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Shoulder biomechanics of RC repair and Instability: A systematic review of cadaveric methodology

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ABSTRACT

Background: Numerous biomechanical studies have addressed normal shoulder function and the factors that affect it. While these investigations include a mix of *in-vivo* clinical reports, *ex-vivo* cadaveric studies, and computer-based simulations, each has its own strengths and limitations. A robust methodology is essential in cadaveric work but does not always come easily. Precise quantitative measurements are difficult in *in-vivo* studies, and simulation studies require validation steps. This review focuses on *ex-vivo* cadaveric studies to emphasize the best research methodologies available to simulate physiologically and clinically relevant shoulder motion.

Methods: A PubMed and Web of Science search was conducted in March 2017 (and updated in May 2018) to identify the cadaveric studies focused on the shoulder and its function. The key words for this search included rotator cuff (RC) injuries, RC surgery, and their synonyms. The protocol of the study was registered on PROSPERO and is accessible at CRD42017068873.

Results: Thirty one studies consisting of 167 specimens with various biomechanical methods met our inclusion criteria. All studies were level V cadaveric studies. Cadaveric biomechanical models are widely used to study shoulder instability and RC repair. These models are commonly limited to the glenohumeral joint by a fixed scapula, passively and discretely move the humerus, and statically load the RC without regard for the integrity of the glenohumeral capsule.

Conclusion: All studies captured in this review evaluated shoulder biomechanics. Recent studies in patients suggest that some assumptions made in this space may not fully characterize motion of the human shoulder. With reproducible scapular positioning, dynamic RC activation, and preservation of glenohumeral capsule integrity, cadaveric studies can facilitate proper validation for simulation models and broaden our understanding of the shoulder environment during motion in healthy and disease states.

1. Introduction

The dynamic nature of the shoulder joint, overuse, and age are major risk factors for injury, pain and disability. In the shoulder, as is the case for many joints, the ligaments and bones limit motion. However, shoulder motion is not limited to glenohumeral joint motion and accurate assessment of shoulder injury depends on analysis of the entire shoulder girdle (Lefevre-Colau et al., 2018). These elements work together in an intricate balance of mechanisms that rely on the active coordination of stabilizing musculature to safely achieve the joint's wide range of motion (Inman et al., 1944; Ludewig and Cook, 2000; Lunden et al. 2010). If an injury is unattended, further ailments may follow. For example, instability can be associated with rotator cuff (RC) tear, and lead to persistent pain, dysfunction, and arthritis (Gombera and Sekiya, 2014). Similarly, RC abnormalities can be asymptomatic, which makes it difficult for clinicians to determine when intervention is needed (Pedowitz et al., 2011; Teunis et al., 2014). These conditions and the uncertainty associated with when and how to treat shoulder injury motivate multifaceted studies of the shoulder.

To understand the interplay between motion and control, three main research settings have been used to study the shoulder: *in-vivo, ex-vivo*, and simulation, each with its own limitations.

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In-vivo studies cannot measure the pressure experienced within the joint nor can the forces produced by muscles be fully recorded. *Ex-vivo* studies attempt to fill this gap by artificially loading muscles while measuring the forces on the joint. In this case, the muscles are not alive, so force is externally applied using estimations. In many cases, shoulder integrity is compromised during specimen preparation. Moreover, glenohumeral capsule integrity, scapular orientation and motion, and RC muscle-activation also limit transfering findings of cadaveric studies to clinic.

Simulation studies attempt to bridge the gap between the two approaches. Ideally, a shoulder model created from CT images of an *in-vivo* shoulder, activated with muscle trajectories of *in-vivo* shoulder motion, and validated with thorough biomechanical testing would balance the drawbacks in either an *in-vivo* or *ex-vivo* approach. Nevertheless, this method can also prove to be computationally difficult if proper boundary conditions, higher order constitutive relationships, and complex motion are incorporated. In order to motivate accurate and precise simulation studies, *ex-vivo* biomechanical studies must be optimized to match the *in-vivo* shoulder. Overall, by leveraging each technique against the others, a more in-depth understanding of the healthy shoulder can be achieved as a conduit for more comprehensive studies of shoulder pathologies. By highlighting the most physiologically relevant methods used in the cadaveric setting, the aim is to improve translation between this and other research settings, heighten our ability to translate conclusions to the clinic and ultimately improve patient care.

This work presents a systematic literature review that aims to highlight the best practices for studying shoulder kinematics and kinetics in the cadaveric setting. Specifically, we aimed to identify the shortcomings of current cadaveric biomechanical study methodology, in doing so we identified what we consider the three main challenges to cadaveric shoulder studies: glenohumeral capsule integrity, scapular orientation, and RC muscle-activation.

2. Methods

Following PRISMA guideline (Moher et al., 2009) (Appendix 1, PRISMA Checklist), a PubMed and Web of Science search was conducted in March 2017 (and updated in May 2018) to identify cadaveric studies focused on the shoulder and its function. The PubMed search strategy was: "RC Injuries" [All Fields] AND "RC/Surgery" [All Fields] NOT ("Epidemiologic Studies"[Mesh]), which was later adopted for searching Web of Science. Additional sources of potential studies were the references of each included study and contacting authors of included studies to identify additional studies. A total of 1391 abstracts (989 Pubmed, 396 Web of Science, and 6 from additional resources) were considered. Only studies published in the English language and conducted on cadavers were included. Review papers, clinical studies, studies performed on animals, and those performed using simulation software were excluded (Flowchart of systematic review; Fig. 1). A total of 31 articles were included in this review. For ease of review, we have presented the results in the following three categories: scapula orientation, RC muscle activation, and glenohumeral capsule integrity. The protocol of the study was registered with PROSPERO and is accessible at CRD42017068873.

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.jbiomech.2018.11.005.

3. Results

The electronic database search and title screening resulted in 116 papers eligible for detailed assessment. After screening, 31 articles were included in this review. Details of the article screening are presented in Fig. 1, and a detailed outline of the included studies is included in Appendix 2.

Based on the scope of this review, all studies were level V cadaveric studies. The studies captured in this search cover a number of different topics regarding the structure, function, and repair of the shoulder joint, and each has its own unique methodology. Some studies controlled for the key factors that limited our previous cadaveric work, but no study was able to fully overcome all three. We categorized studies based on each of three topics: scapular orientation and scapular status (Table 1), simulation of muscle-activation and glenohumeral motion (Table 2) and the condition of the glenohumeral joint capsule (Table 3).

3.1. Scapula

Out of 31 included studies, only two studies allowed for passive motion of the scapula(Mueller et al., 2014; Rosso et al., 2013). The remaining studies fixed the scapula during testing. Many of the studies attempted to isolate glenohumeral joint motion by rigidly fixing the scapula and reporting the abduction angles, considering a 2:1 scapulohumeral rhythm (Malicky et al., 2002, 2015, 2016, 2012; Provencher et al., 2007; Shin et al., 2013; Oh et al., 2012; Oh et al., 2013; Omid et al., 2015), or a 5:4 ratio after 30° of elevation (Hatakeyama et al., 2001a,b; Poppen and Walker, 1976; Yamamoto et al., 2006a; Yoo et al., 2014) (Table 1). In 24 studies, the scapula was fixed in 0° upward rotation and two didn't report scapular orientation (Ahmad et al., 2005; Yamamoto et al., 2006a). The remaining studies tilted the scapula to match an in-vivo resting position, though these angles do not match between studies. The aim of fixing the scapula was mostly reported to isolate glenohumeral motion. This method allowed for comparison between studies and provided the opportunity to explore specific glenohumeral functions.

3.2. Muscle-activation

Twenty four of the 31 included studies elected to discretely position the humerus and statically load the RC muscles, Table 3 (Hatakeyama et al., 2001a,b; Provencher et al., 2007; Shin et al., 2013; Yamamoto et al., 2006a; Yoo et al., 2014; Mihata et al., 2015, 2016a,b, 2012; Oh et al., 2012; Oh et al., 2013; Omid et al., 2015). This method allowed for reproducible humeral positioning and precise concavity compression calculation.

3.3. Capsule

Capsule status was addressed in 29 studies, from which the majority of the studies tested a vented capsule (19 studies). Two studies subsequently sealed a vented capsule in order to restore the native intraarticular pressure associated with the intact shoulder that is essential to the glenohumeral joint's kinematics (DeAngelis et al., 2015; Hurschler et al., 2000; Wuelker et al., 1994b).

4. Discussion

The body of literature in this review spans a number of shoulder joint pathologies, repair methods, and motions, but one consistent theme is the simulation of the intact or healthy shoulder environment. This condition commonly serves as the control and therefore is crucial to the advancement of knowledge concerning the shoulder in health and disease. The methodologies of the studies presented herein are judged according to the current understanding of shoulder joint function, not that of the time of each study's pub-

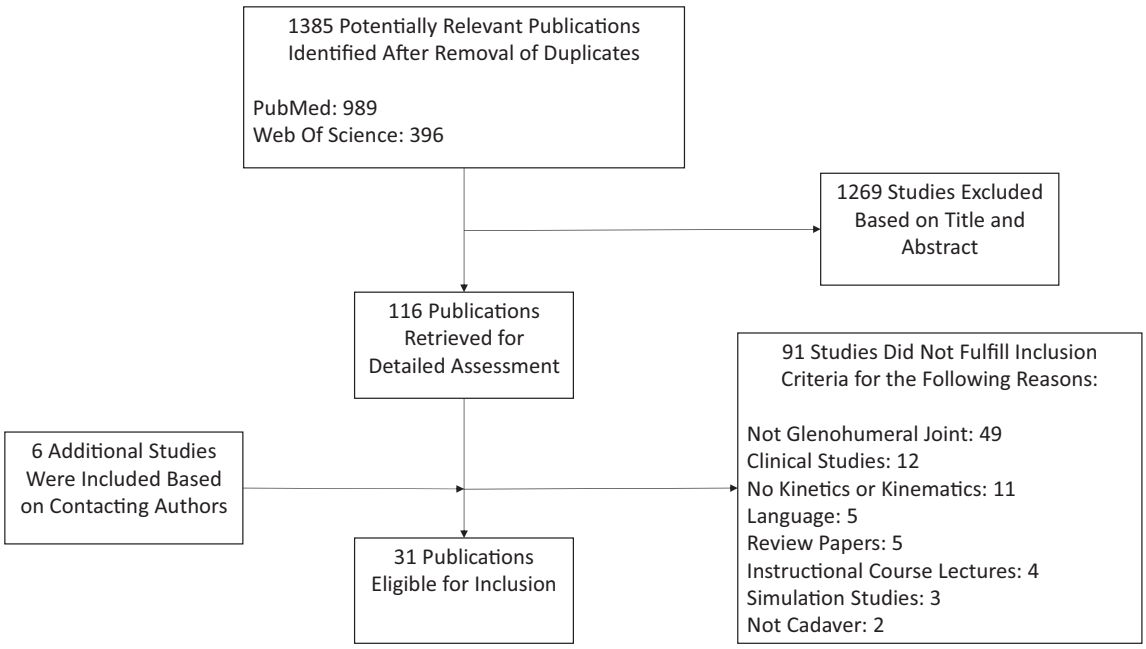

Fig. 1. The flowchart of the systematic review methodology.

lication. All studies captured by this search are level V, we cannot comment directly on their methodological quality due to absence of an objective quality assessment measure. The goal of this review is to present a perspective on how to balance the methodological successes of previous cadaveric studies with the constraints inherent to modeling the shoulder in this setting and to share our perspective on where cadaveric shoulder models fit into future advancement of this field.

4.1. Scapula

The scapula floats against the posterior ribcage suspended by the periscapular muscles, which help position the scapula during motion of the arm and keep it in place. Inman et al. explained the scapula as the foundation of shoulder motion and described the contributions of both scapular and clavicular motion as major contributors to the shoulder joint's wide range of motion (Inman et al., 1944). The scapulohumeral rhythm was measured radiographically and averaged to a 2:1 ratio of glenohumeral angle to scapular upward rotation over the course of shoulder elevation as early as the 1930s (Codman and Akerson, 1931; Inman et al., 1944), offering early insight into the complexity of shoulder motion. The same co-dependence of humeral and scapular motion is still assumed in many studies today. Further research has evaluated scapular motion in three dimensions and shown a nonlinear scapulohumeral rhythm and a dependence on shoulder load (McClure et al., 2001; McQuade and Smidt, 1998).

Many cadaveric shoulder studies attempt to isolate glenohumeral joint motion by rigidly fixing the scapula and reporting the abduction angles considering a 2:1 scapulohumeral rhythm (Malicky et al., 2002; Mihata et al., 2015, 2016, 2012; Provencher et al., 2007; Shin et al., 2013; Oh et al., 2012; Oh et al., 2013; Omid et al., 2015), or a 5:4 ratio after 30° of elevation (Hatakeyama et al., 2001a,b; Poppen and Walker, 1976; Yamamoto et al., 2006a; Yoo et al., 2014) (Table 1). However, the clinical variation in scapular-dynamics limits the generalizability of these studies, as this conversion may not be universal (Braman et al., 2009; Lawrence et al., 2014a; McClure et al., 2001). In 1944, Inman et al. hypothesized that the resting position of the scapula affects the scapulohumeral rhythm early in abduction and may be specific to the individual's habitual resting position (Inman et al., 1944).

Currently, there is no consensus on scapular orientation during static simulation of glenohumeral motion. Many cadaveric studies orient the scapular spine vertically, so it is perpendicular to the ground, while others attempt to tilt it into an *in-vivo* position. However, periscapular muscular activity controls its position during motion (Inman et al., 1944; McClure et al., 2001). Additionally, recent radiographic studies have attempted to correlate scapular geometry with shoulder conditions like RC impingement, osteoarthritis, and RC tear progression (Chalmers et al., 2017; Li et al., 2017; Mantell et al., 2017). The intricate relationship between scapular morphology and scapular motion are still not well understood.

In-vivo studies have attempted to expand our understanding of scapular motion during simple movements (Braman et al., 2009; Lawrence et al., 2014a,b), but a more thorough understanding of scapular contribution to shoulder motion is needed to recreate clinically relevant scapular dynamics *ex-vivo*. In a study using electromagnetic sensors attached to pins surgically implanted into the shoulder girdle, Braman et al. investigated the scapula's contribution to shoulder kinematics during forward elevation and abduction (Braman et al., 2009). They found that scapulohumeral rhythm was not consistent throughout the entire motion—scapulohumeral rhythm was greatest in the first 30 degrees of forward elevation and consistently higher while the arm was lowered. Further, they found that scapular upward rotation and posterior tilting progressively increased until maximal elevation. This suggests scapular motion is not limited to one axis of rotation, nor is it a simple ratio of humeral and scapular rotations even in simple-patterned movement.

To fully understand scapular activity, slow, discrete motions are insufficient because they do not accurately represent normal *in-vivo* activity. Evidence of change with increased speed is in the results of a study performed by Fayad et al. This study measured three-dimensional (3D) scapular kinematics during rapid arm elevations in healthy subjects and concluded that statically recorded

Table 1
The status and orientation of scapula during mechanical testing of shoulder biomechanics.

Study	Scapula orientation	Scapula status
Ahmad (2005)	Not specified	Fixed
Grimberg (2016)	17° Upward Rotation, 22° Anterior Tilt	Fixed
Halder (2002)	0° Upward Rotation, Tilt Unspecified	Fixed
Hansen (2008)	0° Upward Rotation, 10° Anterior Tilt in Sagittal Plane	Fixed
Hatakeyama (2001) – Effect of Arm Elevation	0° Upward Rotation, Tilt Unspecified	Fixed
Hatakeyama (2001) – Effect of Superior Capsule	0° Upward Rotation, Tilt Unspecified	Fixed
Hockman (2004)	0° Upward Rotation, 10° Anterior Tilt	Fixed
Liu (1998)	0° Upward Rotation, Tilt Unspecified	Fixed
Malicky (1996)	0° Upward Rotation, 20° Anterior Tilt (Soslowsky, 1992)	Fixed
Malicky (2001)	0° Upward Rotation, Tilt Unspecified	Fixed
Malicky (2002)	0° Upward Rotation, Tilt Unspecified	Fixed
Malicky (2009)	0° Upward Rotation, Tilt Unspecified	Fixed
Mazzocca (2011)	0° Upward Rotation, Tilt Unspecified	Fixed
Mihata (2012)	0°,15°,30° Upward Rotation (Adjusted to mimic 2:1 upward rotation), Tilt Unspecified	Fixed
Mihata (2015)	30° Upward Rotation, Tilt Unspecified	Fixed
Mihata (2016) – Biomechanical Effect of Thickness and Tension	0° Upward Rotation, 20° Anterior Tilt in Sagittal Plane	Fixed
Mihata (2016) - Biomechanical Role of Capsular Continuity	0° Upward Rotation, 20° Anterior Tilt in Sagittal Plane	Fixed
Mueller (2014)	Full Torso: Scapula moved passively with glenohumeral motion	Passive Motion Allowed
Muraki (2007)	0° Upward Rotation, Tilt Unspecified	Fixed
Oh (2013)	0° Upward Rotation, 20° Anterior Tilt in Sagittal Plane	Fixed
Oh (2012)	0° Upward Rotation, 20° Anterior Tilt in Sagittal Plane	Fixed
Omid (2015)	0° Upward Rotation, 20° Anterior Tilt in Sagittal Plane	Fixed
Provencher (2007)	0° Upward Rotation, Tilt Unspecified	Fixed
Rosso (2013)	Full Torso: Scapula moved passively with glenohumeral motion	Passive Motion Allowed
Shin (2013)	0° Upward Rotation, 20° of Anterior Tilt in Sagittal Plane	Fixed
Soslowsky (1997)	0° upward rotation, Tilt Unspecified (Mounted upside down relative to anatomic frame)	Fixed
Speer (1995)	0° Upward Rotation, Tilt Unspecified	Fixed
Yamamoto (2006)	Unspecified	Fixed
Yoo (2014)	0° Upward Rotation, 20° Anterior Tilt in Sagittal Plane	Fixed
Yu (2005)	0° Upward Rotation, Tilt Unspecified	Fixed
Zuckerman (1991)	0° Upward Rotation, Tilt Unspecified	Fixed

positions cannot fully explain the scapular-dynamics (Fayad et al., 2006). Still, the dynamic and sometimes rapid nature of *in-vivo* scapular motion is not currently incorporated into most *ex-vivo* shoulder models. Dynamic humerothoracic motion potentially affects scapular contribution and timing. McQuade et al. compared 3D scapular kinematics and electromyographic activity during elevation against maximal resistance to assess the effect of fatigue on scapular kinematics. They observed that fatigue increased scapular upward rotation, which alters the scapulohumeral rhythm (McQuade and Smidt, 1998), suggesting muscle recovery may also be a factor in proper scapular dynamics.

Furthermore, soft tissue composition potentially plays a major part in this setting as hypothesized by Roach et al. In an evolutionary biology study of shoulder function considering the anthropometric advantages in the shoulder joint during throwing, they hypothesized that ligaments of the elbow and shoulder store elastic energy during the early phases of throwing, and then release this energy to increase the speed of the object (Roach et al., 2013). In recognizing that the shoulder is not restricted to simple motions, the *in-vivo* scapular-dynamics need to be considered. Speed, shoulder morphology, and the soft tissue material properties need to be accurately represented to fully characterize shoulder function.

Presently, the best approach for simulating shoulder motion focuses on isolated glenohumeral motion, because a more robust understanding of *in-vivo* scapular kinematics is needed to reliably incorporate scapulothoracic motion. As Inman remarked with respect to proprioceptive shoulder mechanisms: "motion, and motion alone, is the only known stimulus able to engender, in phase and degree, the muscle activity requisite for the establishment of the pattern as a whole." (Inman et al., 1944).

4.2. Muscle-activation

Cadaveric studies have been used to analyze the integrity of surgical techniques and examine how they contribute to the motion, function, and stability of the glenohumeral joint, (Table 2) (Grimberg et al., 2016; Hansen et al., 2008; Hatakeyama et al., 2001a,b; Liu et al., 1998; Malicky et al., 2002; Malicky and Soslowsky, 2009; Malicky et al., 2001; Mazzocca et al., 2011; Mueller et al., 2014; Oh et al., 2012, 2013; Provencher et al., 2007; Rosso et al., 2013; Shin et al., 2013; Speer et al., 1995; Yamamoto et al., 2006a; Yoo et al., 2014; Yu et al., 2005; Zuckerman et al., 1991; Mihata et al., 2016a,b, 2012). Many of these investigations have drawbacks in simulating the normal healthy shoulder, as each study has neglected an essential component that contributes to the shoulder's stability. Reed et al. demonstrated that the restriction to the humeral head's translation, and therefore the joint's stability, are contingent on the dynamic RC muscle coordination during movement of the arm (Reed et al., 2016) (Fig. 2).

Dynamic shoulder stability depends on coordinated muscle-activation to position the shoulder girdle. Veeger et al. described the shoulder's balance between mobility and stability (Veeger and van der Helm, 2007). Even with this understanding, the shoulder's dynamic nature is not well understood, since there has been no comprehensive measurement of *in-vivo* muscle-activation.

Our understanding of the shoulder's stability is further complicated by the normal variation in glenohumeral translation in healthy individuals (Pagnani and Warren, 1994). This behavior is explained by the concept of concavity compression, a balance between shear force, compressive force, and humeral translation at the glenohumeral articulation (Veeger and van der Helm, 2007). The components of concavity compression vary between

Table 2
Rotator cuff muscle activation during mechanical testing of shoulder biomechanics.

Study	Glenohumeral motion	Angles	Rotator cuff force	Muscle activation
Ahmad (2005)	Manually Cycled (Passive)	10 min of loading to allow viscoelastic creep, Cycled 60° internal rotation and 60° of external rotation 10 times; humerus at 0° abduction and elevation	Supraspinatus (3 kg free weight)	Static
Grimberg (2016)	Postero-anterior load (50 N) at 10 mm/min speed was applied on the proximal part of the humerus close to the lower insertion of the rotator cuff using Instron	90° abduction in frontal plane and maximal external rotation	None: origin and insertion attached	None
Halder (2002)	Single Position	Humerus in the hanging arm position and neutral rotation	Supraspinatus (25.6 N), Infraspinatus (46.7 N), Teres Minor (14.3 N), and Subscapularis (66.3 N)	Static
Hansen (2008)	Neuromuscular Controller	5° intervals from 10° to 80° of glenohumeral abduction in the scapular plane	Stepper motors, closed-loop feedback control position, measure force of RC muscles	Static*
Hatakeyama (2001) – Effect of Arm Elevation	Manually Placed at Discrete Angles (Passive)	(a) In scapular, coronal, and sagittal plans: arm elevations 0°,15°,30°,45° relative to scapula (so 0°,15°,30°, an 60° of arm elevation) (b) At each elevated position, arm manually rotated from neutral rotation to 30° and 60° of internal rotation, back to neutral, and then to 30° and 60° of external rotation	None: origin and insertion attached	Static
Hatakeyama (2001) – Effect of Superior Capsule	Manually Placed at Discrete Angles (Passive)	(a) In scapular, coronal, and sagittal plans: arm elevations 0°,15°,30°,45° relative to scapula (so 0°,15°,30°, an 60° of arm elevation) (b) At each elevated position, arm manually rotated from neutral rotation to 30° and 60° of internal rotation, back to neutral, and then to 30° and 60° of external rotation	None: origin and insertion attached	Static
Hockman (2004)	Manually Placed at Discrete Angles (Passive)	Humerus positioned (manually) in combinations of 0°, 30°, and 60° abduction; 0°, 20°, and 40° extension; 30° internal rotation, neutral, 30° external rotation, and 20° flexion.	Subscapularis, infraspinatus, and teres minor, (25 N each)	Static
Liu (1998)	Passive motion over 10-second period by experimenter	Elevated from 0° (the hanging position) to maximum elevation in the scapular plane (over 10 s)	(Middle, Anterior, Posterior) Deltoid, Supraspinatus, Subscapularis, Infraspinatus; (2.5 N each)	Static
Malicky (1996)	Manually Placed at Discrete Angles (Passive)	(a) Arm Elevation: 30° increments from 0 to 180° (b) Stability testing: anterior displacements of humeral neck	(a) Supraspinatus (67 ± 7 N (mean ± SD)), Subscapularis (53 ± 7 N), External rotators (55 ± 10 N), Biceps (31 N), Anterior Deltoid (37 ± 25 N), Middle Deltoid (49 ± 14 N), and Posterior Deltoid (37 ± 13 N) (b) One muscle force randomly varied	Static
Malicky (2001)	Manually Placed at Discrete Angles (Passive)	Glenohumeral abduction: 60°, humerus 15° behind the plane of the scapula	Subscapularis, Supraspinatus, and External Rotators (53 N each)	None
Malicky (2002)	Manually Placed at Discrete Angles (Passive)	Glenohumeral abduction: 60°, humerus 15° behind the plane of the scapula	Subscapularis, Supraspinatus, and External Rotators (53 N each)	None
Malicky (2009)	Manually Placed at Discrete Angles (Passive)	Glenohumeral abduction: 60°, humerus 15° behind the plane of the scapula	Subscapularis, Supraspinatus, and External Rotators (53 N each)	None
Mazzocca (2011)	Manually Placed at Discrete Angles (Passive)	Glenohumeral abduction 10° intervals 0° and 60°	Supraspinatus (11 N), Subscapularis (5.5 N), and infraspinatus (5.5 N)	Static
Mihata (2012)	Manually Placed at Discrete Angles (Passive)	0°, 45°, and 90° of abduction (plane not specified)	(a) Deltoid (40 N), Pectoralis Major (20 N); Latissimus Dorsi (20 N), Supraspinatus (10 N), Infraspinatus and Teres Minor Unit (10 N), Subscapularis (10 N) (b) Deltoid (80 N), Supraspinatus (10 N), Infraspinatus and Teres Minor Unit (10 N), Subscapularis (10 N)	Static
Mihata (2015)	Manually Placed at Discrete Angles (Passive)	Humerus at 90° of shoulder abduction (30° of scapular upward rotation and 60° of glenohumeral abduction) and 30° of horizontal abduction with respect to the scapular plane (simulated coronal plane)	Late-cocking phase, Supraspinatus (1 N), Subscapularis (14 N), Infraspinatus and Teres Minor Unit (5 N). Acceleration phase, Supraspinatus (0.6 N), Subscapularis (17 N), and Infraspinatus and Teres Minor Unit (1.2 N)	Static

Table 2 (*continued*)

Study	Glenohumeral motion	Angles	Rotator cuff force	Muscle activation
Mihata (2016) – Biomechanical Effect of Thickness and Tension	Manually Placed at Discrete Angles (Passive)	0°, 30°, and 60° of glenohumeral abduction, which corresponded to 0°, 45°, and 90° of shoulder abduction, respectively	(a) Deltoid (40 N), Pectoralis Major (20 N); Latissimus Dorsi (20 N), Supraspinatus (10 N), Infraspinatus and Teres Minor Unit (10 N), Subscapularis (10 N) (b) Deltoid (80 N), Supraspinatus (10 N), Infraspinatus and Teres Minor Unit (10 N), Subscapularis (10 N)	Static
Mihata (2016) – Biomechanical Role of Capsular Continuity	Manually Placed at Discrete Angles (Passive)	(a) 0°, 30°, and 60° of glenohumeral abduction, which corresponded to 0°, 45°, and 90° of shoulder abduction, respectively, rotation angle set to 30° external rotation (b) Humeral rotational range of motion (ROM) measured at 0°, 30°, and 60° of glenohumeral abduction in the scapular plane	(a) Deltoid (40 N), Pectoralis Major (20 N); Latissimus Dorsi (20 N), Supraspinatus (10 N), Infraspinatus and Teres Minor Unit (10 N), Subscapularis (10 N) (b) Deltoid (80 N), Supraspinatus (10 N), Infraspinatus and Teres Minor Unit (10 N), Subscapularis (10 N)	Static
Mueller (2014)	Programmable Actuator for Continuous Motion	120° of external rotation to midcoronal plane, Glenohumeral abduction 90°	None; origin and insertion attached	None
Muraki (2007)	Manually Placed at Discrete Angles (Passive)	0° and 30° glenohumeral abduction in the scapular plane	Infraspinatus (11 N) and Subscapularis (11 N)	Static
Oh (2013)	Static loading, see what rotation occurs and then max internal/ external rotation	0°, 30°, and 60° shoulder abduction using 2:1 ratio of glenohumeral to scapulothoracic abduction	(a) Supraspinatus (10 N); Subscapularis (24 N), Infraspinatus and Teres Minor (24 N), Deltoid (48 N), Pectoralis Major (24 N), and Latissimus Dorsi (24 N) (b) Latissimus dorsi (48 N)	Static
Oh (2012)	Manually Placed at Discrete Angles (Passive)	0°, 30°, and 60° shoulder abduction using 2:1 ratio of glenohumeral to scapulothoracic abduction	Supraspinatus (20 N), Subscapularis (30 N), Infraspinatus (20 N), Teres minor (10 N), Deltoid (60 N), Pectoralis Major (30 N), and Latissimus Dorsi (30 N)	Static
Omid (2015)	Manually Placed at Discrete Angles (Passive)	0°, 20°, and 40° of glenohumeral abduction	Supraspinatus (10 N across 2 lines of pull), Subscapularis, Pectoralis Major, Latissimus Dorsi, and Infraspinatus and Teres Minor Unit (24 N total across their 3 lines of pull, Deltoid (48 N across 3 lines of pull), Biceps (8 N), and 3 loading conditions for the trapezius (12 N, 24 N, 36 N).	Static
Provencher (2007)	Manually Placed at Discrete Angles (Passive) 6 DOF positioning (Passive)	60° glenohumeral abduction and flexion	Supraspinatus (3.5 N), Infraspinatus and Teres Minor Unit (9.1 N), and Subscapularis (9.4 N)	Static
Rosso (2013)	Programmable Actuator for Continuous Motion	0–160° coronal plane abduction		None
Shin (2013)	Manually Placed at Discrete Angles (Passive)	30° and 60° of glenohumeral abduction in scapular plane; maximum internal to maximum external rotation in 30° increments	Supraspinatus (10 N), Subscapularis (15 N), and Infraspinatus and Teres Minor Unit (15 N)	Static
Soslowsky (1997)	Manually Placed at Discrete Angles (Passive), Subluxation tested via MTS	(a) Subluxation: 0° abduction, humeral rotation: 0° and 10° (b) Stability tests: a single test cycle started at 0-mm, then subluxed inferiorly to 10 mm, reversed to -4mm, and finally returned to 0 mm, all at 0.5 mm/sec	Rotator Cuff Muscles (53 N each), Long Head Biceps (31 N)	Static*
Speer (1995)	Manually Placed at Discrete Angles (Passive)	(a) Neutral rotation and 0° and 45° glenohumeral elevation scapular plane (b) Anterior-posterior test also in 30° of internal and external rotation	None: origin and insertion attached	None
Yamamoto (2006)	Manually Placed at Discrete Angles (Passive)	0°, 30°, 45°, and 60° glenohumeral abduction	Subscapularis (10 N), Supraspinatus (3.5 N), and Infraspinatus and Teres Minor (8.5 N)	Static
Yoo (2014)	Manually Placed at Discrete Angles (Passive)	0°, 30°, and 60° shoulder abduction in scapular plane (30° anterior to the coronal plane), considering a 2:1 ratio of glenohumeral to scapulothoracic abduction.	Supraspinatus (20 N with 10 N each line of pull), Subscapularis (30 N), Infra-spinatus and Teres Minor Unit (30 N with 7.5 N each line of pull)	Static
Yu (2005)	Manually Placed at Discrete Angles (Passive)	10° glenohumeral abduction with neutral rotation and 60° abduction with neutral rotation	Supraspinatus, Subscapularis, Infraspinatus, Teres Minor, Pectoralis Major, Latissimus Dorsi, and Teres Major 60 N each) and Deltoid (90 N)	Static

(*continued on next page*)

Table 2 (*continued*)

Study	Glenohumeral motion	Angles	Rotator cuff force	Muscle activation
Zuckerman (1991)	Manually Placed at Discrete Angles (Passive)	(a) 0°, 15°, 30°, 60°, 90° glenohumeral abduction in scapular plane (b) 30° flexion, neutral, and 30° extension (in sagittal plane) (c) 30° internal rotation, netural, and 30° external rotation	None: origin and insertion attached	Static

[*] These studies likely had the ability to actively coordinate rotator cuff muscle activation during motion. This was not performed in these cases or the data was reported at discrete angles, likely because continuous data capture was not within the scope of the present study.

Table 3
The status of capsule during mechanical testing of shoulder biomechanics.

Study	Procedure	Capsule status
Ahmad (2005)	Not specified	–
Grimberg (2016)	Not specified	–
Halder (2002)	Capsule preserved	Intact
Hansen (2008)	Glenohumeral joint vented during dissection	Vented
Hatakeyama (2001) – Effect of Arm Elevation	Intact, vented, and repaired; *Rotator interval capsule vented with 22-gauge needle to eliminate the effect of intraarticular pressure*	Vented[*]
Hatakeyama (2001) – Effect of Superior Capsule	Supraspinatus tendon sharply dissected from greater tuberosity[*]; *Though they state capsular conditions: (1) with the capsule intact, (2) with the superior capsule released, and (3) with the superior capsule and the coracohumeral ligament released*	Vented[*]
Hockman (2004)	Entire supraspinatus origin and insertion and 5–10 mm of the superior edge of the infraspinatus were removed.	Vented
Liu (1998)	Superior portion of capsule cut open from superior labral margin to expose humeral head	Vented
Malicky (1996)	Vented to eliminate stability contribution of changing intracapsular pressure	Vented
Malicky (2001)	The acromion and coracoacromial ligament were resected; Two air ports made through superoposterior labrum for inflation of the capsule and pressure measurements	Vented
Malicky (2002)	Acromion and coracoacromial ligament were resected;Two air ports made through superoposterior labrum for inflation of the capsule and pressure measurements	Vented
Malicky (2009)	Coracoacromial ligament and acromion were resected; Capsule inflated to remove most capsular redundancy and wrinkling	Vented
Mazzocca (2011)	Entire supraspinatus excised to create large retracted rotator cuff tear	Vented
Mihata (2012)	Capsule preserved	Intact
Mihata (2015)	Capsule preserved	Intact
Mihata (2016) – Biomechanical Effect of Thickness and Tension	Capsule preserved	Intact
Mihata (2016) – Biomechanical Role of Capsular Continuity	Capsule preserved	Intact
Mueller (2014)	Capsule preserved	Intact
Muraki (2007)	Capsule reserved to avoid the loss of intraarticular negative pressure in glenohumeral joint	Intact
Oh (2013)	Glenohumeral joint vented through rotator interval	Vented
Oh (2012)	Glenohumeral joint vented through rotator interval	Vented
Omid (2015)	Arthrotomy in rotator interval to normalize negative intraarticular pressure	Vented
Provencher (2007)	Capsule intact for execution of arthroscopic and open procedures	Vented
Rosso (2013)	Capsule preserved	Intact
Shin (2013)	Rotator interval opened for glenohumeral joint ventilation	Vented
Soslowsky (1997)	Vented to eliminate confounding effect of intracapsular pressure differences before and after ligament sectioning.	Vented
Speer (1995)	Capsule preserved	Intact
Yamamoto (2006)	Before measurement of intact RI, punctured capsule anteriorly to vent capsule to eliminate effect of intraarticular pressure on shoulder stability	Vented
Yoo (2014)	Vented through the rotator interval to remove the negative intraarticular pressure	Vented
Yu (2005)	Capsule incised to vent to atmosphere	Vented
Zuckerman (1991)	Intact cuff condition tested	Intact

[*] Though capsule was considered intact, with regard to the seal of the capsule, the procedure described likely vented the capsule.

subjects due to different osseous morphologies and muscle tone. The balance between force and motion outlined by concavity compression can be understood in abduction (Fig. 2).

Many studies have highlighted the importance of active muscular contraction in midrange shoulder motion because of the limited passive stability provided by capsuloligamentous structures (Reed et al., 2016; Veeger and van der Helm, 2007; Wuelker et al., 1994b). Veeger et al. hypothesized that joint stabilization is maintained by the use of a control system based on short- and long-latency reflexes. They discounted continuous RC muscle contraction during motion due to its metabolic expense and the low percentage of Type-I muscle fibers present to perform this function (Johnson et al., 1973). Measuring RC muscle activity is invasive, so this hypothesis hasn't been thoroughly tested. However, one recent *in-vivo* study performed by Reed et al. attempted to minimize the error associated with surface electrodes by implanting EMG electrodes in the shoulder muscles (Reed et al., 2016). They found that the RC muscles were continuously activated, and increasing

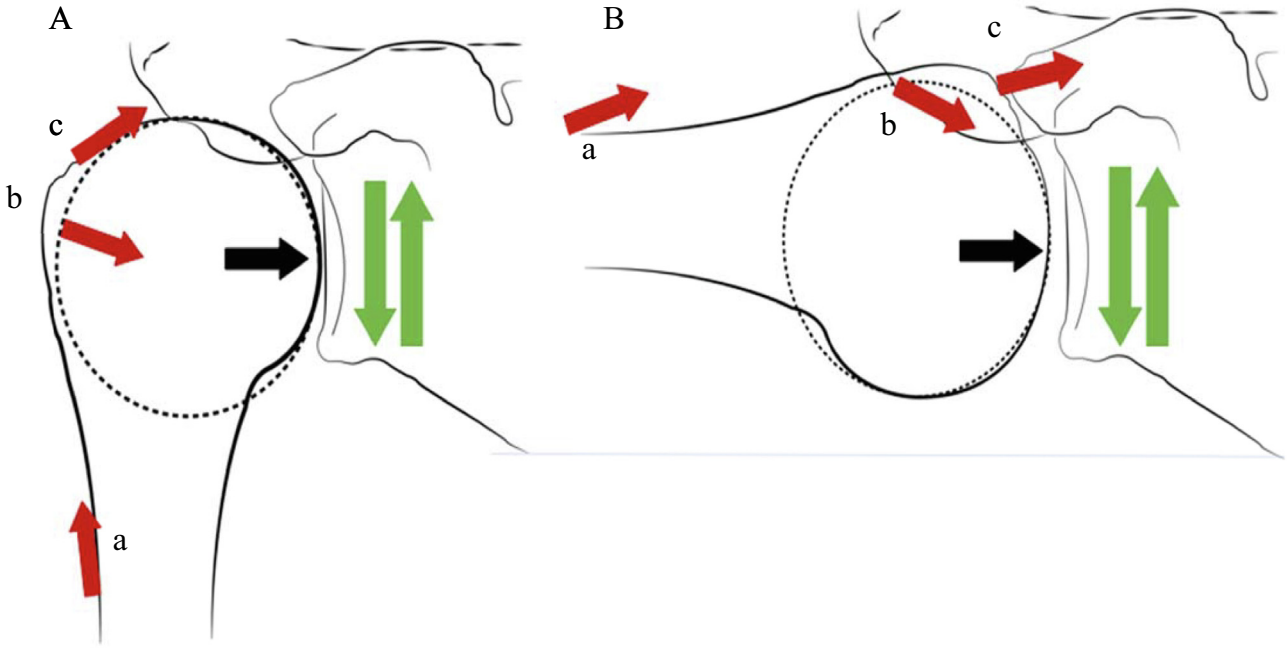

Fig. 2. Anterior view of the components of Concavity Compression of the glenohumeral joint in (A) 0° of Glenohumeral Abduction and (B) 90° of Glenohumeral Abduction in the frontal plane. Red Arrows indicate the direction of muscle force for the (a) deltoid, (b) subscapularis, and (c) supraspinatus, Green Arrows indicate the direction of shearing forces, and Black Arrows indicate the compressive force. As the arm abducts due to contraction of the deltoid (a), the reaction force of the glenoid against the humeral head (Black Arrow) cannot counteract the superior component of that force. The deltoid adds shear (Green Arrows) and compressive forces (Black Arrows), while the reaction force of the glenoid is limited to compression. To minimize translation, the rotator cuff muscles counteract shear force and stabilize the humeral head. In a healthy patient, the rotator cuff muscles easily balance the forces in this situation. The infraspinatus is not pictured here as it inserts on the posterior side of the humerus.

the force of shoulder abduction also increases their activation. These findings affirm the hypothesis that the RC seeks to counterbalance translation even in simple motions (Reed et al., 2016). Most of the included cadaveric studies elected to discretely position the humerus and statically load the RC muscles, Table 2 (Hatakeyama et al., 2001a,b; Provencher et al., 2007; Shin et al., 2013; Yamamoto et al., 2006a; Yoo et al., 2014; Mihata et al., 2015, 2016, 2016, 2012; Oh et al., 2012, 2013; Omid et al., 2015). This method allows for precise calculation of concavity compression, limits complications due to acceleration at the beginning and end of continuous motion, and increases reproducibility. Additionally, the humeral head is compressed into the glenoid stabilizing the shoulder, while data acquisition can be performed quickly in a reproducible manner with minimal post-processing (Warner et al., 1999). Using this technique, many experiments can be performed on the same specimen using the same setup. However, this approach is limited to discrete measurements. It does not fully capture the stabilizing functions of the RC muscles, because they depend on coordinated muscle-activation based on arm position.

The remaining studies actively loaded the RC during continuous motion to explore the relationship between muscle-activation and joint stability, Table 2 (Apreleva et al., 1998; Hansen et al., 2008; Hurschler et al., 2000; Konrad et al., 2006; McMahon et al., 1995; Wellmann et al., 2008; Wuelker et al., 1998, 1994a,b, 1995). This approach has the advantage of allowing for continuous motion, the application of *in-vivo* kinematics, and muscle-activation.

With physiologic muscle-activation, the joint contact and humeral head kinematics are comparable to *in-vivo* observations. Wuelker et al. used hydrodynamic actuators to dynamically load the RC muscles during motion and showed that this method better simulates translation at the humeral head compared to studies using static loading (Wuelker et al., 1994b). They showed that while the supraspinatus is not the major agonist in abduction, it is necessary for joint compression during elevation (Wuelker et al., 1994a).

The limitations associated with actively loading muscles in the cadaveric setting stem from our inability to fully characterize muscle-activation *in-vivo*. Furthermore, both static and dynamic muscle loading have major limitations. Muscles are assumed to have a single line of action, muscle contraction cannot be fully achieved, and the precise muscle force at a given position is not known. The forces are estimated based on muscle geometry, arm weight, and shoulder position. During active loading, studies have been limited to linear increases in muscle force based on the arm's position using a ratio of force between the deltoid and RC muscles. Recent *in-vivo* electromyographic (EMG) and modeling studies have improved our understanding of muscle-activation (Alpert et al., 2000; Chadwick et al., 2014; Favre et al., 2012; Kelly et al., 2005; Webb et al., 2014). By combining these two data sets, the calculation of muscle moment arms as a function of EMG data and arm position provides a more precise characterization of muscle-activation.

Cadaveric simulation of arm motion can serve to expand our knowledge of current surgical techniques and offers the ability to validate simulation models. Many of the studies presented here offer a perspective on procedures that cannot be gained from *in-vivo* studies. However, complete simulation of the *in-vivo* shoulder is limited by muscle-activation and scapular motion as highlighted above. Robust validation of computer simulation models using cadaveric data can make the most of the strengths of both approaches to improve our understanding of these procedures (Prinold et al., 2013; Zheng et al., 2017). As the cadaveric setting is limited to dead tissue, simulation studies offer the best opportunity to explore different dynamic muscle-activation models (Johnson et al., 1996; Kim et al., 2015; Veeger et al., 1991). One strength of simulation is that multiple iterations can be run

rapidly, whereas cadaveric samples can be used once. Nonetheless, the software's ability to accurately simulate contact, material properties, and muscle-activation can also be limited (Bolsterlee et al., 2013). Overall, the cadaveric setting marked with robust RC activation facilitates precise glenohumeral motion replication and thorough computer simulation validation.

4.3. Capsule

The joint capsule is the layer of soft tissue encapsulating the joint. Thickenings in the capsule form the ligaments and tendons essential to the shoulder's stability. The capsule also plays a role in concavity compression because it helps maintain the contact between the humeral head and the glenoid through tension and negative pressure (Gibb et al., 1991; Hurschler et al., 2000; Kumar and Balasubramaniam, 1985; Zuckerman et al., 1991). This contact is essential to the healthy shoulder's function; when injured, the shoulder may become unstable and experience premature degenerative change.

Negative pressure associated with the intact shoulder is also essential to the glenohumeral joint's kinematics (DeAngelis et al., 2015; Hurschler et al., 2000; Wuelker et al., 1994b). Negative pressure may be reduced in patients with RC tears, but it may not be re-established post-surgery in those who have undergone open capsular procedures (Habermeyer et al., 1992; Hashimoto et al., 1995; Hurschler et al., 2000; Speer et al., 1995). Veeger et al. remarked that capsular contribution is small until extremes of motion (Veeger and van der Helm, 2007), but this conclusion has been disputed. Hurschler et al. employed a dynamic shoulder simulator to quantify humeral head translation with and without negative pressure during active shoulder motion and found relationships between abduction angle and translation that were comparable to those estimated to occur with RC injuries *in-vivo* (Hurschler et al., 2000).

The majority of cadaveric studies open the capsule during specimen preparation and eliminate negative pressure's effect on the joint, Table 3 (Hansen et al., 2008; Liu et al., 1998; Yoo et al., 2014; Yu et al., 2005; Malicky et al., 2002, 1996, 2001; Malicky and Soslowsky, 2009). While this approach may be necessary, an accurate simulation of the healthy shoulder requires the normal contribution of negative intraarticular pressure. As the capsule of a cadaveric sample cannot heal, and it is common to receive specimens that have disturbed capsules, kinematic data should be obtained from an intact capsule before puncturing.

The benefit of negative pressure is often substituted with static RC loading or artificial glenohumeral joint compression to maintain contact between the humeral head and the glenoid, Table 3 (Hockman et al., 2004; Mazzocca et al., 2008; Mihata et al., 2015; Provencher et al., 2007; Yamamoto et al., 2006a; Muraki et al., 2007; Oh et al., 2012; Oh et al., 2013; Omid et al., 2015; Shin et al., 2013; Soslowsky et al., 1997; Speer et al., 1995). While the RC does stabilize the joint, loading the RC muscles may not accurately overcome the lost benefits due to negative pressure of the intact capsule (Hurschler et al., 2000; Itoi et al., 1993; Kumar and Balasubramaniam, 1985; Yamamoto et al., 2006b). Bowen et al. studied glenohumeral compression with respect to joint stability and found that 111 N of static compression centers the humeral head and minimizes humeral head translations (Warner et al., 1999). Many cadaveric studies use this method of joint compression to achieve reproducible glenohumeral positioning and limit translation. However, this method is limited to discrete, static testing. In dynamic motion, active RC loading affects ligament contribution and may affect the capsule's contribution to joint compression.

Further studies are needed to understand the function of intraarticular negative pressure and the role of the capsule and the RC in the shoulder's stability. This interplay becomes increasingly important when simulating dynamic motions using more complex RC muscle-activation. Many cadaveric studies are performed discretely, and the integrity of the shoulder capsule is not always preserved. A more thorough understanding of the capsule's contribution to shoulder stability is needed to model the stable motion of the humeral head during glenohumeral motion.

Understanding the strengths and limitations of a study's design and methodology can help to maximize the transfer of knowledge from the lab to clinic. Shoulder studies should consider negative articular pressure, dynamic muscle-activation, and scapular position to advance clinical knowledge and improve patient outcomes. A shift is occurring in shoulder research moving biomechanical studies from cadaveric models to computer-based simulations. This change can be attributed to the cost of lab-based studies and the lack of invasive procedures to measure different quantities. For this reason, dynamic shoulder studies will rely extensively on the balance between *in-vivo* data and our ability to model it in simulations. At this stage, cadaveric studies are indispensable for model validation, and may play a major role in the study of dynamic motions of the shoulder. Cadaveric studies may still play a role in studying implants, surgical techniques, and shoulder pathology for as long as the healthy shoulder environment can be systematically modelled. Most shoulder pathologies rely greatly on stability and shoulder girdle positioning. Therefore, our ability to recreate these factors in both the healthy and diseased conditions determines the clinical reliability of cadaveric studies. If robust simulation of scapular contribution, muscle-activation, and capsular effects on stability can be achieved, these studies may provide the clinician with a reliable indication of the *in-vivo* shoulder environment in a myriad of situations.

This systematic review is limited by the lack of quality assessment tools available for cadaveric biomechanics studies. It was therefore difficult to assess the quality of each of the studies as is done in other review settings. This review focused on the methodology utilized in cadaveric studies of shoulder biomechanics with a wide range of goals that each study were designed to achive. Each of the described methodologies may appropriately serve the aims of the original study, while the same methodology may not be appropriate for a smiliar study with a different goal.

5. Conclusion

Cadaveric studies are indispensable for model validation, and may play an explicit role in the study of dynamic motions of the shoulder. Cadaveric studies may still play a role in studying implants, surgical techniques, and shoulder pathology for as long as the healthy shoulder environment can be systematically modelled. If robust simulation of scapular contribution, muscle-activation, and capsular effects on stability can be achieved, these studies may provide the clinician with a reliable indication of the in-vivo shoulder environment in a myriad of situations.

Conflict of interest

We confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

References

Ahmad, C.S., Stewart, A.M., Izquierdo, R., Bigliani, L.U., 2005. Tendon-bone interface motion in transosseous suture and suture anchor rotator cuff repair techniques. Am. J. Sports Med. 33 (11), 1667–1671. https://doi.org/10.1177/0363546505278252.

Alpert, S.W., Pink, M.M., Jobe, F.W., McMahon, P.J., Mathiyakom, W., 2000. Electromyographic analysis of deltoid and rotator cuff function under varying loads and speeds. J. Shoulder Elb. Surg. 9 (1), 47–58.
Apreleva, M., Hasselman, C.T., Debski, R.E., Fu, F.H., Woo, S.L., Warner, J.J., 1998. A dynamic analysis of glenohumeral motion after simulated capsulolabral injury. A cadaver model. J. Bone Joint Surg. Am. 80 (4), 474–480.
Bolsterlee, B., Veeger, D.H., Chadwick, E.K., 2013. Clinical applications of musculoskeletal modelling for the shoulder and upper limb. Med. Biol. Eng. Comput. 51 (9), 953–963. https://doi.org/10.1007/s11517-013-1099-5.
Braman, J.P., Engel, S.C., Laprade, R.F., Ludewig, P.M., 2009. In vivo assessment of scapulohumeral rhythm during unconstrained overhead reaching in asymptomatic subjects. J. Shoulder Elbow Surg. 18 (6), 960–967. https://doi.org/10.1016/j.jse.2009.02.001.
Chadwick, E.K., Blana, D., Kirsch, R.F., van den Bogert, A.J., 2014. Real-time simulation of three-dimensional shoulder girdle and arm dynamics. IEEE Trans. Biomed. Eng. 61 (7), 1947–1956. https://doi.org/10.1109/TBME.2014.2309727.
Chalmers, P.N., Salazar, D., Steger-May, K., Chamberlain, A.M., Yamaguchi, K., Keener, J.D., 2017. Does the critical shoulder angle correlate with rotator cuff tear progression? Clin. Orthop. Relat. Res. 475 (6), 1608–1617. https://doi.org/10.1007/s11999-017-5249-1.
Codman, E.A., Akerson, I.B., 1931. The pathology associated with rupture of the supraspinatus tendon. Ann. Surg. 93 (1), 348–359.
DeAngelis, J.P., Hertz, B., Wexler, M.T., et al., 2015. Posterior capsular plication constrains the glenohumeral joint by drawing the humeral head closer to the glenoid and resisting abduction. Orthop. J. Sports Med. 3 (8). https://doi.org/10.1177/2325967115599347. 2325967115599347.
Favre, P., Senteler, M., Hipp, J., Scherrer, S., Gerber, C., Snedeker, J.G., 2012. An integrated model of active glenohumeral stability. J. Biomech. 45 (13), 2248–2255. https://doi.org/10.1016/j.jbiomech.2012.06.010.
Fayad, F., Hoffmann, G., Hanneton, S., et al., 2006. 3-D scapular kinematics during arm elevation: effect of motion velocity. Clin. Biomech. (Bristol, Avon) 21 (9), 932–941. https://doi.org/10.1016/j.clinbiomech.2006.04.015.
Gibb, T.D., Sidles, J.A., Harryman 2nd, D.T., McQuade, K.J., Matsen 3rd., F.A., 1991. The effect of capsular venting on glenohumeral laxity. Clin. Orthop. Relat. Res. 268, 120–127.
Gombera, M.M., Sekiya, J.K., 2014. Rotator cuff tear and glenohumeral instability: a systematic review. Clin. Orthop. Relat. Res. 472 (8), 2448–2456. https://doi.org/10.1007/s11999-013-3290-2.
Grimberg, J., Diop, A., Bou Ghosn, R., Lanari, D., Canonne, A., Maurel, N., 2016. Bankart repair versus Bankart repair plus remplissage: an in vitro biomechanical comparative study. KneeSurg. Sports Traumatol. Arthrosc. 24 (2), 374–380. https://doi.org/10.1007/s00167-014-3052-z.
Habermeyer, P., Schuller, U., Wiedemann, E., 1992. The intra-articular pressure of the shoulder: an experimental study on the role of the glenoid labrum in stabilizing the joint. Arthroscopy 8 (2), 166–172.
Halder, A.M., O'Driscoll, S.W., Heers, G., et al., 2002. Biomechanical comparison of effects of supraspinatus tendon detachments, tendon defects, and muscle retractions. J. Bone Joint Surg. Am. 84-a (5), 780–785.
Hansen, M.L., Otis, J.C., Johnson, J.S., Cordasco, F.A., Craig, E.V., Warren, R.F., 2008. Biomechanics of massive rotator cuff tears: implications for treatment. J Bone Joint Surg Am 90 (2), 316–325. https://doi.org/10.2106/JBJS.F.00880.
Hashimoto, T., Suzuki, K., Nobuhara, K., 1995. Dynamic analysis of intraarticular pressure in the glenohumeral joint. J. Shoulder Elbow Surg. 4 (3), 209–218.
Hatakeyama, Y., Itoi, E., Urayama, M., Pradhan, R.L., Sato, K., 2001b. Effect of superior capsule and coracohumeral ligament release on strain in the repaired rotator cuff tendon. A cadaveric study. Am. J. Sports Med. 29 (5), 633–640. https://doi.org/10.1177/03635465010290051701.
Hatakeyama, Y., Itoi, E., Pradhan, R.L., Urayama, M., 2001a. Sato K. Effect of arm elevation and rotation on the strain in the repaired rotator cuff tendon. A cadaveric study. Am. J. Sports Med. 29 (6), 788–794. https://doi.org/10.1177/03635465010290061901.
Hockman, D.E., Lucas, G.L., Roth, C.A., 2004. Role of the coracoacromial ligament as restraint after shoulder hemiarthroplasty. Clin. Orthop. Relat. Res. 419, 80–82.
Hurschler, C., Wulker, N., Mendila, M., 2000. The effect of negative intraarticular pressure and rotator cuff force on glenohumeral translation during simulated active elevation. Clin. Biomech. (Bristol, Avon) 15 (5), 306–314.
Inman, V.T., Saunders, J.B., Abbott, L.C., 1944. Observations of the function of the shoulder joint. Clin. Orthop. Relat. Res. 1996 (330), 3–12.
Itoi, E., Motzkin, N.E., Browne, A.O., Hoffmeyer, P., Morrey, B.F., An, K.N., 1993. Intraarticular pressure of the shoulder. Arthroscopy 9 (4), 406–413.
Johnson, M.A., Polgar, J., Weightman, D., Appleton, D., 1973. Data on the distribution of fibre types in thirty-six human muscles. An autopsy study. J. Neurol. Sci. 18 (1), 111–129.
Johnson, G.R., Spalding, D., Nowitzke, A., Bogduk, N., 1996. Modelling the muscles of the scapula morphometric and coordinate data and functional implications. J. Biomech. 29 (8), 1039–1051.
Kelly, B.T., Williams, R.J., Cordasco, F.A., et al., 2005. Differential patterns of muscle activation in patients with symptomatic and asymptomatic rotator cuff tears. J. Shoulder Elbow Surg. 14 (2), 165–171. https://doi.org/10.1016/j.jse.2004.06.010.
Kim, H., Sandercock, T.G., Heckman, C.J., 2015. An action potential-driven model of soleus muscle activation dynamics for locomotor-like movements. J. Neural Eng. 12 (4), 046025. https://doi.org/10.1088/1741-2560/12/4/046025.
Konrad, G.G., Markmiller, M., Jolly, J.T., et al., 2006. Decreasing glenoid inclination improves function in shoulders with simulated massive rotator cuff tears. Clin. Biomech. (Bristol, Avon) 21 (9), 942–949. https://doi.org/10.1016/j.clinbiomech.2006.04.013.
Kumar, V.P., Balasubramaniam, P., 1985. The role of atmospheric pressure in stabilising the shoulder. An experimental study. J. Bone Joint Surg. Br. 67 (5), 719–721.
Lawrence, R.L., Braman, J.P., Staker, J.L., Laprade, R.F., Ludewig, P.M., 2014b. Comparison of 3-dimensional shoulder complex kinematics in individuals with and without shoulder pain, part 2: glenohumeral joint. J. Orthop. Sports Phys. Ther. 44 (9). https://doi.org/10.2519/jospt.2014.5556. 646–55, B1–3.
Lawrence, R.L., Braman, J.P., Laprade, R.F., Ludewig, P.M., 2014a. Comparison of 3-dimensional shoulder complex kinematics in individuals with and without shoulder pain, part 1: sternoclavicular, acromioclavicular, and scapulothoracic joints. J. Orthop. Sports Phys. Ther. 44 (9). https://doi.org/10.2519/jospt.2014.5339. 636–45, A1–8.
Lefevre-Colau, M.M., Nguyen, C., Palazzo, C., et al., 2018. Kinematic patterns in normal and degenerative shoulders. Part II: Review of 3-D scapular kinematic patterns in patients with shoulder pain, and clinical implications. Ann. Phys. Rehabil. Med. 61 (1), 46–53. https://doi.org/10.1016/j.rehab.2017.09.002.
Li, X., Xu, W., Hu, N., et al., 2017. Relationship between acromial morphological variation and subacromial impingement: a three-dimensional analysis. PLoS One 12 (4), e0176193. https://doi.org/10.1371/journal.pone.0176193.
Liu, J., Hughes, R.E., O'Driscoll, S.W., An, K.N., 1998. Biomechanical effect of medial advancement of the supraspinatus tendon. A study in cadavera. J. Bone Joint Surg. Am. 80 (6), 853–859.
Ludewig, P.M., Cook, T.M., 2000. Alterations in shoulder kinematics and associated muscle activity in people with symptoms of shoulder impingement. Phys. Ther. 80 (3), 276–291.
Lunden, J.B., Braman, J.P., Laprade, R.F., Ludewig, P.M., 2010. Shoulder kinematics during the wall push-up plus exercise. J. Shoulder Elbow Surg. 19 (2), 216–223. https://doi.org/10.1016/j.jse.2009.06.003.
Malicky, D.M., Soslowsky, L.J., Blasier, R.B., Shyr, Y., 1996. Anterior glenohumeral stabilization factors: progressive effects in a biomechanical model. J. Orthop. Res. 14 (2), 282–288. https://doi.org/10.1002/jor.1100140217.
Malicky, D.M., Soslowsky, L.J., Kuhn, J.E., et al., 2001. Total strain fields of the antero-inferior shoulder capsule under subluxation: a stereoradiogrammetric study. J. Biomech. Eng. 123 (5), 425–431.
Malicky, D.M., Soslowsky, L.J., 2009. Relationships between total and non-recoverable strain fields in glenohumeral capsule during shoulder subluxation. Ann. Biomed. Eng. 37 (12), 2547–2555. https://doi.org/10.1007/s10439-009-9784-0.
Malicky, D.M., Kuhn, J.E., Frisancho, J.C., Lindholm, S.R., Raz, J.A., Soslowsky, L.J., 2002. Neer Award 2001: nonrecoverable strain fields of the anteroinferior glenohumeral capsule under subluxation. J. Shoulder Elbow. Surg. 11 (6), 529–540. https://doi.org/10.1067/mse.2002.127093.
Mantell, M.T., Nelson, R., Lowe, J.T., Endrizzi, D.P., Jawa, A., 2017. Critical shoulder angle is associated with full-thickness rotator cuff tears in patients with glenohumeral osteoarthritis. J. Shoulder Elbow Surg. 26 (12), e376–e381. https://doi.org/10.1016/j.jse.2017.05.020.
Mazzocca, A.D., Spang, J.T., Rodriguez, R.R., et al., 2008. Biomechanical and radiographic analysis of partial coracoclavicular ligament injuries. Am. J. Sports Med. 36 (7), 1397–1402. https://doi.org/10.1177/0363546508315200.
Mazzocca, A.D., Bollier, M., Fehsenfeld, D., et al., 2011. Biomechanical evaluation of margin convergence. Arthroscopy 27 (3), 330–338. https://doi.org/10.1016/j.arthro.2010.09.003.
McClure, P.W., Michener, L.A., Sennett, B.J., Karduna, A.R., 2001. Direct 3-dimensional measurement of scapular kinematics during dynamic movements in vivo. J. Shoulder Elbow. Surg. 10 (3), 269–277. https://doi.org/10.1067/mse.2001.112954.
McMahon, P.J., Debski, R.E., Thompson, W.O., Warner, J.J., Fu, F.H., Woo, S.L., 1995. Shoulder muscle forces and tendon excursions during glenohumeral abduction in the scapular plane. J. Shoulder Elbow Surg. 4 (3), 199–208.
McQuade, K.J., Smidt, G.L., 1998. Dynamic scapulohumeral rhythm: the effects of external resistance during elevation of the arm in the scapular plane. J. Orthop. Sports Phys. Ther. 27 (2), 125–133. https://doi.org/10.2519/jospt.1998.27.2.125.
Mihata, T., McGarry, M.H., Pirolo, J.M., Kinoshita, M., Lee, T.Q., 2012. Superior capsule reconstruction to restore superior stability in irreparable rotator cuff tears: a biomechanical cadaveric study. Am. J. Sports Med. 40 (10), 2248–2255. https://doi.org/10.1177/0363546512456195.
Mihata, T., McGarry, M.H., Ishihara, Y., et al., 2015. Biomechanical analysis of articular-sided partial-thickness rotator cuff tear and repair. Am. J. Sports Med. 43 (2), 439–446. https://doi.org/10.1177/0363546514560156.
Mihata, T., McGarry, M.H., Kahn, T., Goldberg, I., Neo, M., Lee, T.Q., 2016a. Biomechanical role of capsular continuity in superior capsule reconstruction for irreparable tears of the supraspinatus tendon. Am. J. Sports Med. 44 (6), 1423–1430. https://doi.org/10.1177/0363546516631751.
Mihata, T., McGarry, M.H., Kahn, T., Goldberg, I., Neo, M., Lee, T.Q., 2016a. Biomechanical effect of thickness and tension of fascia lata graft on glenohumeral stability for superior capsule reconstruction in irreparable supraspinatus tears. Arthroscopy 32 (3), 418–426. https://doi.org/10.1016/j.arthro.2015.08.024.
Moher, D., Liberati, A., Tetzlaff, J., Altman, D.G., Group, P., 2009. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. J. Clin. Epidemiol. 62 (10), 1006–1012. https://doi.org/10.1016/j.jclinepi.2009.06.005.
Mueller, A.M., Rosso, C., Entezari, V., et al., 2014. The effect of supraspinatus tears on glenohumeral translations in passive pitching motion. Am. J. Sports Med. 42 (10), 2455–2462. https://doi.org/10.1177/0363546514547348.

Muraki, T., Aoki, M., Uchiyama, E., Miyasaka, T., Murakami, G., Miyamoto, S., 2007. Strain on the repaired supraspinatus tendon during manual traction and translational glide mobilization on the glenohumeral joint: a cadaveric biomechanics study. Man. Ther. 12 (3), 231–239. https://doi.org/10.1016/j.math.2006.06.017.

Oh, J.H., McGarry, M.H., Jun, B.J., et al., 2012. Restoration of shoulder biomechanics according to degree of repair completion in a cadaveric model of massive rotator cuff tear: importance of margin convergence and posterior cuff fixation. Am. J. Sports Med. 40 (11), 2448–2453. https://doi.org/10.1177/0363546512458775.

Oh, J.H., Tilan, J., Chen, Y.J., Chung, K.C., McGarry, M.H., Lee, T.Q., 2013. Biomechanical effect of latissimus dorsi tendon transfer for irreparable massive cuff tear. J. Shoulder Elbow Surg. 22 (2), 150–157. https://doi.org/10.1016/j.jse.2012.01.022.

Omid, R., Heckmann, N., Wang, L., McGarry, M.H., Vangsness Jr., C.T., Lee, T.Q., 2015. Biomechanical comparison between the trapezius transfer and latissimus transfer for irreparable posterosuperior rotator cuff tears. J. Shoulder Elbow Surg. 24 (10), 1635–1643. https://doi.org/10.1016/j.jse.2015.02.008.

Pagnani, M.J., Warren, R.F., 1994. Stabilizers of the glenohumeral joint. J. Shoulder Elbow Surg. 3 (3), 173–190. https://doi.org/10.1016/S1058-2746(09)80098-0.

Pedowitz, R.A., Yamaguchi, K., Ahmad, C.S., et al., 2011. Optimizing the management of rotator cuff problems. J. Am. Acad. Orthop. Surg. 19 (6), 368–379.

Poppen, N.K., Walker, P.S., 1976. Normal and abnormal motion of the shoulder. J. Bone Joint Surg. Am. 58 (2), 195–201.

Prinold, J.A., Masjedi, M., Johnson, G.R., Bull, A.M., 2013. Musculoskeletal shoulder models: a technical review and proposals for research foci. Proc. Inst. Mech. Eng. H 227 (10), 1041–1057. https://doi.org/10.1177/0954411913492303.

Provencher, M.T., Mologne, T.S., Hongo, M., Zhao, K., Tasto, J.P., An, K.N., 2007. Arthroscopic versus open rotator interval closure: biomechanical evaluation of stability and motion. Arthroscopy 23 (6), 583–592. https://doi.org/10.1016/j.arthro.2007.01.010.

Reed, D., Cathers, I., Halaki, M., Ginn, K.A., 2016. Does load influence shoulder muscle recruitment patterns during scapular plane abduction? J. Sci. Med. Sport 19 (9), 755–760. https://doi.org/10.1016/j.jsams.2015.10.007.

Reed, D., Cathers, I., Halaki, M., Ginn, K.A., 2016. Does changing the plane of abduction influence shoulder muscle recruitment patterns in healthy individuals? Man. Ther. 21, 63–68. https://doi.org/10.1016/j.math.2015.04.014.

Roach, N.T., Venkadesan, M., Rainbow, M.J., Lieberman, D.E., 2013. Elastic energy storage in the shoulder and the evolution of high-speed throwing in Homo. Nature 498 (7455), 483–486. https://doi.org/10.1038/nature12267.

Rosso, C., Muller, A.M., Entezari, V., et al., 2013. Preliminary evaluation of a robotic apparatus for the analysis of passive glenohumeral joint kinematics. J. Orthop. Surg. Res. 8, 24. https://doi.org/10.1186/1749-799X-8-24.

Shin, S.J., Yoo, J.C., McGarry, M.H., Jun, B.J., Lee, T.Q., 2013. Anterior capsulolabral lesions combined with supraspinatus tendon tears: biomechanical effects of the pathologic condition and repair in human cadaveric shoulders. Arthroscopy 29 (9), 1492–1497. https://doi.org/10.1016/j.arthro.2013.05.031.

Soslowsky, L.J., Flatow, E.L., Bigliani, L.U., Pawluk, R.J., Ateshian, G.A., Mow, V.C., 1992. Quantitation of in situ contact areas at the glenohumeral joint: a biomechanical study. J Orthop Res. 10, 524–534.

Soslowsky, L.J., Malicky, D.M., Blasier, R.B., 1997. Active and passive factors in inferior glenohumeral stabilization: a biomechanical model. J. Shoulder Elbow Surg. 6 (4), 371–379.

Speer, K.P., Deng, X., Torzilli, P.A., Altchek, D.A., Warren, R.F., 1995. Strategies for an anterior capsular shift of the shoulder. A biomechanical comparison. Am. J. Sports Med. 23 (3), 264–269. https://doi.org/10.1177/036354659502300302.

Teunis, T., Lubberts, B., Reilly, B.T., Ring, D., 2014. A systematic review and pooled analysis of the prevalence of rotator cuff disease with increasing age. J. Shoulder Elbow Surg. 23 (12), 1913–1921. https://doi.org/10.1016/j.jse.2014.08.001.

Veeger, H.E., Van der Helm, F.C., Van der Woude, L.H., Pronk, G.M., Rozendal, R.H., 1991. Inertia and muscle contraction parameters for musculoskeletal modelling of the shoulder mechanism. J. Biomech. 24 (7), 615–629.

Veeger, H.E., van der Helm, F.C., 2007. Shoulder function: the perfect compromise between mobility and stability. J. Biomech. 40 (10), 2119–2129. https://doi.org/10.1016/j.jbiomech.2006.10.016.

Warner, J.J., Bowen, M.K., Deng, X., Torzilli, P.A., Warren, R.F., 1999. Effect of joint compression on inferior stability of the glenohumeral joint. J. Shoulder Elbow Surg. 8 (1), 31–36.

Webb, J.D., Blemker, S.S., Delp, S.L., 2014. 3D finite element models of shoulder muscles for computing lines of actions and moment arms. Comput. Methods Biomech. Biomed. Eng. 17 (8), 829–837. https://doi.org/10.1080/10255842.2012.719605.

Wellmann, M., Petersen, W., Zantop, T., Schanz, S., Raschke, M.J., Hurschler, C., 2008. Effect of coracoacromial ligament resection on glenohumeral stability under active muscle loading in an in vitro model. Arthroscopy 24 (11), 1258–1264. https://doi.org/10.1016/j.arthro.2008.01.015.

Wuelker, N., Schmotzer, H., Thren, K., Korell, M., 1994. Translation of the glenohumeral joint with simulated active elevation. Clin. Orthop. Relat. Res. 309, 193–200.

Wuelker, N., Plitz, W., Roetman, B., Wirth, C.J., 1994. Function of the supraspinatus muscle. Abduction of the humerus studied in cadavers. Acta Orthop. Scand. 65 (4), 442–446.

Wuelker, N., Wirth, C.J., Plitz, W., Roetman, B., 1995. A dynamic shoulder model: reliability testing and muscle force study. J. Biomech. 28 (5), 489–499.

Wuelker, N., Korell, M., Thren, K., 1998. Dynamic glenohumeral joint stability. J. Shoulder Elbow Surg. 7 (1), 43–52.

Yamamoto, N., Itoi, E., Tuoheti, Y., et al., 2006b. The effect of the inferior capsular shift on shoulder intra-articular pressure: a cadaveric study. Am. J. Sports Med. 34 (6), 939–944. https://doi.org/10.1177/0363546505283834.

Yamamoto, N., Itoi, E., Tuoheti, Y., et al., 2006a. Effect of rotator interval closure on glenohumeral stability and motion: a cadaveric study. J. Shoulder Elbow Surg. 15 (6), 750–758. https://doi.org/10.1016/j.jse.2005.12.009.

Yoo, J.C., McGarry, M.H., Jun, B.J., Scott, J., Lee, T.Q., 2014. The influence of partial subscapularis tendon tears combined with supraspinatus tendon tears. J. Shoulder Elbow Surg. 23 (6), 902–908. https://doi.org/10.1016/j.jse.2013.09.015.

Yu, J., McGarry, M.H., Lee, Y.S., Duong, L.V., Lee, T.Q., 2005. Biomechanical effects of supraspinatus repair on the glenohumeral joint. J. Shoulder Elbow Surg. 14 (1 Suppl S), 65S–71S. https://doi.org/10.1016/j.jse.2004.09.019.

Zheng, M., Zou, Z., Bartolo, P.J., Peach, C., Ren, L., 2017.. Finite element models of the human shoulder complex: a review of their clinical implications and modelling techniques. Int. J. Numer. Method Biomed. Eng. 33 (2). https://doi.org/10.1002/cnm.2777.

Zuckerman, J.D., Leblanc, J.M., Choueka, J., Kummer, F., 1991. The effect of arm position and capsular release on rotator cuff repair. A biomechanical study. J. Bone Joint Surg. Br. 73 (3), 402–405.