2017	yes	yes	yes	yes	no	yes	yes	yes	yes	yes	yes	yes	yes	High
Kramer 2018	yes	yes	yes	yes	no	no	yes	yes	yes	yes	yes	no	yes	Good
Ntalos 2019	yes	yes	yes	no	no	no	yes	no	no	yes	yes	no	yes	Low
Ruder 2019	yes	no	yes	no	no	no	yes	yes	yes	yes	yes	yes	yes	Moderate
Lacheta 2020	yes	yes	yes	no	no	no	yes	yes	yes	yes	yes	yes	yes	Good
Gülecyüz 2020	yes	yes	yes	yes	no	no	yes	yes	yes	yes	yes	yes	yes	Good