Journal of Biomechanics 45 (2012) 614–618

Contents lists available at SciVerse ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

Short communication

Low-dose CT imaging of radio-opaque markers for assessing human rotator cuff repair: Accuracy, repeatability and the effect of arm position

K.A. Derwin[a,b,c,*], R.A. Milks[a], I. Davidson[c], J.P. Iannotti[a,b,c], J.A. McCarron[d], M.J. Bey[e]

[a] Department of Biomedical Engineering and Orthopedic and Rheumatologic Research Center, Cleveland Clinic, Cleveland, OH, USA
[b] Department of Orthopedic Surgery, Orthopedic and Rheumatologic Institute, Cleveland Clinic, Cleveland, OH, USA
[c] Cleveland Clinic Lerner College of Medicine, Cleveland Clinic, Cleveland, OH, USA
[d] Orthopedic Surgery Section, Department of VA Medical Center, Portland, OR, USA
[e] Henry Ford Hospital, Bone and Joint Center, Detroit, MI, USA

ARTICLE INFO

Article history:
Accepted 18 November 2011

Keywords:
CT imaging
Rotator cuff repair
Tantalum beads

ABSTRACT

Previous studies have used radiostereometric analysis (RSA) to assess the integrity and mechanical properties of repaired tendons and ligament grafts. A conceptually similar approach is to use CT imaging to measure the 3D position and distance between implanted markers. The purpose of this study was to quantify the accuracy and repeatability of measuring the position and distance between metallic markers placed in the rotator cuff using low-dose CT imaging. We also investigated the effect of repeated or variable positions of the arm on position and distance measures. Six human patients had undergone rotator cuff repair and placement of tantalum beads in the rotator cuff at least one year prior to participating in this study. On a single day each patient underwent nine low-dose CT scans in seven unique arm positions. CT scans were analyzed to assess bias, precision and RMS error of the measurement technique. The effect of repeated or variable positions of the arm on the 3D position of the beads and the distance between these beads and suture anchors in the humeral head were also assessed. Results showed the CT imaging method is accurate and repeatable to within 0.7 mm. Further, measures of bead position and anchor-to-bead distance are influenced by arm position and location of the bead within the rotator cuff. Beads located in the posterior rotator cuff moved medially as much as 20 mm in abduction or external rotation. When clinically relevant CT arm positions such as the hand on umbilicus or at side were repeated, bead position varied less than 4 mm in any anatomic direction and anchor-to-bead distance varied +2.8 to −1.6 mm (RMS 1.3 mm). We conclude that a range of ±3 mm is a conservative estimate of the uncertainty in anchor-to-bead distance for patients repeatedly scanned in clinically-relevant arm positions.

1. Introduction

Rotator cuff tears affect 30–40% or more of the population over age 60 (Milgrom et al., 1995; Sher et al., 1995; Tempelhof, 1999), resulting in 75,000 repair surgeries annually in the United States (Vitale et al., 2007). Although surgical treatment and rehabilitation strategies for rotator cuff repair continue to evolve, failure rates of 20–70% for medium to large tears remain a significant clinical challenge (Bjornsson et al., 2011; Koh et al., 2011; Tashjian et al., 2010; Toussaint et al., 2011). The outcome of rotator cuff repair surgery is assessed by questionnaires, physical exam and ultrasound (US), magnetic resonance imaging (MRI), or computed tomography (CT) arthrogram imaging modalities. Although imaging modalities are used to assess healing, the appearance of the repaired rotator cuff tendon during the first post-operative year can be highly variable and often difficult to interpret (Crim et al., 2010).

Previous studies have used radiostereometric analysis (RSA), an imaging technique that allows the three-dimensional (3D) measurement of distance between metallic markers from two, synchronized, plain radiographs, to assess the integrity and mechanical properties of repaired tendons and ligament grafts in vivo (Baring et al., 2011; Bey et al., 2011; Khan et al., 2006; Schepull et al., 2007; Schepull et al., 2011). A conceptually similar approach is to use CT imaging to measure the 3D position and distance between implanted markers, however, the accuracy and repeatability of this technique for assessing soft tissue repair has not been previously evaluated. Hence, the purpose of this study was to quantify the accuracy and repeatability of measuring the position and distance between

* Corresponding author at: Cleveland Clinic, Department of Biomedical Engineering, ND20, 9500 Euclid Avenue, Cleveland, OH 44195, United States.
Tel.: +1 216 445 5982; fax: +1 216 444 9198.
E-mail addresses: derwink@ccf.org, derwink@bme.ri.ccf.org (K.A. Derwin).

0021-9290/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jbiomech.2011.11.046

metallic markers placed in the rotator cuff using low dose CT imaging. We also investigated the effect of repeated or variable positions of the arm on position and distance measures.

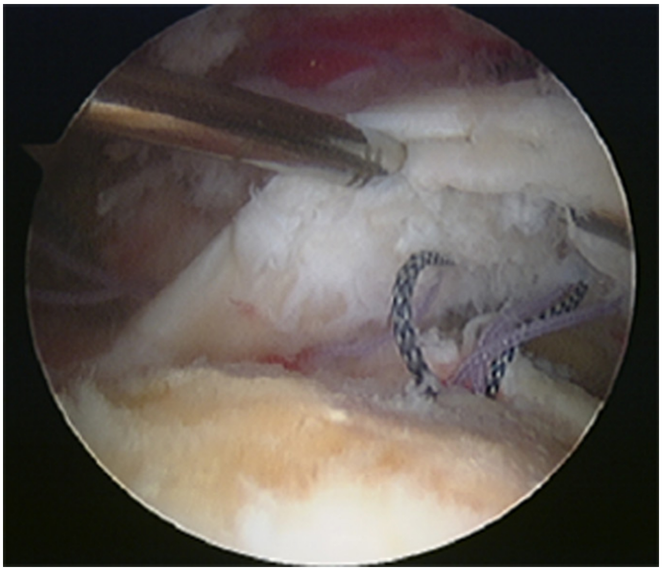

Fig. 1. Intra-operative photo showing that the arthroscopic bead delivery device was inserted into the lateral edge of the tendon prior to tying down the repair sutures, and the beads were deployed 1.5–2 cm medial to the lateral edge.

2. Methods

Six patients participating in an interrelated study at our institution were enrolled in this IRB-approved study. These patients had undergone arthroscopic repair of supraspinatus or supraspinatus/infraspinatus rotator cuff tears using a suture–bridge technique (Park et al., 2006), at least 52 weeks prior to participating in this study. At surgery, one or two 1.6 mm diameter tantalum beads had been deployed within the repaired rotator cuff tendons of each patient using a custom, cannulated, arthroscopic delivery device. Specifically, the delivery device was inserted into the lateral edge of the tendon prior to tying down the repair sutures (Fig. 1). The beads were deployed 1.5–2 cm medial to the lateral edge but not otherwise attached to the tendon. The beads were located medial to the repair suture line but within the tendinous portion of the rotator cuff. Across all patients, four beads were located in the anterior supraspinatus ("anterior beads"), and seven beads were in the posterior supraspinatus, the junction of supraspinatus/infraspinatus, or the infraspinatus tendons ("posterior beads"). At the time of participation in this study, none of the six patients had experienced any complications related to the use of the beads.

2.1. CT scanning

On a single day each patient underwent nine CT scans (Siemens Sensation 16, Siemens Medical Solutions, Malvern, PA), in seven unique arm positions (Table 1). A low-dose scanning protocol was used (100 kV, 45 mAs), and the voxel size was $0.4 \times 0.4 \times 0.7$ mm. A brace (Omo Immobil, Otto Bock, Duderstadt, Germany) was used to facilitate arm positioning. Two positions were repeated at the beginning and end of the scan sequence: "Umb" – shoulder in 0° abduction, 0° flexion and internally rotated with the palm of hand on the umbilicus, and "Zero" – shoulder in 0° abduction, flexion and rotation, with the palm resting on the thigh.

Table 1
Scan position and sequence; * = arm was in brace for these scans, ** = arm was supported by 30° wedge for this scan.

Scan order	Arm position	Description
1	Umb_1	Shoulder abducted and flexed 0°, internally rotated with hand on umbilicus
2	Zero_1	Shoulder abducted, flexed and rotated 0°, with hand on thigh
3	30-deg ABD*	Shoulder abducted 30°, elbow flexed 90°
4	60-deg ABD*	Shoulder abducted 60°, elbow flexed 90°
5	30-deg ER*	Shoulder abducted and flexed 0°, externally rotated 30°, elbow flexed 90°
6	30-deg IR*	Shoulder abducted and flexed 0°, internally rotated 30°, elbow flexed 90°
7	Zero_2	REPEAT Zero_1
8	30-deg FF**	Shoulder forward flexed 30°, elbow fully extended and thumb facing upward
9	Umb_2	REPEAT Umb_1

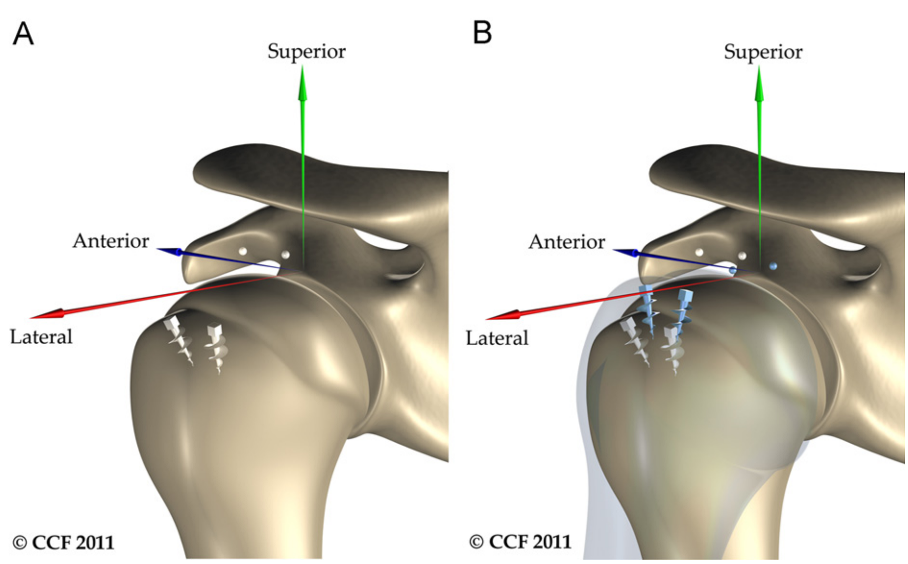

Fig. 2. Schematic of CT scans from a left shoulder. (A) The 3D positions of each tendon bead, and the superficial end of each anchor (the end at bone surface), were determined in a scapula-based coordinate system whose origin was located at the superior glenoid rim. (B) Changes in arm position caused movement of the anchors and implanted beads relative to the scapular coordinate system. Represented here are the Umb (gray) and 30-degree ABD (blue) arm positions as described in Table 1. Reprinted with permission, Cleveland Clinic Center for Medical Art & Photography © 2011. All Rights Reserved.

2.2. Image analysis and bead measurements

CT scans were analyzed using custom software (VolNinja, ImageIQ, Cleveland, OH). The three-dimensional (3D) position of each bead and the superficial end of each anchor were determined in a scapula-based coordinate system (Wu et al., 2005) with the origin on the superior glenoid rim (Fig. 2A). The scalar distances between each bead and its nearest anchor – "anchor-to-bead distance" – were computed for each scan. For each bead, the anchor-to-bead distance was consistently measured to the same "nearest anchor" across all scans for a given patient. In addition, the length of each anchor was measured directly using VolNinja. In total eleven anchor–bead pairs were analyzed across the six patients.

2.3. Accuracy of the measurement technique

Accuracy was quantified in terms of bias, precision (ASTM, 1996) and root mean square (RMS) error. The eleven measures of anchor length were compared to the 13.0 mm nominal length of a Fastin® RC 5.0 anchors (Depuy Mitek, Raynham, MA), which was used for tendon repair. Bias was defined as the mean difference between each anchor's measured length and the nominal length. Precision was defined as the standard deviation of the eleven measures of anchor length. RMS error was defined as the RMS difference between measured and nominal anchor length.

2.4. Repeatability of the measurement technique

Using the nine CT scans from one patient, bead position and anchor-to-bead distance for two anchor–bead pairs were repeated three times for each scan. The standard deviation of each set of triplicate measures was determined. Repeatability was assessed by averaging the standard deviations for each outcome measure. For bead position, 54 standard deviations were averaged (9 CT scans, 2 beads per scan, 3 position coordinates per bead). For anchor-to-bead distance, 18 standard deviations were averaged (9 CT scans, 2 anchor-to-bead distances per scan).

2.5. Effect of arm position

The effect of arm position on bead position and anchor-to-bead distance was assessed by the range and RMS difference of these outcomes compared to the Umb_1 position. To assess repeatability of the same arm position, comparisons were made between the Umb_1 and Umb_2 positions and Zero_1 and Zero_2 positions.

3. Results

3.1. Accuracy and repeatability

The bias of measuring anchor length was −0.56 mm and the precision was 0.30 mm. The RMS error of measuring anchor length was 0.63 mm.

The repeatability of determining 3D bead position was 0.56 ± 0.27 mm in any anatomic direction, and the repeatability of determining anchor-to-bead distance was 0.38 ± 0.27 mm.

3.2. Effect of arm position

Changes in arm position caused movement of the anchors and implanted beads relative to the scapular coordinate system (Fig. 2B). The most pronounced effect on bead position was medial movement, in some instances as much as 20 mm for abduction and external rotation, particularly for beads located in the posterior rotator cuff (Fig. 3A). Superior/inferior (Fig. 3B) or anterior/posterior (Fig. 3C) movement of the beads in the scapular coordinate system tended to be less than 10 mm for all arm positions. Bead position moved less than 4 mm in any anatomic direction when the same arm position was repeated (Umb or Zero) (Table 2).

Across all patients/beads, the difference in anchor-to-bead distance between Umb_1 and any other arm position ranged from +4.1 to −7.4 mm (Fig. 4). The anchor-to-bead distance of beads in the posterior rotator cuff tended to vary more than anterior beads in abduction and external rotation arm positions,

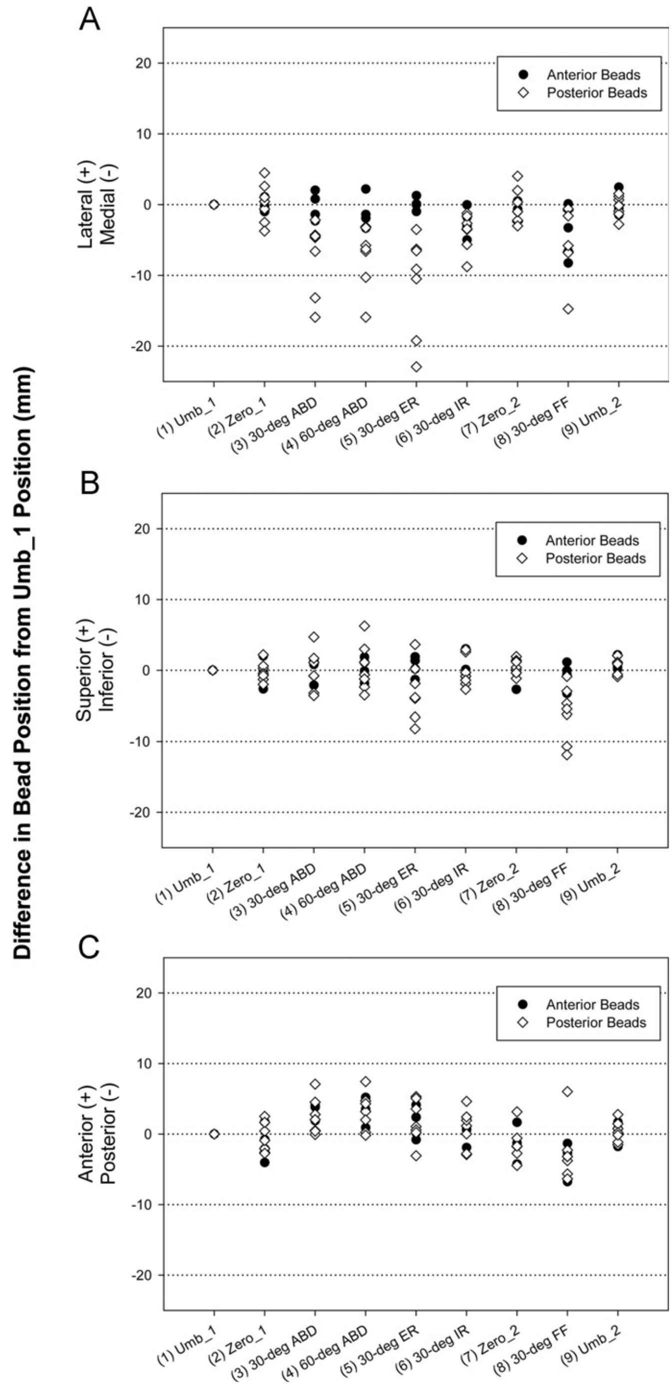

Fig. 3. Variability introduced in (A) medial/lateral, (B) superior/inferior, (C) anterior/posterior bead position from placing the arm in different positions with respect to Umb_1, for anterior beads (n=4) and posterior beads (n=7).

while the anchor-to-bead distance of anterior beads tended to vary more than posterior beads in forward flexion. The difference in anchor-to-bead distance at repeated arm positions ranged from +2.4 to −1.6 mm (RMS 1.3 mm) for Umb_1 versus Umb_2 (Fig. 4, Table 2) and +2.8 to −1.7 mm (RMS 1.3 mm) for Zero_1 versus Zero_2 (Table 2).

4. Discussion

The purpose of this study was to characterize the accuracy and repeatability of the low-dose CT imaging technique in the context

Table 2
Maximum differences in bead position or anchor-to-bead distance on repeated scans of the same arm position ($n=11$ for each comparison).

Repeated arm positions compared	Maximum differences in bead position (mm)						Maximum differences in anchor–bead distance (mm)	
	Lat	Med	Sup	Inf	Ant	Post	Min	Max
Umb_2–Umb_1	2.5	−2.8	2.2	−0.9	2.8	−1.8	−1.6	2.4
Zero_2–Zero_1	2.8	−3.2	1.9	−0.6	1.0	−3.6	−1.7	2.8

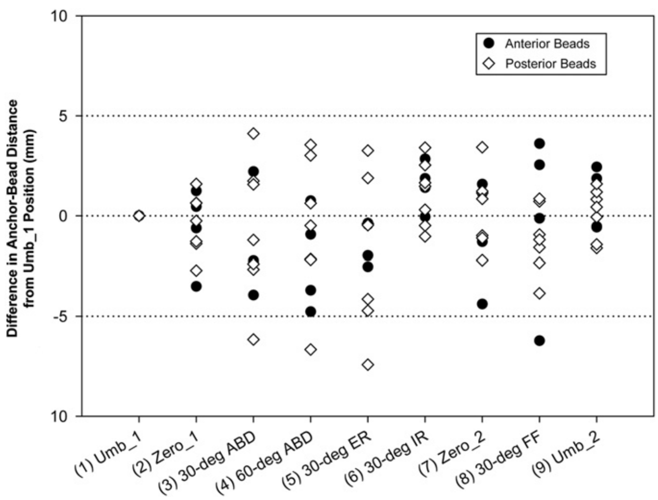

Fig. 4. Variability introduced in anchor-to-bead distance from placing the arm in different positions with respect to Umb_1, for anterior beads ($n=4$) and posterior beads ($n=7$).

of human rotator cuff repair and then investigate the effect of arm position on bead position and anchor-to-bead distance. This technique is accurate and repeatable to within 0.7 mm, which is less than one-half the bead diameter and on the order of the voxel size of the CT scanner used.

This study demonstrated that bead position and anchor-to-bead distance were influenced by both arm position and the location of the bead within the rotator cuff. In particular beads located in the posterior rotator cuff moved medially as much as 20 mm in abduction or external rotation. Variability in bead position and distance could arise from stretching or unloading of the tendon in the different arm positions. Although not assessed in this study, variability may also depend on tendon integrity. Specifically, we would expect that the variability in bead position and/or anchor-to-bead distance would be lower in normal/healed tendons and higher if the tendon was re-torn or if its connection to bone was through scant scar tissue.

When clinically relevant CT arm positions such as hand on umbilicus or at side were repeated, bead position varied less than 4 mm in any anatomic direction and similarly for all beads regardless of their anatomic location. Anchor-to-bead distance varied +2.8 to −1.6 mm (RMS 1.3 mm) across repeat scans of the same arm position. This variability likely reflects the inability to perfectly reposition the patient in the same exact arm position within the CT scanner. We conclude that a range of ±3 mm is a conservative estimate of the uncertainty in anchor-to-bead distance for patients repeatedly scanned in clinically-relevant arm positions.

In summary, we investigated the use of low-dose CT imaging for assessing human rotator cuff repair by evaluating accuracy, repeatability and the effect of arm position. We showed that this method is accurate and repeatable to within 0.7 mm, and that measures of bead position and anchor-to-bead distance are influenced by arm position and location of the bead within the rotator cuff. For clinically relevant CT arm positions such as hand on umbilicus or at side, we conclude that ±3 mm is a conservative estimate of the uncertainty in anchor-to-bead distance measures. These methods are being used in our ongoing study monitoring tendon gap formation in human rotator cuff repair patients over the first year post-operatively.

Conflict of interest statement

None of the authors have any conflicts related to the subject of this manuscript.

Acknowledgment

The authors acknowledge Mena Mesiha, MD, who oversaw the CT scanning of the patients in this study. Funding for the work was provided in part by Pfizer, who otherwise had no involvement in the study design, collection, analysis, interpretation, writing, or decision to submit this manuscript for publication. Funding was also provided in part by the Cleveland Clinic Department of Orthopedics and Henry Ford Hospital Department of Orthopedics.

References

ASTM, (1996). E177-90a (1996) Standard Practice for Use of the Terms Precision and Bias in ASTM Test Methods. West Conshohocken, PA, pp. 1–12.
Baring, T.K., Cashman, P.P., Reilly, P., Emery, R.J., Amis, A.A., 2011. Rotator cuff repair failure in vivo: a radiostereometric measurement study. Journal of Shoulder and Elbow Surgery 20 (8), 1194–1199. doi:10.1016/j.jse.2011.04.010.
Bey, M.J., Kline, S.K., Baker, A.R., McCarron, J.A., Iannotti, J.P., Derwin, K.A., 2011. Estimation of dynamic, in vivo soft-tissue deformation: experimental technique and application in a canine model of tendon injury and repair. Journal of Orthopaedic Research 29, 822–827.
Bjornsson, H.C., Norlin, R., Johansson, K., Adolfsson, L.E., 2011. The influence of age, delay of repair, and tendon involvement in acute rotator cuff tears. Acta Orthopaedica 82, 187–192.
Crim, J., Burks, R., Manaster, B.J., Hanrahan, C., Hung, M., Greis, P., 2010. Temporal evolution of MRI findings after arthroscopic rotator cuff repair. American Journal of Roentgenology 195, 1361–1366.
Khan, R., Konyves, A., Rama, K.R., Thomas, R., Amis, A.A., 2006. RSA can measure ACL graft stretching and migration: development of a new method. Clinical Orthopaedics and Related Research 448, 139–145.
Koh, K.H., Kang, K.C., Lim, T.K., Shon, M.S., Yoo, J.C., 2011. Prospective Randomized Clinical Trial of Single- Versus Double-Row Suture Anchor Repair in 2- to 4-cm Rotator Cuff Tears: Clinical and Magnetic Resonance Imaging Results. Arthroscopy 27, 453–462.
Milgrom, C., Schaffler, M., Gilbert, S, van Holsbeeck, M., 1995. Rotator-cuff changes in asymptomatic adults. The effect of age, hand dominance and gender. Journal of Bone and Joint Surgery 77 (2), 296–298.
Park, M.C., Elattrache, N.S., Ahmad, C.S., Tibone, J.E., 2006. "Transosseous-equivalent" rotator cuff repair technique. Arthroscopy 22, 1360–1365.
Schepull, T., Kvist, J., Andersson, C., Aspenberg, P., 2007. Mechanical properties during healing of Achilles tendon ruptures to predict final outcome: a pilot Roentgen stereophotogrammetric analysis in 10 patients. BMC Musculoskeleton Disorder 8 (116), 116.
Schepull, T., Kvist, J., Norrman, H., Trinks, M., Berlin, G., Aspenberg, P., 2011. Autologous platelets have no effect on the healing of human achilles tendon ruptures: a randomized single-blind study. American Journal of Sports Medicine 39, 38–47.
Sher, J.S., Uribe, J.W., Posada, A., Murphy, B.J., Zlatkin, M.B., 1995. Abnormal findings on magnetic resonance images of asymptomatic shoulders. Journal of Bone and Joint Surgery 77, 10–15.
Tashjian, R.Z., Hollins, A.M., Kim, H.M., Teefey, S.A., Middleton, W.D., Steger-May, K., Galatz, L.M., Yamaguchi, K., 2010. Factors Affecting Healing Rates After Arthroscopic Double-Row Rotator Cuff Repair. American Journal of Sports Medicine 38, 2435–2442.
Tempelhof, S., 1999. Age-related prevalance of rotator cuff tears in asymptomatic shoulders. Journal of Shoulder and Elbow Surgery 8, 296–299.
Toussaint, B., Schnaser, E., Bosley, J., Lefebvre, Y., Gobezie, R., (2011). Early Structural and Functional Outcomes for Arthroscopic Double-Row

Transosseous-Equivalent Rotator Cuff Repair. American Journal of Sports Medicine.

Vitale, M.A., Vitale, M.G., Zivin, J.G., Braman, J.P., Bigliani, L.U., Flatow, E.L., 2007. Rotator cuff repair: an analysis of utility scores and cost-effectiveness. Journal of Shoulder and Elbow Surgery 16, 181–187.

Wu, G., van der Helm, F.C., Veeger, H.E., Makhsous, M., Van, R.P., Anglin, C., Nagels, J., Karduna, A.R., McQuade, K., Wang, X., Werner, F.W., Buchholz, B., 2005. ISB recommendation on definitions of joint coordinate systems of various joints for the reporting of human joint motion–Part II: shoulder, elbow, wrist and hand. Journal of Biomechanics 38, 981–992.