Clin Orthop Relat Res (2008) 466:661–669
DOI 10.1007/s11999-007-0089-z

SYMPOSIUM: NEW APPROACHES TO SHOULDER SURGERY

CT Scan Method Accurately Assesses Humeral Head Retroversion

P. Boileau MD, R. T. Bicknell MD, MSc, FRCSC, N. Mazzoleni MD, G. Walch MD, J. P. Urien MD

Abstract Humeral head retroversion is not well described with the literature controversial regarding accuracy of measurement methods and ranges of normal values. We therefore determined normal humeral head retroversion and assessed the measurement methods. We measured retroversion in 65 cadaveric humeri, including 52 paired specimens, using four methods: radiographic, computed tomography (CT) scan, computer-assisted, and direct methods. We also assessed the distance between the humeral head central axis and the bicipital groove. CT scan methods accurately measure humeral head retroversion, while radiographic methods do not. The retroversion with respect to the transepicondylar axis was 17.9° and 21.5° with respect to the trochlear tangent axis. The difference between the right and left humeri was 8.9°. The distance between the central axis of the humeral head and the bicipital groove was 7.0 mm and was consistent between right and left humeri. Humeral head retroversion may be most accurately obtained using the patient's own anatomic landmarks or, if not, identifiable retroversion as measured by those landmarks on contralateral side or the bicipital groove.

Each author certifies that he or she has no commercial associations (eg, consultancies, stock ownership, equity interest, patent/licensing arrangements, etc) that might pose a conflict of interest in connection with the submitted article.

P. Boileau, R. T. Bicknell, N. Mazzoleni, J. P. Urien
Department of Orthopaedic Surgery and Sports Traumatology, Hôpital de L'Archet, University of Nice, Nice, France

G. Walch
Department of Orthopaedic Surgery, Clinique Sainte Anne Lumière, Lyon, France

R. T. Bicknell (✉)
Division of Orthopaedic Surgery, Department of Surgery, Kingston General Hospital, Queen's University, Nickle 3, 76 Stuart Street, Kingston, Ontario, Canada K7L 2V7
e-mail: rtbickne@yahoo.ca

Introduction

Humeral head retroversion affects the mechanics of the glenohumeral joint. Mobility and stability of the shoulder are directly dependent on the amount of retroversion [5, 31, 32, 38, 41, 50, 51]. Clinically, reestablishing normal retroversion is essential when implanting a humeral prosthesis for any indication, but particularly in fractures of the proximal humerus [3, 4, 9, 10, 12, 21, 39–42, 44]. Correct retroversion of the humeral component is important because it affects the position of the instant center of rotation [5], the stability of the joint [38, 50, 51], and the amount of external rotation [39, 41]. However, establishing humeral head retroversion has been controversial in previous literature (Table 1). This is owing to several factors, including the definition of humeral head retroversion, varying methods of measurement, ranges of normal values, contralateral variations, and the accuracy of anatomic landmarks to guide determination of anatomic retroversion. Humeral head retroversion is generally defined with respect to the plane of the humeral head articular surface proximally, but distally, the reference axis has been debatable, including the transepicondylar axis [2, 7, 11, 23, 28, 33, 34, 46, 47, 48–51], trochlear tangent axis [16, 24, 31, 32, 43, 45, 52], or the forearm axis [9, 10, 23, 40–42]. Methods of measurement have included direct anatomic [6, 28, 33, 37], radiographic [11, 12, 31, 32, 46, 50–52], ultrasound [26], computed tomography scan [7, 23, 34, 47], MRI [15], and computer-assisted methods [13, 48, 49].

Table 1. Review of the literature

Series	Number of specimens	Measurement methods	Mean retroversion (range or standard deviation; degrees)	Contralateral difference	Stable/Unstable difference
Martin [37], 1933		Direct	16 (NA)	NA	NA
Krahl [28], 1944	178	Direct	15.6 (2–84)	Yes	NA
Debevoise et al. [12], 1971	66	Radiographic	29 (5–43)	No	Yes
Saha [50], 1971	23	Radiographic	30 (4–60)	No	Yes
Cyprien [11], 1983	100	Radiographic	24 (11.6)	Yes	No
Lauman and Kramps [34], 1984	32	Computed tomography scan	29.5 (28–31)	NA	No
Pieper [46], 1985	240	Radiographic	40.1 (5.7)	NA	Yes
Randelli and Gambrioli [47], 1986	90	Computed tomography scan	30 (25–35)	NA	No
Kronberg et al. [32], 1990	100	Radiographic	31	Yes	Yes
			Dominant, 33 (9.3);		
			nondominant, 29 (8.4)		
Roberts et al. [48], 1991	39	Computer-assisted	21.4 (18.5–25)	NA	NA
Doyle and Burks [15], 1998	41	MRI	26.8 (−2–52)	NA	NA
Kummer et al. [33], 1998	420	Direct	28.3 (4–66)	NA	NA
Robertson et al. [49], 2000	60	Computer-assisted	19 (9–31)	No	NA
Hernigou et al. [23], 2002	120	Computed tomography scan	17.6 (1–32)	No	NA
Cassagnaud et al. [7], 2003	64	Computed tomography scan	9.37 (−28–54)	Yes	NA
DeLude et al. [13], 2007	28	Computer-assisted	38.4 (21.9–53)	No	NA

NA = information not available.

Mean normal values are quite variable, ranging from 10° to 40° (Table 1). As well, some authors have found a considerable difference between contralateral measurements [7, 16], whereas others have found no difference [13, 23, 43]. Finally, some authors have found the bicipital groove is a useful anatomic landmark for guiding anatomic recreation of retroversion [8, 15, 22, 24, 25, 27, 33]. Treatment of a variety of shoulder abnormalities requires a thorough knowledge of normal values of humeral head retroversion and an accurate objective method for determination and reproduction of the normal humeral head retroversion of the patient.

Therefore, our primary objective was to ascertain normal values of humeral head retroversion. Our secondary objectives were to assess the precision of radiographic and computed tomography (CT) scan methods of measurement, and to assess the accuracy of using the contralateral humerus or the bicipital groove as bony landmarks to guide reproduction of anatomic humeral head retroversion. We hypothesized: (1) normal values of humeral head retroversion would be at the lower end of previously reported values; (2) radiographic methods would be less accurate than CT scan methods of measurement; and (3) contralateral humeral head retroversion and the bicipital groove would provide consistent landmarks to guide reproduction of humeral head retroversion.

Materials and Methods

We determined humeral head retroversion in cadaveric humeri using four different measurement methods: a radiographic method; a CT scan method; a computer-assisted method; and a direct method. We assessed the precision of the radiographic and CT scan method using the computer-assisted and direct methods as "gold-standard" references. We then determined the relationship between the retroversion of the contralateral humeri and between the location of the bicipital groove and the humeral head retroversion, and assessed the precision of using these methods to guide reproduction of humeral head retroversion.

In a pilot study performed prior to this study, two observers (PB, GW) measured the humeral head retroversion in 10 specimens (unpublished data). Each observer performed five measurements using each method. The intraobserver variation in the measurements was less than 3° for each measurement method. Using the computer-assisted method, the standard deviation for both intra- and interobserver error was less than 1 mm for linear measurements and less than 1° for angular measurements. The direct method was more subject to intraobserver error and therefore was not used as the method of reference. Based on the data obtained in this pilot study, a power analysis was performed to estimate the sample size needed to detect what would be considered clinically relevant differences in humeral head retroversion. The alpha level was set at 0.05 to detect a desired difference of 80% of normal values, and a minimal detectable difference was set at 5°. To detect a difference between measurement methods, 50 specimens were required, using a one-way analysis of variance (ANOVA).

We used 65 fresh humeri from 39 white cadavers with a mean age of 86 years (range, 67–95 years). This included 33 right and 32 left humeri, of which 52 were paired (ie, 26 pairs). Information about the patient gender of the humeri was unavailable. We carefully dissected the humeri free of all soft tissue, taking care to avoid damage to the articular cartilage. We excluded any humeri with evidence of arthritis, trauma, or dysplasia.

Measuring humeral head retroversion required defining several axes on each humeri: (1) the humeral head axis, a line perpendicular to the plane formed by the boundaries of the humeral head articular surface; (2) the elbow transepicondylar axis, determined by a line between the most medial and the most lateral extension of the distal humerus; and (3) the elbow trochlear tangent axis, defined as the axis tangent to the anterior border of the trochlea and the lateral condyle.

The first method of humeral head retroversion measurement, a radiographic method described by Kronberg et al. [31, 32, 52], used a single radiograph taken in the semiaxial view. The humerus was placed on a special frame in the position recommended by these authors, in which the humeral head and epicondyles were clearly projected onto a radiograph. We then determined humeral head retroversion as the angle between the humeral head axis and the elbow tangent axis (Fig. 1).

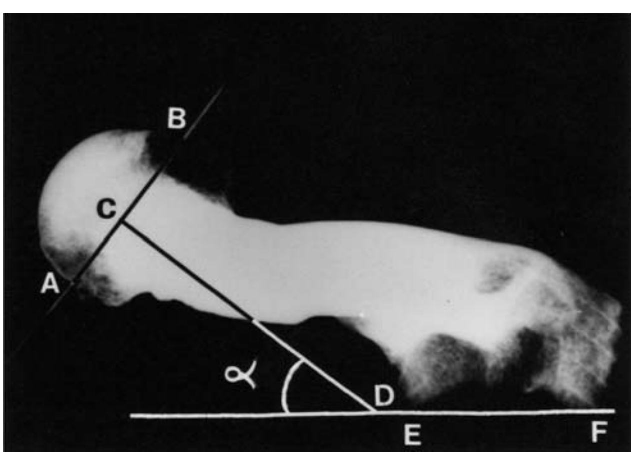


Fig. 1 The radiographic method is illustrated. Line A-B marks the boundaries of the humeral head articular surface. Line C-D is perpendicular to A-B and defines the humeral head axis. Line E-F marks the elbow trochlear tangent axis. The humeral head retroversion angle (∝) is shown.

The second method used a CT scan performed in the axial plane with 5-mm-thick contiguous slices of the proximal and the distal epiphysis of each humerus. We performed the CT scans either with an Elscint 2400 (Elscint, Hackensack, NJ) or a CGR 1000 (General Electric Co Medical System Division, Milwaukee, WI) CT scanner equipped with software for measurement of the linear and angular parameters. Two methods have been described in the literature for determining the boundaries of the articular surface of the humeral head on CT scan (Fig. 2A). The method of Bernageau [2] uses the boundaries of the anatomic neck axis indicated by the junctions between the humeral head articular surface and the lesser tuberosity anteriorly and the greater tuberosity posteriorly. However, these boundaries, marked by a depression corresponding to the insertion of the articular capsule, are not always easily identified. For this reason, we chose to define the boundaries of the articular surface using the limits of the

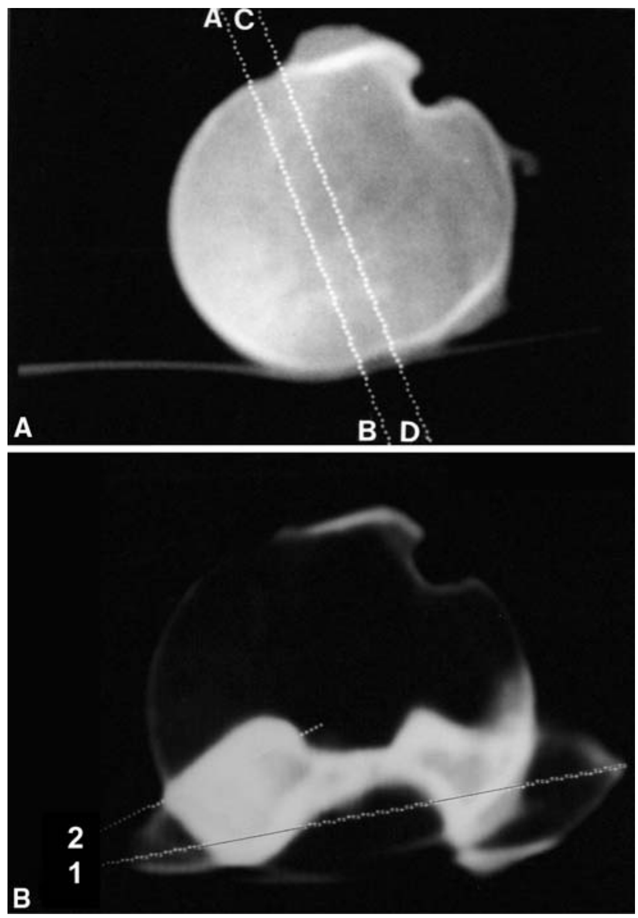
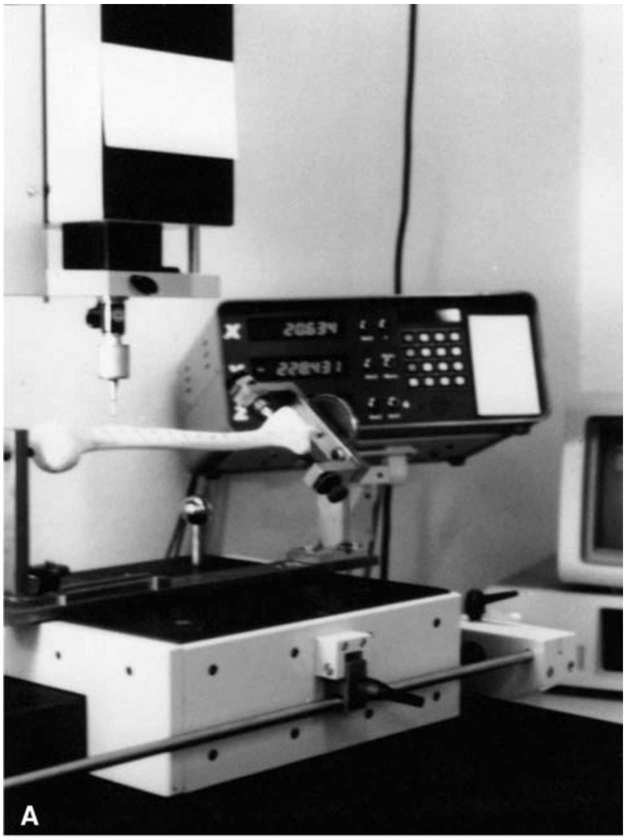


Fig. 2A–B The computed tomography scan method is shown. (**A**) Line A-B marks the boundaries of the humeral head articular surface using the limits of the subchondral bone (Lauman and Kramps [34]), whereas line C-D marks the anterior and posterior depressions corresponding to the insertion of the articular capsule (Bernageau [2]). These two lines are approximately parallel. (**B**) Line 1 defines the epicondylar axis. Line 2 defines the humeral head axis.



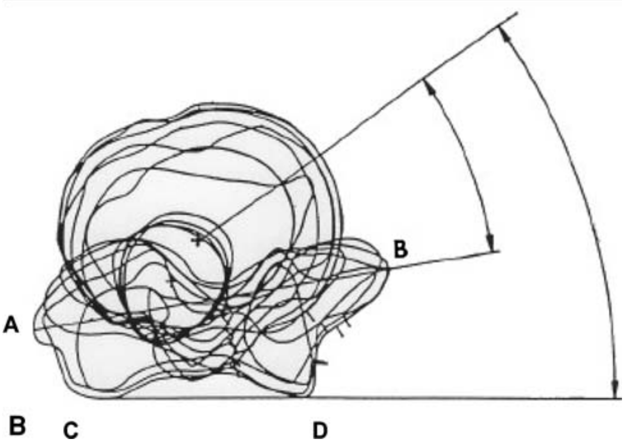


Fig. 3A–B The computer-assisted method is shown. (**A**) The industrial coordinate measuring machine connected with a computer is used to determine humeral head retroversion. (**B**) The retroversion angle can be measured in relation to the transepicondylar axis A-B (digitized method 1) or in relation to the trochlear tangent axis C-D (digitized method 2).

subchondral bone as described by Laumann and Kramps [34]. This decision was reinforced by the fact the limits of the humeral head articular cartilage, and therefore the subchondral bone, were the same as those chosen for the other three methods used in our study. Humeral head retroversion was defined as the angle between the humeral head axis and the elbow epicondylar axis (Fig. 2B).

The third method, the "computer-assisted" method, used surface measurements performed using an industrial coordinate measuring machine (METROLOGIC MT1; Metrologic Instruments, Meylan, France) and accompanying software (METROSOFT-3D; Metrologic Instruments). This machine was equipped with a custom-designed frame to hold the humerus fixed at the humeral head and the elbow, allowing rotation about its diaphyseal axis (Fig. 3A). After calibration, we obtained points on the surface of the humerus using a probe to digitize a series of parallel slices at 5-mm intervals at the level of the proximal and distal epiphysis and at 10-mm intervals along the diaphysis. The probe digitized 36 points for each slice. We also obtained points on the articular surface and at the periphery of the humeral head articular surface. A minimum of 1200 points were digitized for each humerus. We then created a three-dimensional reconstruction of the humerus. The computer software calculated a best-fit sphere of the articular surface of the humeral head and the plane of the anatomic neck axis. Humeral head retroversion was defined as the angle between the humeral head axis and both the elbow epicondylar axis and the elbow tangent axis (Fig. 3B). The accuracy of this coordinate measuring machine, as quoted by the manufacturer, was 10 μm and was considered unimportant for this application.

The fourth method, the "direct" method, used direct calculation of humeral head retroversion after an osteotomy at the periphery of the humeral head articular cartilage (ie, the anatomic neck) as is usually performed during humeral head arthroplasty. We measured humeral head retroversion using a custom-designed apparatus modeled after the "tropometer" of Broca [6] and the "torsionometer" of Krahl and Evans [17, 28–30] (Fig. 4). The humeri were secured in a vice and a 180° protractor was fixed on the epicondyles using a pair of pointers. A cursor, on which was mounted an axis of adjustable length, was able to slide on the protractor and was adjustable to rest flat on the cut surface of the anatomic neck osteotomy. We then measured the humeral head retroversion as the angle between the humeral head axis and the elbow epicondylar axis. We found this method more precise than those proposed by Broca [6] and Krahl and Evans [17, 28–30] because it eliminated the subjective determination of the axis of the humeral head.

Each humerus underwent measurement sequentially by the radiographic method and the CT scan method, followed by the computer-assisted method, and finally the direct method. Each method was performed by a single observer (PB) who was blind to the results of previous measurement techniques.

The CT scan method and the computer-assisted method enabled measurement of the distance between the central axis of the humeral head (defined as the center of rotation

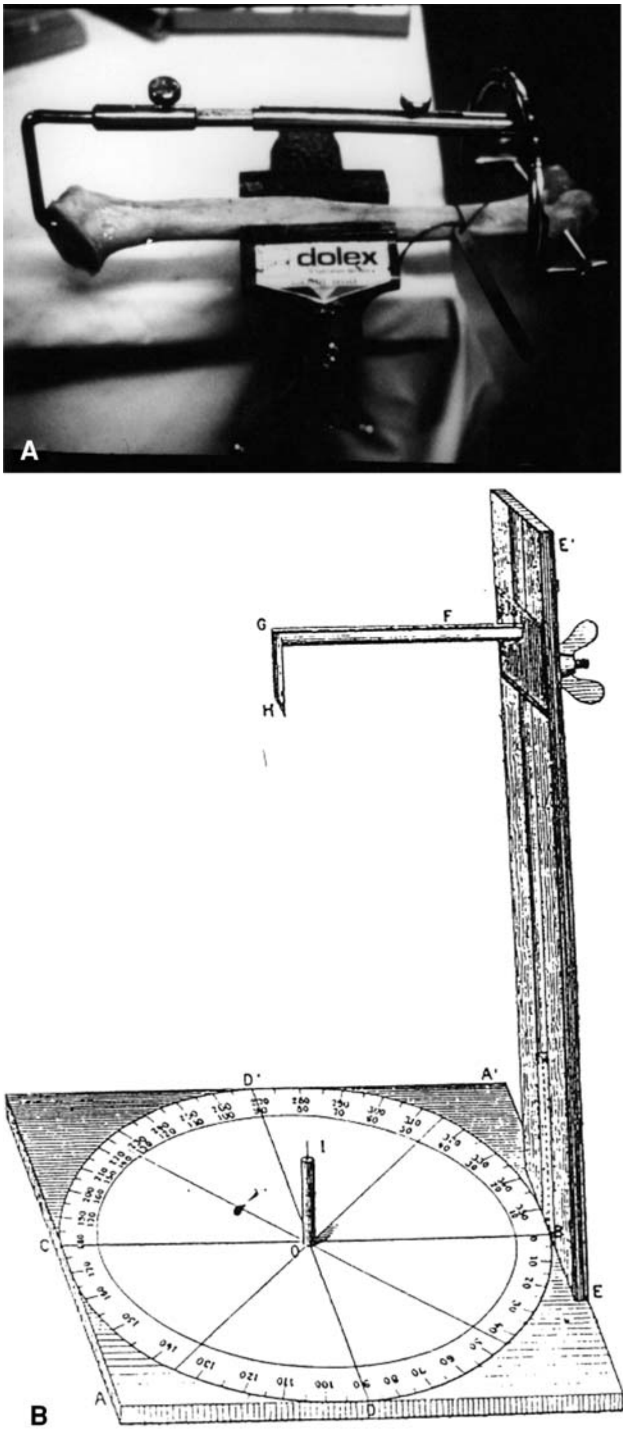


Fig. 4A–B The direct method is shown. (**A**) The special device constructed and used after osteotomizing the humeral head articular surface is illustrated. (**B**) The "tropometer" of Broca, which inspired our apparatus, is illustrated.

of the humeral head articular surface) and the posterior margin of the bicipital groove as performed by Tillet et al. [54]. This was performed on 20 humeri (ie, 10 pairs) to allow comparison of contralateral differences.

We used a one-way analysis of variance (ANOVA) to compare the measurements obtained with the radiographic and CT scan methods with those obtained with the method of reference (ie, the computer-assisted method). We examined correlation between paired right and left humeri using a regression analysis. Significance was set at $p < 0.05$.

Results

The mean retroversion angle obtained with the computer-assisted method was 17.9° (95% confidence limit, 14.5–21.3) when measured with respect to the transepicondylar axis (Table 2, Fig. 5), and 21.5° (95% confidence limit, 17.5–25.2) when measured with respect to the elbow trochlear tangent axis (Table 2).

The radiographic method overestimated ($p = 0.046$) the humeral head retroversion in comparison to the computer-assisted method. However, there was no difference ($p > 0.05$) between humeral head retroversion obtained by the CT scan method, the direct method and the computer-assisted method.

Mean retroversion differed ($p = 0.0008$) between the right and left humeri by 8.9° (95% confidence limit, 7.1–10.7). However, the right and left retroversion correlated ($r = 0.79$, $p = 0.0007$) in the same individual (Fig. 6). The equation of the regression line was $y = 0.79x + 5.27$, in which y is the right retroversion and x is the left retroversion for the same individual. The mean distance between the central axis of the humeral head and the posterior margin of the bicipital groove was 7.0 mm (95% confidence limit, 6.1–7.9) (Fig. 7). There was no difference (ie, < 1-mm difference) between right and left humeri.

Discussion

Many authors have attempted to determine values of humeral head retroversion using a variety of techniques [6, 7, 11, 12, 13, 17, 23, 26, 28–34, 37, 46–52] (Table 1). However, confusion remains as to normal values and the precision of different measurement methods. Clinically, reproducing normal retroversion is essential when implanting a humeral prosthesis, but the method of measurement, particularly in situations where direct assessment of anatomy has been compromised, remains elusive [3, 4, 9, 10, 12, 21, 39–42, 44]. Therefore, the aims of this study were to ascertain normal values of humeral head retroversion, to assess the accuracy of radiographic and CT scan methods of measurement and to assess the accuracy of using the contralateral humerus or the bicipital groove as

Table 2. Overall results

	Computer-assisted method		Radiographic method (tangent axis)	CT scan method (epicondylar axis)	Direct method (epicondylar axis)
	(Epicondylar axis)	(Tangent axis)			
Average	17.9	21.5	22.2	16.1	17.2
Standard deviation	13.7	15.1	14.9	13.3	12.6
Minimum	−6.7	−10.3	−17	−17	−5
Maximum	47.5	56.5	55	44	50

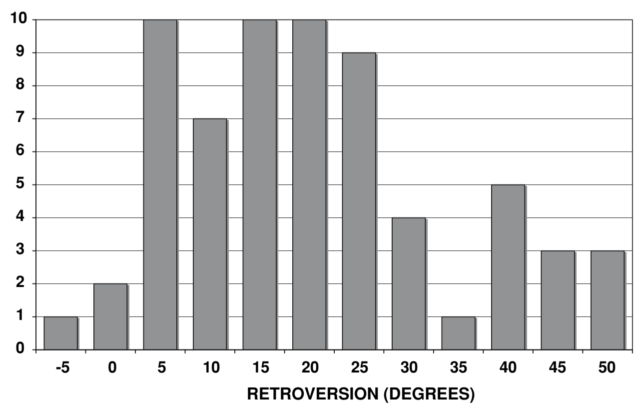


Fig. 5 The mean retroversion angle obtained with the computer-assisted method for the 65 humeri was 17.9° (95% confidence limit, 14.5–21.3) when measured with respect to the transepicondylar axis.

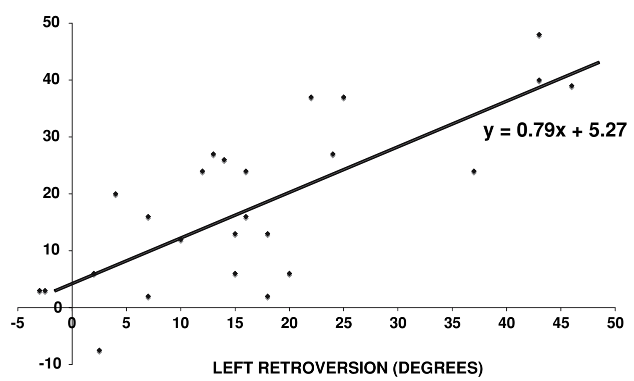


Fig. 6 The mean difference between the right and left humeri was 8.9 (95% confidence limit, 7.1–10.7; p = 0.0008). The equation of the regression line is y = 0.79x + 5.27, in which y is the right retroversion and x is the left retroversion for the same individual (r = 0.79, p = 0.0007).

landmarks to guide reproduction of humeral head retroversion.

There are several limitations of this study. First, only one measurement was performed for each specimen using each method of measurement by a single observer. However, in a previous pilot study, intra- and interobserver error was minimal. Second, for the computer-assisted method, used as the reference method, some error may still be attributed to the selection of the data points on the bone surface. We attempted to reduce the margin of error by using a reproducible methodology and homogeneous temperature conditions. Finally, the cadaveric nature of this study and the fact that each specimen was stripped of soft tissue may have contributed to errors in assessment of anatomy and measurement. However, we believe these errors are minimized with our standardized methods.

The mean humeral head retroversion found in this study is at the lower end of values previously reported in the anatomic literature [6, 7, 11, 13, 15, 17, 23, 28, 30, 35, 37, 49]. However, values recommended in the surgical literature are between 30° and 40° [9, 10, 12, 19, 32–34, 40–42, 46–48, 50]. Two geometric considerations can assist in explaining this difference. First, previous interpretations of retroversion have not taken into account the posterior displacement of the humeral head articular surface, which is between 2 mm and 7 mm [4, 48, 54]. It is probable that a larger retroversion has been recommended to avoid increased anterior offset of the prosthetic humeral head [4, 14, 20]. Second, there is a mean carrying angle of 10° to 20° at the elbow [36, 47, 53, 55, 56]. Adding this angle to the mean retroversion of 20° found in this study with respect to the transepicondylar axis achieves a close approximation of the 30° to 40° in the surgical literature. However, previous authors report some variation is present between individuals for both values of humeral head posterior offset [4, 48, 54] and carrying angle [36, 47, 53, 55, 56]. Therefore, accounting for these differences by increasing retroversion may result in correct positioning in some patients, but large errors in others.

The CT scan method appears superior to the radiographic method for evaluation of humeral head retroversion. This is consistent with the findings of previous authors [23]. However, other factors may still result in a CT scan method being somewhat less desirable. First, pain may limit the ability of the patient to undergo extensive CT scans of both the shoulder and elbow. Also, the additional time, cost and radiation dose may limit the usefulness of this method. However, in comparison to the costs and risks associated with a poor outcome or revision surgery, we believe this minimal.

The large variation of humeral head retroversion between individuals and from side to side in the same

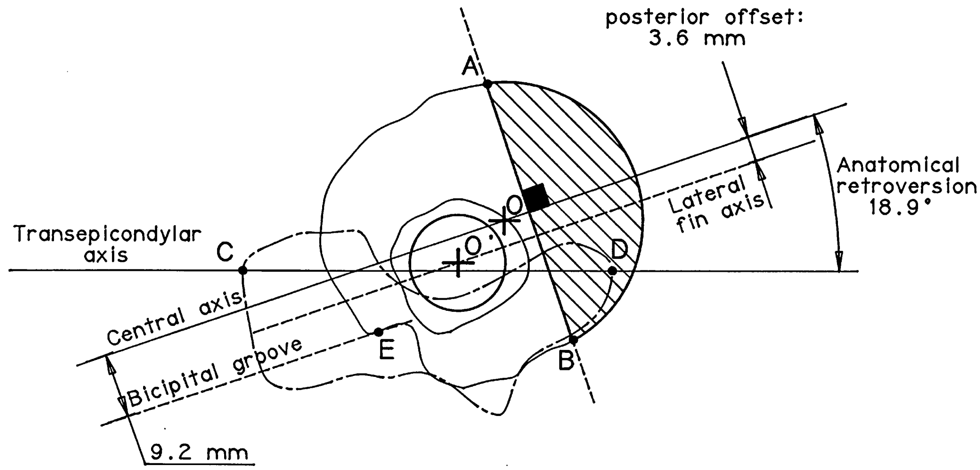


Fig. 7 Contrary to humeral head retroversion, the distance between the central axis of the humeral head and the bicipital groove is essentially constant (average, 7.0 mm, 95% confidence limit, 6.1–7.9) and the difference between sides is less than 1 mm.

individual found in this study makes questionable its reproduction using a standard value. Surgeons should seek more accurate landmarks to ensure recreation of humeral head retroversion. The true anatomic neck represents the first important landmark and can be identified by trimming the marginal osteophytes from around the humeral head before the humeral head osteotomy [4, 18, 40]. However, in situations in which the anatomic neck is not identifiable (ie, severe bony destruction and proximal humerus fractures), another method may be useful. One method would be to use the contralateral humerus as a guide. Some authors have found a considerable side-to-side difference [7, 16], whereas others have found none [13, 23, 43]. Although we found a considerable side-to-side difference, further analysis shows this may still be a better approximation than using a constant value. Using a constant value of 20° for humeral head retroversion (as often suggested for proximal humerus fractures) we found a mean miscalculation of 11.5° (95% confidence interval, 9.6–13.4). This is a lower miscalculation than the mean miscalculation of 8.9° (95% confidence limit, 7.1–10.7) found using the contralateral humerus. Therefore, although certainly less accurate than using the ipsilateral native anatomic axis, contralateral measurements appear more accurate than using a set constant value.

A second method is to use the bicipital groove as a guide. Placing the lateral fin of the prosthesis 7 mm posterior to the posterior margin of the bicipital groove allows reproduction of anatomic humeral head retroversion with a good approximation. This is similar to the findings of other authors, who have found an average distance between 6 mm and 11.8 mm [8, 15, 24, 33]. However, the bicipital groove is somewhat S-shaped with the groove being more retroverted distally; therefore, one must be careful of the level of measurement [1, 25]. A more accurate step would be to measure this distance on the normal side preoperatively with a CT scan and extrapolate it to the abnormal side, because the difference between contralateral sides is less than 1 mm in our study.

We compared several methods of measurement of humeral head retroversion in cadaveric humeri. We found a mean value of humeral head retroversion of approximately 20° with respect to the epicondylar axis of the elbow. A CT scan method allowed accurate measurement of humeral head retroversion, but a radiographic method did not. However, there was a large variation between specimens and, to a lesser extent, between contralateral paired humeri. Bicipital groove location was also a reproducible landmark between contralateral paired humeri. Therefore, assessment of anatomic humeral head retroversion may be most accurately achieved based on the patient's own anatomic landmarks or, if these are not identifiable, the contralateral retroversion based on those landmarks or the bicipital groove.

References

1. Balg F, Boulianne M, Boileau P. Bicipital groove orientation: considerations for the retroversion of a prosthesis in fractures of the proximal humerus. *J Shoulder Elbow Surg.* 2006;15:195–198.
2. Bernageau J. Imaging of the shoulder in orthopedic pathology [in French]. *Rev Prat.* 1990;40:983–92.
3. Boileau P, Krishnan SG, Tinsi L, Walch G, Coste JS, Mole D. Tuberosity malposition and migration: reasons for poor outcomes after hemiarthroplasty for displaced fractures of the proximal humerus. *J Shoulder Elbow Surg.* 2002;11:401–412.
4. Boileau P, Walch G. The three-dimensional geometry of the proximal humerus. Implications for surgical technique and prosthetic design. *J Bone Joint Surg Br.* 1997;79:857–865.

5. Boileau P, Walch G, Liotard JP. Radio-cinematographic study of active elevation of the prosthetic shoulder [in French]. *Rev Chir Orthop.* 1992;78:355–364.
6. Broca P. La torsion de I'humerus et le tropometre, instrument destine a mesurer la torsion des os. *Revue d'Anthrop. 2eme serie.* 1881;4:193–210, 385–423, 1577–1592.
7. Cassagnaud X, Maynou C, Petroff E, Dujardin C, Mestdagh H. A study of reproducibility of an original method of CT measurement of the lateralization of the intertubercular groove and humeral retroversion. *Surg Radiol Anat.* 2003;25:145–151.
8. Christoforakis J, Kontakis GM, Maris T, Damilakis J, Katonis P, Prassopoulos P, Hadjipavlou AG. An individualized approach for the implantation of a humeral prosthesis with the proper retroversion in fractures. *Arch Orthop Trauma Surg.* 2001;121:227–229.
9. Cofield RH. Unconstrained total shoulder prostheses. *Clin Orthop Relat Res.* 1983;173:97–108.
10. Compito CA, Self EB, Bigliani LU. Arthroplasty and acute shoulder trauma: reasons for success and failure. *Clin Orthop Relat Res.* 1994;307:27–36.
11. Cyprien JM, Vasey HM, Burdet A, Bonvin JC, Kritsikis N, Vuagnat P. Humeral retrotorsion and glenohumeral relationship in the normal shoulder and in recurrent anterior dislocation (scapulometry). *Clin Orthop Relat Res.* 1983;175:8–17.
12. Debevoise NT, Hyatt GW, Townsend GB. Humeral torsion in recurrent shoulder dislocations. A technic of determination by x-ray. *Clin Orthop Relat Res.* 1971;76:87–93.
13. DeLude JA, Bicknell RT, MacKenzie GA, Ferreira LM, Dunning CE, King GJW, Johnson JA, Drosdowech DS. An anthropometric study of the bilateral anatomy of the humerus. *J Shoulder Elbow Surg.* 2007;16:477–83.
14. Dines DM, Warren RF, Inglis AE, Pavlov H. The coracoid impingement syndrome. *J Bone Joint Surg Br.* 1990;72:314–316.
15. Doyle AJ, Burks RT. Comparison of humeral head retroversion with the humeral axis/biceps groove relationship: a study in live subjects and cadavers. *J Shoulder Elbow Surg.* 1998;7:453–457.
16. Edelson G. Variations in the retroversion of the humeral head. *J Shoulder Elbow Surg.* 1999;8:142–145.
17. Evans FG, Krahl VE. The torsion of the humerus: a phylogenetic survey from fish to man. *Am J Anat.* 1945;76:303–337.
18. Fenlin JM, Ramsey ML, Allardyce TJ, Frienman BG. Modular total shoulder replacement: design rationale, indications and results. *Clin Orthop Relat Res.* 1994;307:37–46.
19. Frich LH, Moller BN. Retroversion of the humeral prosthesis in shoulder arthroplasty: measurements of angle from standard radiographs. *J Arthroplasty.* 1989;4:277–280.
20. Gerber C, Terrier F, Zehnder R, Ganz R. The subcoracoid space: an anatomic study. *Clin Orthop Relat Res.* 1987;215:132–138.
21. Hasan SS, Leith JM, Campbell B, Kapil R, Smith KL, Matsen FA 3rd. Characteristics of unsatisfactory shoulder arthroplasties. *J Shoulder Elbow Surg.* 2002;11:431–441.
22. Hempfing A, Leunig M, Ballmer FT, Hertel R. Surgical landmarks to determine humeral head retrotorsion for hemiarthroplasty in fractures. *J Shoulder Elbow Surg.* 2001;10:460–463.
23. Hernigou P, Duparc F, Hernigou A. Determining humeral retroversion with computed tomography. *J Bone Joint Surg Am.* 2002;84:1753–1762.
24. Hertel R, Knothe U, Ballmer FT. Geometry of the proximal humerus and implications for prosthetic design. *J Shoulder Elbow Surg.* 2002;11:331–338.
25. Itamura J, Dietrick T, Roidis N, Shean C, Chen F, Tibone J. Analysis of the bicipital groove as a landmark for humeral head replacement. *J Shoulder Elbow Surg.* 2002;11:322–326.
26. Ito N, Eto M, Maeda K, Rabbi ME, Iwasaki K. Ultrasonographic measurement of humeral torsion. *J Shoulder Elbow Surg.* 1995;4:157–161.
27. Kontakis GM, Damilakis J, Christoforakis J, Papadakis A, Katonis P, Prassopoulos P. The bicipital groove as a landmark for orientation of the humeral prosthesis in cases of fracture. *J Shoulder Elbow Surg.* 2001;10:136–139.
28. Krahl VE. An apparatus for measuring the torsion angle in long bones. *Science.* 1944;99:498.
29. Krahl VE. The torsion of the humerus: its localization, cause and duration in man. *Am J Anat.* 1947;80:276–319.
30. Krahl VE, Evans FG. Humeral torsion in man. *Am J Phys Anthrop.* 1945;3:229–253.
31. Kronberg M, Broström LA. Humeral head retrotorsion in patient with unstable humeroscapular joints. *Clin Orthop Relat Res.* 1990;260:207–211.
32. Kronberg M, Broström LA, Soderlund V. Retroversion of the humeral head in the normal shoulder and its relationship to the normal range of motion. *Clin Orthop Relat Res.* 1990;253:113–117.
33. Kummer FJ, Perkins R, Zuckerman JD. The use of the bicipital groove for alignment of the humeral stem in shoulder arthroplasty. *J Shoulder Elbow Surg.* 1998;7:144–146.
34. Lauman V, Kramps HA. Computer tomography on recurrent shoulder dislocation. In: Bateman YE, Welsh RP, eds. *Surgery of the Shoulder*. Philadelphia PA: Decker; 1984:84.
35. Le Damany. Les torsions osseuses (leur role dans la transformation osseuse des membres). *J Anat et Physiol.* 1903;39:126–134, 161–165, 313–339.
36. London JT. Kinematics of the elbow. *J Bone Joint Surg Am.* 1981;63:529–535.
37. Martin CP. The cause of torsion of the humerus and of the notch on the anterior edge of the glenoid cavity of the scapula. *J Anat.* 1933;67:573–582.
38. Moeckel BH, Altchek DW, Warren RF, Wickiewicz TL, Dines DM. Instability of the shoulder after arthroplasty. *J Bone Joint Surg Am.* 1993;75:492–497.
39. Neer CS. Articular replacement for the humeral head. *J Bone Joint Surg Am.* 1955;37:215–228.
40. Neer CS, Watson KC, Stanton FJ. Recent experience in total shoulder replacement. *J Bone Joint Surg Am.* 1982;64:319–337.
41. Ovesen J, Nielsen S. Prosthesis position in shoulder arthroplasty: a cadaver study of the humeral component. *Acta Orthop Scand.* 1985;56:330.
42. Ovesen J, Sojbjerg JO, Sneppen O. A humeral head cutting guide: instrument to secure correct humeral component retroversion in shoulder joint arthroplasty. *Clin Orthop Relat Res.* 1987;216:193–194.
43. Oztuna V, Ozturk H, Eskandari MM, Kuyurtar F. Measurement of the humeral head retroversion angle. A new radiographic method. *Arch Orthop Trauma Surg.* 2002;122:406–409.
44. Pearl ML. Proximal humeral anatomy in shoulder arthroplasty: implications for prosthetic design and surgical technique. *J Shoulder Elbow Surg.* 2005;14:99S–104S.
45. Pearl ML, Volk AG. Retroversion of the proximal humerus in relationship to prosthetic replacement arthroplasty. *J Shoulder Elbow Surg.* 1995;4:286–289.
46. Pieper HG. Shoulder dislocation in skiing: choice of surgical method depending on the degree of humeral head retroversion. *Int J Sports Med.* 1985;6:155–160.
47. Randelli M, Gambrioli PL. Glenohumeral osteometry by computed tomography in normal and unstable shoulders. *Clin Orthop Relat Res.* 1986;208:151–156.
48. Roberts SNJ, Foley APJ, Swallow HM, Wallace WA, Coughlan DP. The geometry of the humeral head and the design of prostheses. *J Bone Joint Surg Br.* 1991;73:647–650.
49. Robertson DD, Yuan J, Bigliani LU, Flatow EL, Yamaguchi K. Three-dimensional analysis of the proximal part of the humerus: relevance to arthroplasty. *J Bone Joint Surg Am.* 2000;82:1594–1602.

50. Saha AK. Dynamic stability of the glenohumeral joint. *Acta Orthop Scand.* 1971;42:491–505.
51. Saha AK. Recurrent Dislocation of the Shoulder: *Physiopathology and Operative Corrections*, 2nd ed. Stuttgart, Germany: Thieme; 1981.
52. Soderlund V, Kronberg M, Sneppen O. Radiologic assessment of humeral head retroversion. Description of a new method. *Acta Radiol.* 1989;30:501–505.
53. Steel FLD, Tomlinson JDW. The carrying angle in man. *J Anat.* 1958;92:315–317.
54. Tillet E, Smith M, Fulcher M, Shanklin J. Anatomic determination of humeral head retroversion: the relationship of the central axis of the humeral head to the bicipital groove. *J Shoulder Elbow Surg.* 1993;2:255–256.
55. Van Roy P, Baeyens JP, Fauvart D, Lanssiers R, Clarijs JP. Arthro-kinematics of the elbow: study of the carrying angle. *Ergonomics.* 2005;48:1645–1656.
56. Yilmaz E, Karakurt L, Belhan O, Bulut M, Serin E, Avci M. Variation of carrying angle with age, sex, and special reference to side. *Orthopedics.* 2005;28:1360–1363.