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The Walch type B humerus: glenoid retroversion is associated with torsional differences in the humerus

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Background: The Walch type B glenoid has the hallmark features of retroversion, joint subluxation, and bony erosion. Although the type B glenoid has been well described, the morphology of the corresponding type B humerus is poorly understood. As such, the aim of this imaging-based anthropometric study was to investigate humeral torsion in Walch type B shoulders.
Methods: Three-dimensional models of the full-length humerus were generated from computed tomography data for the Walch type B group (n = 59) and for a control group of normal nonarthritic shoulders (n = 59). An anatomic humeral head-neck plane was created and used to determine humeral torsion relative to the epicondylar axis. Measurements were repeated, and intraclass correlation coefficients were calculated.
Results: The type B humeri had significantly ($P < .001$) less retrotorsion (14° ± 9°) than the control group (36° ± 12°) relative to the epicondylar axis. Male and female individuals within the control group showed statistically significant differences in humeral torsion ($P = .043$), which were not found in the type B group. Inter-rater reliability showed excellent agreement for humeral torsion (intraclass correlation coefficient, 0.962). A subgroup analysis between Walch type B2 and B3 shoulders showed no significant differences in any of the humeral or glenoid parameters.
Conclusion: The Walch type B humerus has significantly less retrotorsion than non-osteoarthritic shoulders. At present, it is unknown whether the altered humeral retrotorsion is a cause or effect of the type B glenoid. In addition, it is unknown whether surgeons should be reconstructing type B2 humeral component version to pathologic torsion or to nonpathologic population means to optimize arthroplasty survivorship.
Level of evidence: Anatomy Study; Imaging

Keywords: Walch; B2; B3; shoulder osteoarthritis; retroversion; shoulder arthroplasty

This study was reviewed and approved by the Western University Health Science Research Ethics Board (file No. 105912).

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In their landmark publication, Walch et al[44] defined the type B pattern of glenoid wear. This classification was modified using 3-dimensional (3D) imaging in 2016, and the Walch type B3 glenoid was introduced.[1] The Walch type B shoulder has the hallmark features of glenoid retroversion, posterior humeral head subluxation, and posteroinferior glenoid erosion.[1,7,8,44] The Walch B1 subtype has preferential posterior joint space narrowing, subchondral sclerosis, and osteophyte formation.[44] The B2 subtype has a biconcave pattern of glenoid wear with the formation of a new eroded posterior facet, known as the neoglenoid.[44] The type B3 glenoid has been theorized to be a progression of the type B2 deformity.[1,8,24,45] The type B3 glenoid is characterized by uniconcavity with the absence of the paleoglenoid (premorbid anterior facet of the glenoid), retroversion, medialization, and posterior humeral head subluxation.[1,7,8]

Humeral head version affects the mechanics of the glenohumeral joint. Mobility and stability of the shoulder are dependent on the amount of humeral retroversion.[3,26-28,32,39-41] Correct retrotorsion of the humeral component during shoulder arthroplasty is important because it affects the position of the instantaneous center of rotation,[3] the stability of the joint,[28,39,40] and the amount of external rotation.[31,32] Humeral head retrotorsion is generally defined with respect to the plane of the humeral head articular surface proximally, but distally, the reference axis has been debated. The transepicondylar axis,[15,47] trochlear tangent axis,[12,16,34,41] and forearm axis[15,32,33] have all been used. Methods of measurement have included direct anatomic methods,[16] radiographic methods,[26,27,39,41] computed tomography (CT) scans,[15,47] magnetic resonance imaging,[11] and computer-assisted methods.[9] Mean normal values are quite variable for humeral retrotorsion and range from 10° to 40°.[2,16,47]

Although our understanding of the pathoanatomy of bone loss as well as its evolution in Walch type B glenoids has improved, its etiology remains unclear. Furthermore, the morphology of the humerus in Walch type B shoulders has not been extensively studied. We hypothesized that glenoid retroversion and posterior subluxation of the humeral head may be associated with torsional differences in the humerus. The aim of this imaging-based anthropometric study was to examine humeral torsion in Walch type B shoulders and compare it with a control group of non-arthritic normal humeri.

Materials and methods

Study and control groups

Digital Imaging and Communications in Medicine (DICOM) data were extracted from the preoperative planning CT scans of 59 patients (23 women and 36 men; average age, 70 years; age range, 39-95 years) with Walch type B2 and B3 shoulders. Scans included the proximal humerus and distal humeral epicondyle. These data were then converted to 3D models of the full-length humerus, including the distal humerus, using medical imaging software (Mimics, version 20.0; Materialise, Leuven, Belgium).[5,6]

The control group consisted of CT data from 59 complete upper-extremity cadaveric specimens (23 female and 36 male specimens; average age, 72 years; age range, 47-94 years) with all soft tissues intact and no identifiable pathology on CT. Cadaveric specimens with arthritis, trauma, hardware, rotator cuff tears, or tumors were excluded. The CT data from the 59 control specimens were also converted to 3D models.[5,6] Only patients and specimens with clear demarcation of the anatomic head-neck junction were included.

Anatomic coordinate system with epicondylar axis

An anatomic coordinate system referencing the longitudinal axis of the humerus and the medial and lateral epicondyles was created for every 3D humeral model in both groups (Fig. 1, *A*), using a previously published protocol.[35,46] This was achieved by first determining the overall length of the humerus. Once the length was determined, a set of 10 reference points were placed within the inner cortical boundary of the intramedullary humeral canal at 40% of the humeral length. A second set of reference points were placed in a similar manner at 20% of the humeral length. At each of these 2 levels, the center of the canal was estimated as a circle

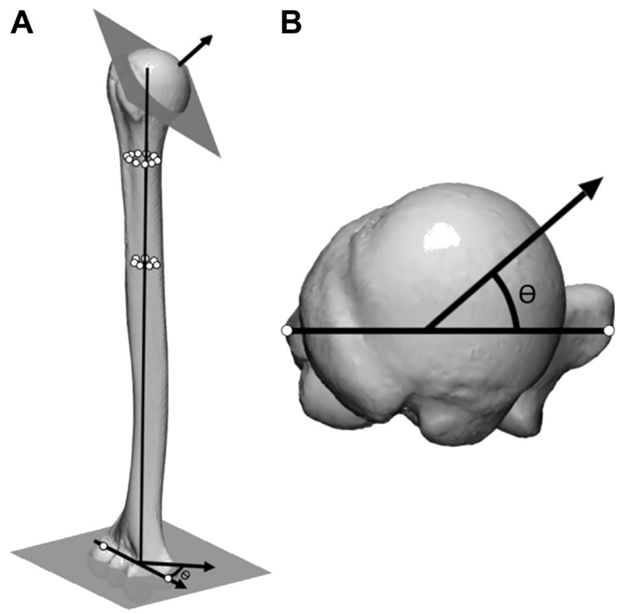

Figure 1 An anatomic coordinate system referencing the medial and lateral epicondyles was created for both the type B and normal cohorts. **(A)** Two sets of reference points were selected within the intramedullary canal at 20% and 40% of the humeral length, and their centers defined the long axis. A simulated humeral head osteotomy plane at the anatomic head-neck junction was created, and its normal vector was projected down the long axis onto a plane containing the epicondylar axis. Humeral torsion was defined as the angle (θ) between the epicondylar axis and the normal osteotomy vector. **(B)** Axial view of the normal vector of the humeral head osteotomy plane and the epicondylar axis, defined by the medial and lateral epicondyles.

fit using a least-squares algorithm (MATLAB, release 2015b; The MathWorks, Natick, MA, USA); through these centers, a vector was created that defined the humeral canal axis.

The epicondylar axis also was defined using a previously published technique,[35] from points placed on the medial and lateral epicondyles. Using the same technique, Roberts et al[38] found the standard deviation was within 4% of the mean, producing a high degree of reproducibility. Previous studies also found a high degree of repeatability using these landmarks.[2,41] A vector defined by the epicondyles was projected orthogonally to the humeral canal axis and defined as the epicondylar axis.

Anatomic humeral head plane

An anatomic humeral head osteotomy plane was virtually oriented by 2 fellowship-trained shoulder surgeons (S.R. and G.S.A.) to coincide with the head-neck junction as previously reported[23,46] (Fig. 1, *A*). This plane was then used to determine humeral torsion and the neck-shaft angle relative to the epicondylar axis (Fig. 1). This technique has been shown to have very good repeatability and reproducibility, with a previous study using the same landmarks having a minimum intraclass correlation coefficient (ICC) of 0.87.[22]

Measurement of humeral torsion and neck-shaft angle

Humeral torsion was defined as the axial rotation of the humeral head about the longitudinal humeral axis as referenced by the epicondylar axis. It was measured as the angle between the projected vector of the anatomic humeral head plane and the epicondylar axis about the humeral canal axis (Fig. 1, *B*). The neck-shaft angle was then calculated by measuring the direct angle between the normal vector of the anatomic humeral head osteotomy plane and the humeral canal axis (Fig. 1, *A*). Measurements were repeated by 2 fellowship-trained shoulder surgeons to determine inter-rater reliability.

Measurement of glenoid parameters

The Walch type B group underwent further analysis to determine whether correlations exist between the measured humeral parameters and the glenoid parameters. Glenoid parameters including glenoid version, glenoid inclination, and posterior humeral head subluxation were calculated using Blueprint 3D Preoperative Planning Software (Wright Medical, Memphis, TN, USA). Specifically, the glenoid version angle was automatically calculated as the angle between the scapular plane and the glenoid best-fit sphere centerline projected on the transverse scapular plane. In addition, the 2-dimensional (2D) critical shoulder angle was measured from the preoperative radiographs of the type B group as described by Moor et al.[29,30]

Statistical analysis

Two-way analyses of variance compared group and sex regarding humeral torsion and the neck-shaft angle. ICCs with a 2-way random-effects model and absolute agreement were used for inter-rater reliability. The Mann-Whitney rank sum test and unpaired *t* test were used to complete a subgroup analysis between Walch type B2 and B3 shoulders for all glenoid and humeral parameters.

Results

Humeral torsion

Statistically significant differences in humeral torsion were found between normal and Walch type B shoulders ($P < .001$). Normal shoulders had humeral retrotorsion of 36° ± 12° whereas Walch type B shoulders had humeral retrotorsion of 14° ± 9° relative to the epicondylar axis (Fig. 2). This difference in humeral torsion between the normal and type B humeri was statistically significant within female individuals (33° ± 12° vs. 16° ± 9°, $P < .001$) and male individuals (39° ± 12° vs. 14° ± 9°, $P < .001$). In addition, a statistically significant difference ($P = .043$) in humeral torsion was found between male and female individuals within the normal group: The normal male humeri had a greater degree of retrotorsion (39° ± 12°) than the female humeri (32° ± 12°). Inter-rater reliability analysis showed excellent agreement for humeral torsion between the 2 fellowship-trained shoulder surgeons. (ICC, 0.962; 95% confidence interval, 0.913-0.983).

Neck-shaft angle

No statistically significant differences in the neck-shaft angle were found between normal and Walch type B shoulders (135° ± 4° and 132° ± 4°, respectively; $P = .433$) or between sexes ($P = .854$) (Fig. 3). Inter-rater reliability analysis showed fair agreement for the neck-shaft angle (ICC, 0.562; 95% confidence interval, −0.28 to 0.809) between the 2 fellowship-trained shoulder surgeons; however, the mean difference in the neck-shaft angle between observers was only 2°.

Glenoid parameters in Walch type B shoulders

Analysis of the glenoid parameters in the Walch type B group showed that mean glenoid retroversion was 22° ± 7°, glenoid inclination was 8° ± 6°, and humeral head subluxation was 80% ± 9%, whereas the 2D critical shoulder angle was 30° ± 5° (Fig. 4). Linear correlation analysis showed no statistical agreement between the humeral and glenoid parameters.

Walch type B2 vs. B3 shoulders

The subgroup analysis with the Mann-Whitney rank sum test or unpaired *t* test showed no significant differences in the neck-shaft angle ($P = .203$), humeral torsion ($P = .729$), glenoid version ($P = .445$), glenoid inclination ($P = .751$), humeral head subluxation ($P = .807$), or critical shoulder angle ($P = .506$) between Walch type B2 and B3 shoulders.

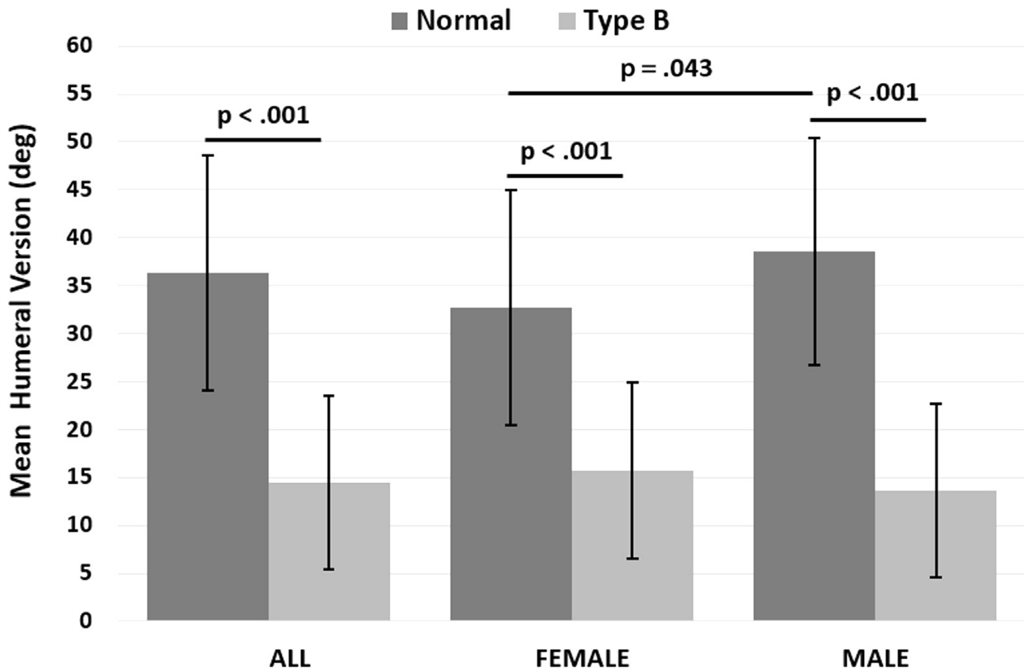

Figure 2 Mean humeral torsion based on humeral head measurements in all individuals, female individuals, and male individuals in control (normal) and type B groups. Significant differences were found between the groups, as well as between female and male individuals within the normal group. *deg*, degrees.

Discussion

This imaging-based anthropometric study showed torsional differences in the humeri of Walch type B shoulders. The Walch type B humerus shows significantly less retrotorsion than the normal nonarthritic humerus; in other words, the type B humerus shows relative antetorsion (Fig. 2). This finding raises questions as to the etiology of the type B shoulder and its evolution; furthermore, it has potential surgical implications. Although we found significant

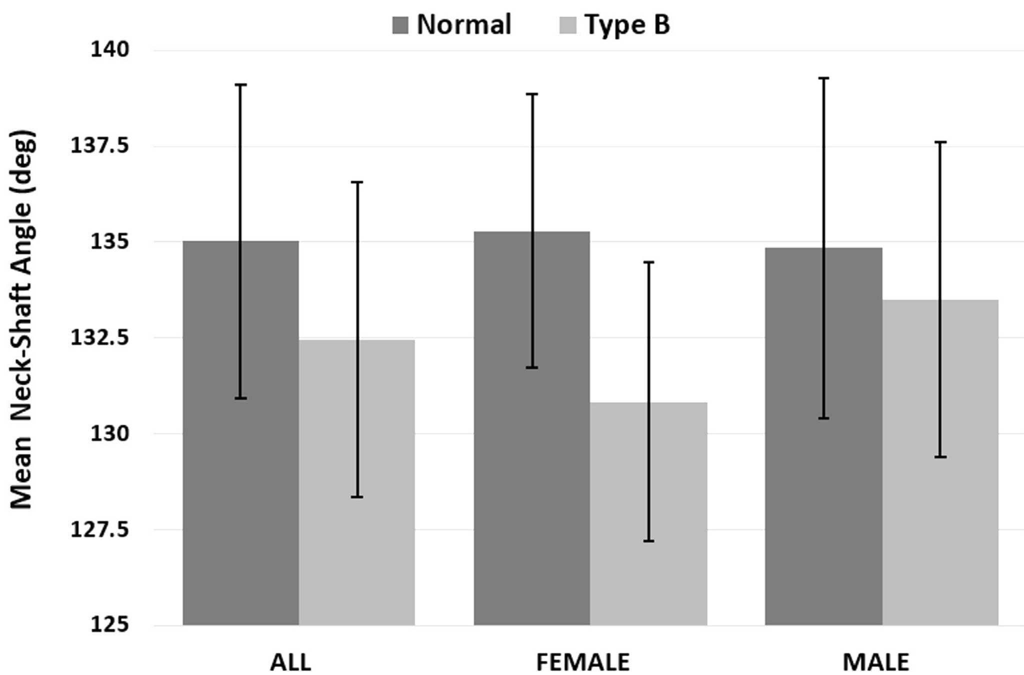

Figure 3 Mean head-neck angle based on humeral head measurements in all individuals, female individuals, and male individuals in control (normal) and type B groups. No significant differences were found between the groups. *deg*, degrees.

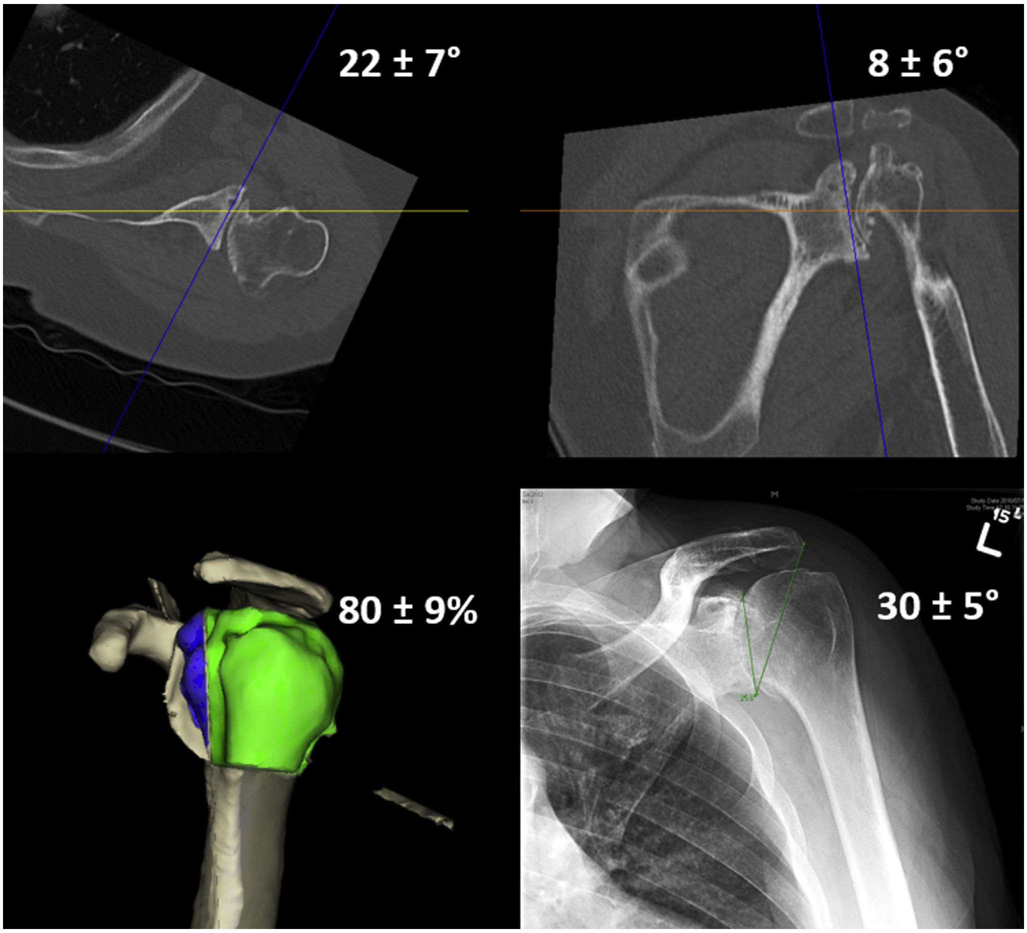

Figure 4 Glenoid parameters including glenoid version, glenoid inclination, and posterior humeral head subluxation were calculated using Blueprint 3D Preoperative Planning Software. The 2-dimensional critical shoulder angle was also measured from the preoperative radiographs of the type B group. Linear correlation analysis showed no statistical agreement between the humeral and glenoid parameters. *L*, left.

changes in humeral torsion, no statistically significant differences in the neck-shaft angle were identified between normal and Walch type B shoulders (Fig. 3).

Walch et al[43] were the first authors to publish the findings of static posterior subluxation of the humeral head before the development of posterior bony erosion or osteoarthritis. They described it as pre-osteoarthritic posterior subluxation of the humeral head (PPSHH), with subluxation of the humeral head preceding erosion. The etiology of this posterior humeral subluxation and the subsequent posteroinferior glenoid wear and its evolution remains unclear. Causes appear to be multifactorial and are likely related to a combination of bone and soft-tissue factors.

Although our findings show a clear association between posterior humeral subluxation in Walch type B shoulders and reduced humeral retrotorsion, the exact nature of this relationship as well as its etiology is unknown. We found no linear correlation between the percentage of posterior humeral subluxation and the degree of relative humeral antetorsion in type B shoulders, nor did we find a linear reciprocal correlation between increasing glenoid retroversion and decreasing humeral retrotorsion. In the type B group, mean glenoid retroversion was $22° \pm 7°$, glenoid inclination was $8° \pm 6°$, and humeral head subluxation was $80\% \pm 9\%$, whereas the 2D critical shoulder angle was $30° \pm 5°$ (Fig. 4). The glenoid indices are consistent with recently published data examining the differences between type B2 and B3 glenoids.[7]

The significantly reduced humeral retrotorsion in type B shoulders may also be an etiologic factor that potentially leads to the posteroinferior glenoid wear and its evolution. In contrast, it may simply be a compensatory manifestation of the arthritic process in the setting of a posteriorly subluxated humeral head. Alternatively, there may be a third, unknown factor that influences both glenoid retroversion and relative humeral antetorsion. If the reduced humeral retrotorsion is a manifestation of an evolving arthritic process, then the degree of relative humeral antetorsion in the type B3 shoulders should be greater than that in the type B2 shoulders, but this was not seen in our study. No statistically significant differences in the humeral or glenoid parameters were found between the type B2 and B3 shoulders. Our findings are similar to those of a recent study by Chan et al,[7] who compared glenoid parameters between type B2 and B3 shoulders, with the hypothesis that the type B3 glenoid would have significantly worse retroversion, inclination, medialization, and posterior humeral head subluxation. Their results also showed no significant differences in the glenoid parameters between type B2 and B3 shoulders.

It is not known whether the reduced humeral retrotorsion is an anatomic variation that predates physeal closure, suggesting either a genetic predisposition or an early developmental process that leads to the formation of a Walch type B shoulder. Alternatively, the decreased torsion may be a gradual adaptive change to the humerus that occurs after skeletal maturity to compensate for the increased glenoid retroversion. If it is a phenomenon that occurs before physeal closure, then we may potentially be able to identify patients in whom type B pathology may go on to develop, similarly to PPSHH. Further studies are needed to identify the etiology and to elucidate the exact nature and position of the torsional variance on the humeral axis.

Some authors have supported the hypothesis that excessive glenoid retroversion is a risk factor for posterior static subluxation,[4,24] whereas others have refuted it.[14,18,21,37] A recent study by Knowles et al[24] showed that patients with type B2 osteoarthritic glenoids have significantly greater premorbid glenoid retroversion than patients with nonarthritic normal glenoids, suggesting that this premorbid morphologic variation may be one contributing factor to posterior humeral head subluxation and subsequent posterior erosion.

It has been suggested that scapulothoracic posture, as well as a scapulohumeral muscle imbalance, secondary to a disturbed transverse force couple between the anterior rotator cuff and posterior rotator cuff, may also have a role in the pathogenesis of type B glenoid morphology. Piepers et al[36] found no significant differences in the muscle volumes between the anterior cuff (subscapularis) and the posterior cuff (infraspinatus and teres minor) in nonpathologic shoulders. This finding suggests that the muscle volumes are in balance, and as a consequence, owing to the correlation between muscle strength and muscle volume, the transverse force couple of nonpathologic shoulders is in balance. Although the state of the transverse force couple has never been investigated in Walch type B shoulders, Donohue et al[10] recently reported that the location and severity of rotator cuff muscle fatty infiltration differed significantly among Walch subtypes. Higher-grade posterior rotator cuff muscle fatty infiltration was associated with type B3 glenoids, increased pathologic glenoid retroversion, and increased joint-line medialization.[10] It is not known what role, if any, a scapulohumeral muscle imbalance may have in causing the development of PPSHH and its progression. Such an imbalance may also have a role in reduced humeral retrotorsion seen in Walch type B humeri.

A recent comparative anatomic imaging study evaluated and compared the size and morphologic patterns between normal and osteoarthritic humeral heads.[23] Although the osteoarthritic humeral head morphology varied significantly from normal, it did not vary as a function of the Walch classification between symmetrical and asymmetrical glenoids.[23] It has been theorized that the posteriorly subluxated humeral head may be eroding the glenoid by rotational articulation with the neoglenoid. Therefore, the radii of the humeral head and neoglenoid in Walch type B2 shoulders would be closely matched. However, surprisingly, in a CT-based study performed to quantify erosion in type B2 glenoids, Knowles et al[25] showed a significant difference between the radius of the humeral head and the radius of the neoglenoid. In fact, the radius of the humeral head more closely approximated the paleoglenoid radius than the neoglenoid radius.[25] This finding suggests that a posteriorly subluxated humeral head may be eroding the neoglenoid by translation as opposed to rotation or, more likely, a combination thereof. These findings indicate that there are multiple and possibly additional unknown variables that contribute to the glenohumeral morphology of the Walch type B shoulder.

The effects of altered retrotorsion on glenohumeral joint stability, loading, and implant survivorship after arthroplasty remain unclear.[3,26-28,32,39-41] Anatomic total shoulder arthroplasty may offer good functional results in Walch type B2 shoulders but requires careful preoperative planning, correction of glenoid retroversion, restoration of the native joint line, and appropriate soft-tissue balancing to ensure stability. Glenoid component malposition, especially component retroversion, is a substantial risk factor for radiographic lucent lines and failure.[17,19] In addition, greater glenoid retroversion has been associated with an increased risk of glenoid component malposition.[14,20] Undercorrection of retroversion can result in persistent posterior humeral head subluxation, which causes eccentric loading of the glenoid component and premature loosening.[13,42] Biomechanical studies have suggested that this risk can be minimized by placing the glenoid component in less than 10° of retroversion.[13] The humeral component also plays a role in restoring the native or pathologic joint line. Proper humeral component positioning can be difficult intraoperatively because of differences in preoperative and intraoperative anatomic landmarks and the associated differences in humeral retrotorsion.

Presently, surgeons managing patients with type B2 glenoids have an awareness of the increased glenoid retroversion and the associated bone loss. To date, little attention has been paid to the humerus. Unfortunately, our study adds to the complexity in managing patients with type B glenoids given that reciprocal changes in torsion have now been identified in the humerus. These torsional differences, as they are unlikely to have been addressed during total shoulder arthroplasty, may be a contributing factor to the poorer outcomes of glenoid implants. In addition, it is not known whether pathologic type B humeral torsion should be corrected to population means or maintained to maximize implant survivorship and minimize complications.

This study has several limitations. We used CT scans of cadaveric shoulders to form the normal group. The torsional differences identified in the Walch type B shoulders may possibly be present in all arthritic shoulders; as such, humeral torsion in the other Walch subtypes requires further investigation. In addition, this study identified torsional differences, but the etiology and treatment recommendations based on these findings remain unknown. The strengths of this study include the relatively large number of patients, the comparative normal cohort, and the inter-rater statistics.

Conclusion

The Walch type B humerus has significantly less retrotorsion than non-osteoarthritic shoulders. At present, it is unknown whether the altered humeral retrotorsion is a cause or effect of the type B glenoid. In addition, it is unknown whether surgeons should be reconstructing type B2 humeral component version to pathologic torsion or to nonpathologic population means to optimize arthroplasty survivorship.

Disclaimer

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References

1. Bercik MJ, Kruse K II, Yalizis M, Gauci MO, Chaoui J, Walch G. A modification to the Walch classification of the glenoid in primary glenohumeral osteoarthritis using three-dimensional imaging. J Shoulder Elbow Surg 2016;25:1601-6. https://doi.org/10.1016/j.jse.2016.03.010
2. Boileau P, Bicknell RT, Mazzoleni N, Walch G, Urien JP. CT scan method accurately assesses humeral head retroversion. Clin Orthop Relat Res 2008;466:661-9. https://doi.org/10.1007/s11999-007-0089-z
3. Boileau P, Walch G, Liotard JP. Etude radiocinématographique de l'élévation active de l'épaule prothésée. [Radio-cinematographic study of active elevation of the prosthetic shoulder]. Rev Chir Orthop Reparatrice Appar Mot 1992;78:355-64 [in French].
4. Bryce CD, Davison AC, Okita N, Lewis GS, Sharkey NA, Armstrong AD. A biomechanical study of posterior glenoid bone loss and humeral head translation. J Shoulder Elbow Surg 2010;19:994-1002. https://doi.org/10.1016/j.jse.2010.04.010
5. Bryce CD, Pennypacker JL, Kulkarni N, Paul EM, Hollenbeak CS, Mosher TJ, et al. Validation of three-dimensional models of in situ scapulae. J Shoulder Elbow Surg 2008;17:825-32. https://doi.org/10.1016/j.jse.2008.01.141
6. Budge MD, Lewis GS, Schaefer E, Coquia S, Flemming DJ, Armstrong AD. Comparison of standard two-dimensional and three-dimensional corrected glenoid version measurements. J Shoulder Elbow Surg 2011;20:577-83. https://doi.org/10.1016/j.jse.2010.11.003
7. Chan K, Knowles NK, Chaoui J, Ferreira LM, Walch G, Athwal GS. Is the Walch B3 glenoid significantly worse than the B2? Shoulder Elbow 2018;10:256-61. https://doi.org/10.1177/1758573217724111
8. Chan K, Knowles NK, Chaoui J, Gauci MO, Ferreira LM, Walch G, et al. Characterization of the Walch B3 glenoid in primary osteoarthritis. J Shoulder Elbow Surg 2017;26:909-14. https://doi.org/10.1016/j.jse.2016.10.003
9. DeLude JA, Bicknell RT, MacKenzie GA, Ferreira LM, Dunning CE, King GJ, et al. An anthropometric study of the bilateral anatomy of the humerus. J Shoulder Elbow Surg 2007;16:477-83. https://doi.org/10.1016/j.jse.2006.09.016
10. Donohue KW, Ricchetti ET, Ho JC, Iannotti JP. The association between rotator cuff muscle fatty infiltration and glenoid morphology in glenohumeral osteoarthritis. J Bone Joint Surg Am 2018;100:381-7. https://dx.doi.org/10.2106/JBJS.17.00232
11. 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;7:453-7.
12. Edelson G. Variations in the retroversion of the humeral head. J Shoulder Elbow Surg 1999;8:142-5.
13. Farron A, Terrier A, Büchler P. Risks of loosening of a prosthetic glenoid implanted in retroversion. J Shoulder Elbow Surg 2006;15:521-6. https://doi.org/10.1016/j.jse.2005.10.003
14. Gerber C, Costouros JG, Sukthankar A, Fucentese SF. Static posterior humeral head subluxation and total shoulder arthroplasty. J Shoulder Elbow Surg 2009;18:505-10. https://doi.org/10.1016/j.jse.2009.03.003
15. Hernigou P, Duparc F, Hernigou A. Determining humeral retroversion with computed tomography. J Bone Joint Surg Am 2002;84-A:1753-62.
16. Hertel R, Knothe U, Ballmer FT. Geometry of the proximal humerus and implications for prosthetic design. J Shoulder Elbow Surg 2002;11:331-8. https://doi.org/10.1067/mse.2002.124429
17. Ho JC, Sabesan VJ, Iannotti JP. Glenoid component retroversion is associated with osteolysis. J Bone Joint Surg Am 2013;95:e82. https://doi.org/10.2106/JBJS.L.00336
18. Hoenecke HR Jr, Tibor LM, D'Lima DD. Glenoid morphology rather than version predicts humeral subluxation: a different perspective on the glenoid in total shoulder arthroplasty. J Shoulder Elbow Surg 2012;21:1136-41. https://doi.org/10.1016/j.jse.2011.08.044
19. Iannotti JP, Greeson C, Downing D, Sabesan V, Bryan JA. Effect of glenoid deformity on glenoid component placement in primary shoulder arthroplasty. J Shoulder Elbow Surg 2012;21:48-55. https://doi.org/10.1016/j.jse.2011.02.011
20. Iannotti JP, Norris TR. Influence of preoperative factors on outcome of shoulder arthroplasty for glenohumeral osteoarthritis. J Bone Joint Surg Am 2003;85-A:251-8.
21. Jacxsens M, Van Tongel A, Henninger HB, De Coninck B, Mueller AM, De Wilde L. A three-dimensional comparative study on the scapulohumeral relationship in normal and osteoarthritic shoulders. J Shoulder Elbow Surg 2016;25:1607-15. https://doi.org/10.1016/j.jse.2016.02.035
22. Jia X, Chen Y, Qiang M, Zhang K, Li H, Jiang Y, et al. Compared to X-ray, three-dimensional computed tomography measurement is a reproducible radiographic method for normal proximal humerus. J Orthop Surg Res 2016;11:82. https://doi.org/10.1186/s13018-016-0417-7
23. Knowles NK, Carroll MJ, Keener JD, Ferreira LM, Athwal GS. A comparison of normal and osteoarthritic humeral head size and

morphology. J Shoulder Elbow Surg 2016;25:502-9. https://doi.org/10.1016/j.jse.2015.08.047

24. Knowles NK, Ferreira LM, Athwal GS. Premorbid retroversion is significantly greater in type B2 glenoids. J Shoulder Elbow Surg 2016; 25:1064-8. https://doi.org/10.1016/j.jse.2015.11.002
25. Knowles NK, Keener JD, Ferreira LM, Athwal GS. Quantification of the position, orientation, and surface area of bone loss in type B2 glenoids. J Shoulder Elbow Surg 2015;24:503-10. https://doi.org/10.1016/j.jse.2014.08.021
26. Kronberg M, Brostrom LA. Humeral head retroversion in patients with unstable humeroscapular joints. Clin Orthop Relat Res 1990:207-11.
27. Kronberg M, Brostrom 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 1990:113-7.
28. Moeckel BH, Altchek DW, Warren RF, Wickiewicz TL, Dines DM. Instability of the shoulder after arthroplasty. J Bone Joint Surg Am 1993;75:492-7.
29. Moor BK, Bouaicha S, Rothenfluh DA, Sukthankar A, Gerber C. Is there an association between the individual anatomy of the scapula and the development of rotator cuff tears or osteoarthritis of the glenohumeral joint?: A radiological study of the critical shoulder angle. Bone Joint J 2013;95-B:935-41. https://doi.org/10.1302/0301-620X.95B7.31028
30. Moor BK, Rothlisberger M, Muller DA, Zumstein MA, Bouaicha S, Ehlinger M, et al. Age, trauma and the critical shoulder angle accurately predict supraspinatus tendon tears. Orthop Traumatol Surg Res 2014;100:489-94. https://doi.org/10.1016/j.otsr.2014.03.022
31. Neer CS II. Articular replacement for the humeral head. J Bone Joint Surg Am 1955;37-A:215-28.
32. Ovesen J, Nielsen S. Prosthesis position in shoulder arthroplasty. A cadaver study of the humeral component. Acta Orthop Scand 1985;56:330-1.
33. 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: 193-4.
34. Oztuna V, Ozturk H, Eskandari MM, Kuyurtar F. Measurement of the humeral head retroversion angle. A new radiographic method. Arch Orthop Trauma Surg 2002;122:406-9. https://doi.org/10.1007/s00402-002-0398-3
35. Pearl ML, Volk AG. Retroversion of the proximal humerus in relationship to prosthetic replacement arthroplasty. J Shoulder Elbow Surg 1995;4:286-9.
36. Piepers I, Boudt P, Van Tongel A, De Wilde L. Evaluation of the muscle volumes of the transverse rotator cuff force couple in nonpathologic shoulders. J Shoulder Elbow Surg 2014;23:e158-62. https://doi.org/10.1016/j.jse.2013.09.027
37. Ricchetti ET, Hendel MD, Collins DN, Iannotti JP. Is premorbid glenoid anatomy altered in patients with glenohumeral osteoarthritis? Clin Orthop Relat Res 2013;471:2932-9. https://doi.org/10.1007/s11999-013-3069-5
38. Roberts SN, Foley AP, Swallow HM, Wallace WA, Coughlan DP. The geometry of the humeral head and the design of prostheses. J Bone Joint Surg Br 1991;73:647-50.
39. Saha AK. Dynamic stability of the glenohumeral joint. Acta Orthop Scand 1971;42:491-505.
40. Saha AK. Zero position of the glenohumeral joint: its recognition and clinical importance. Hunterian Lecture delivered at the Royal College of Surgeons of England on 10th July 1957. RACS London; 1957.
41. Soderlund V, Kronberg M, Brostrom LA. Radiologic assessment of humeral head retroversion. Description of a new method. Acta Radiol 1989;30:501-5.
42. Terrier A, Büchler P, Farron A. Influence of glenohumeral conformity on glenoid stresses after total shoulder arthroplasty. J Shoulder Elbow Surg 2006;15:515-20. https://doi.org/10.1016/j.jse.2005.09.021
43. Walch G, Ascani C, Boulahia A, Nové-Josserand L, Edwards TB. Static posterior subluxation of the humeral head: an unrecognized entity responsible for glenohumeral osteoarthritis in the young adult. J Shoulder Elbow Surg 2002;11:309-14. https://doi.org/10.1067/mse.2002.124547
44. Walch G, Badet R, Boulahia A, Khoury A. Morphologic study of the glenoid in primary glenohumeral osteoarthritis. J Arthroplasty 1999; 14:756-60.
45. Walker KE, Simcock XC, Jun BJ, Iannotti JP, Ricchetti ET. Progression of glenoid morphology in glenohumeral osteoarthritis. J Bone Joint Surg Am 2018;100:49-56. https://doi.org/10.2106/JBJS.17.00064
46. West EA, Knowles NK, Athwal GS, Ferreira LM. A 3D comparison of humeral head retroversion by sex and measurement technique. Shoulder Elbow 2018;10:192-200. https://doi.org/10.1177/1758573217711897
47. Zhang Q, Shi LL, Ravella KC, Koh JL, Wang S, Liu C, et al. Distinct proximal humeral geometry in Chinese population and clinical relevance. J Bone Joint Surg Am 2016;98:2071-81. https://doi.org/10.2106/JBJS.15.01232