

Association of Walch glenoid morphology and fracture patterns in proximal humeral fractures

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Abstract

Purpose

Proximal humeral fracture (PHF) assessment focuses on fracture pattern, bone quality, and patient factors, whereas glenoid morphology—central to biomechanics in glenohumeral arthritis and instability—is overlooked. We hypothesized that pre-existing Walch type B posterior decentring is independently associated with complex, tuberculum-involving PHFs.

Methods

This single-centre, retrospective cohort study analysed 919 patients with a PHF and shoulder computed tomography (CT). Two blinded shoulder-subspecialized orthopedic trauma surgeons independently classified all cases; agreement was quantified with Cohen's κ . Fractures were classified by the Neer and AO/OTA systems and glenoid morphology by the Walch classification. The primary outcome—tuberculum involvement (Neer IV/V)—was analysed by multivariable logistic regression adjusted for age at trauma, sex, and osteoarthritis.

Results

The cohort comprised 919 patients (72.6% female; median age at trauma 69 years). The Walch distribution was type A 42.7%, B 54.4%, C 2.7%, and D 0.2%; osteoarthritis was present in 59.5%. Walch agreement was moderate ($\kappa = 0.53$), with disagreement concentrated at the A1↔B1 decentring boundary ($p < 0.001$). Walch type B was independently associated with tuberculum involvement (adjusted OR 2.07, 95% CI 1.56–2.74, $p < 0.001$) and with greater AO/OTA fracture complexity (adjusted ordinal OR 1.60, $p < 0.001$). Female sex was independently associated with the outcome (OR 1.44, $p = 0.023$); age and osteoarthritis were not significant.

Conclusion

Walch type B glenoid morphology is independently associated with complex, tuberculum-involving proximal humeral fractures. Pre-existing glenoid morphology should be considered during preoperative CT and fracture-pattern assessment.

Level of Evidence

Level III Retrospective Cohort Study Prognostic Study.

1. Introduction

Proximal humeral fractures (PHFs) are among the most common fractures of the upper extremity and rank as the third most frequent fragility fracture in the elderly, with an incidence that continues to rise as populations age [1, 2]. Nationwide registry data document both an increasing fracture incidence and a marked shift toward operative treatment, including a disproportionate growth in shoulder arthroplasty for geriatric fractures [3, 4]. Management remains contentious and must be individualized: non-operative treatment and osteosynthesis by locking-plate or intramedullary fixation are generally preferred in younger patients, whereas reverse total shoulder arthroplasty has become the treatment of choice in elderly patients with poor bone stock or complex fracture patterns [3, 5, 6, 7]. Clinical decision-making relies on the Neer and AO/OTA classifications, which categorize fractures by fragment number, displacement, articular involvement, and dislocation [8, 9]. These systems provide a common descriptive language, but their interobserver reliability is only fair to moderate and varies widely across studies ($\kappa \approx 0.21\text{--}0.67$), and the 2018 AO/OTA revision did not consistently improve agreement; their value for guiding treatment selection or predicting outcome remains limited [10, 11, 12, 13, 14, 15, 16]. This indicates that determinants of fracture behavior extend beyond the descriptive parameters these systems capture.

In glenohumeral osteoarthritis and instability, glenoid morphology is a recognized determinant of joint biomechanics, surgical strategy, and clinical outcome [17, 18, 19, 20]. The Walch classification, developed for the osteoarthritic shoulder, describes glenoid wear and version; type B morphology denotes posterior decentring of the humeral head with posterior glenoid erosion and increased retroversion, progressing from posterior subluxation (B1) to a biconcave glenoid (B2) [19, 20, 21, 22]. Even in the absence of established arthritis, a pre-osteoarthritic, posteriorly subluxated configuration (B0) can be identified, indicating that posterior decentring is a structural trait rather than merely an end-stage degenerative finding [23]. Biomechanically, posterior glenoid bone loss and retroversion displace the humeral head posteriorly and concentrate load eccentrically across the posterior glenoid, thereby altering force transmission across the glenohumeral joint [18, 24]. These altered loading patterns underlie the posterior instability and component-loosening risks associated with type B glenoids [18].

Despite this established role in degenerative and unstable shoulders, glenoid morphology is absent from every contemporary PHF classification, each of which is constructed exclusively from the humeral segments and their displacement [8, 9, 10]. This omission is potentially relevant, because the morphology of the glenoid shapes the vector and distribution of force transmitted to the proximal humerus during a fall, and local load distribution—alongside bone quality—is known to influence where and how the proximal humerus fails [24, 25, 26]. The evidence that bone properties govern fracture pattern is itself mixed: lower local bone quality has been associated with more complex fracture configurations in some cohorts but not in others, suggesting that fracture morphology is multifactorial and may be shaped by loading patterns rather than by bone density alone [27, 28]. To date, only two surgically treated cohorts have related pre-existing glenohumeral pathomorphology—advanced osteoarthritis and cuff-tear arthropathy—to PHF morphology [29, 30]; whether pre-existing Walch glenoid morphology is associated with the resulting fracture pattern in unselected fractures has, to our knowledge, not been examined.

The Neer system organizes fractures into six categories (types I–VI) defined by anatomical location, displacement, and associated dislocation; these categories are descriptive and do not constitute a strictly ordinal severity scale [9, 10]. Within this scheme, Neer types IV and V denote patterns involving the greater and/or lesser tuberculum, which carry distinct clinical importance: the tuberosities are the osseous footprints of the rotator cuff, and their fracture and displacement disrupt the cuff force couple, complicate anatomical reduction and stable fixation, and adversely affect functional outcome [31, 32]. We therefore defined tuberculum involvement (Neer type IV or V) as a single, clinically anchored binary outcome and examined its association with glenoid morphology using multivariable binary logistic regression, complemented by a secondary multinomial analysis across the full Neer spectrum to verify the category-specific nature of the association and by a separate ordinal analysis of AO/OTA fracture type to characterise overall fracture complexity as a distinct construct.

The aim of this retrospective cohort study was to determine whether pre-existing Walch glenoid morphology is associated with tuberculum involvement in acute proximal humeral fractures. We hypothesized that posteriorly decentred Walch type B morphology is independently associated with tuberculum involvement (Neer IV/V) after adjustment for age at trauma, sex, and osteoarthritis status.

2. Materials and methods

2.1 Study design and setting

This was a single-centre, retrospective cohort study conducted at a university-affiliated level-I trauma centre. The study was designed and reported in accordance with the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) statement [33]. The analytic plan—including the a priori designation of the primary hypothesis, the primary exposure and outcome, and the confounder set—was fixed before the inferential analyses were performed. The study was approved by the Hannover Medical School Research Ethics Committee (protocol code 10801_BO_K_2023; approval date 9 March 2023) and was conducted in accordance with the Declaration of Helsinki.

2.2 Data source and study population

Consecutive patients presenting with a proximal humeral fracture and available shoulder computed tomography (CT) with three-dimensional reconstructions were identified from the institutional records for the period between October 2016 and February 2023. DICOM files were uploaded to the Visage imaging workstation (Visage® 7.1 Enterprise Imaging Platform, Visage Imaging, Inc.). For each case, date of birth, sex, date of trauma, and age at the time of trauma (derived from the interval between date of birth and date of trauma) were recorded. The patient selection process is summarized in Fig. 1.

The dataset provided for analysis comprised 919 cases. Data integrity was verified prior to analysis: there were no missing values in any variable, no duplicate patient identifiers, no implausible age values, and no cases in which the trauma date preceded the date of birth. All classification codes were valid for both raters. Consequently, no cases were excluded at the analysis stage, and the full sample of 919

cases entered all analyses. Because the dataset was complete, no imputation of missing data was performed.

2.3 Classification systems and image assessment

Three established classification systems were applied to each case: the Walch classification of glenoid morphology (subtypes A1, A2, B1, B2, B3, C, D) [19, 21]; the Neer classification of proximal humeral fractures (types I–VI) [9]; and the AO/OTA classification of proximal humeral fractures (groups A1–C3) [8]. In addition, the presence of glenohumeral osteoarthritis was recorded as a binary variable (present versus absent), based on established radiographic criteria, with a Kellgren-Lawrence grade of > 2 defined as 'present' and a grade of < 2 defined as 'absent'. [34]. Representative axial CT images of each Walch subtype are shown in Fig. 2.

All 919 cases were independently classified by two orthopedic trauma surgeons with subspecialty expertise in shoulder surgery, who were blinded to one another's assessments. No consensus reading was performed. To preserve a single, internally consistent analytic dataset, the classifications of Rater 1, a senior attending shoulder surgeon, served as the basis for all descriptive, univariate, and multivariable analyses, whereas the classifications of Rater 2 were used exclusively to quantify interrater reliability and to provide an independent cross-rater replication of the primary model.

2.4 Variable definitions

All analysis variables were derived and fixed prior to any statistical testing.

Primary outcome. Tuberculum involvement was defined as a binary variable, coded 1 for Neer types IV or V and 0 for all remaining Neer types (I, II, III, VI).

Primary exposure. Walch B morphology (posterior decentring) was defined as a binary variable, coded 1 for Walch subtypes B1, B2, or B3 and 0 for the remaining subtypes (A1, A2, C, D).

Secondary morphological grouping. The Walch classification was additionally aggregated into the four principal classes A, B, C, and D for subtype-resolved analyses.

Fracture complexity. The AO/OTA classification was operationalized in two ways: (i) as a nine-level ordinal severity rank (A1 = 1 through C3 = 9, with increasing rank reflecting increasing fracture complexity), used for non-parametric group comparisons; and (ii) as the three-level ordinal AO type (A $<$ B $<$ C), used for ordinal regression.

Covariates. Age at trauma (continuous), sex (female versus male), and osteoarthritis (present versus absent) were considered as potential confounders.

2.5 Statistical analysis

All analyses were performed in Python 3.12 (Python Software Foundation, Wilmington, DE, USA) using the pandas, NumPy, SciPy, statsmodels, and scikit-learn libraries. Two-sided p values < 0.05 were

considered statistically significant.

Distributional assessment. The distribution of the continuous variables (age, age at trauma) was assessed using the Shapiro–Wilk test and visually inspected by Q–Q plots. Both age ($W = 0.970$, $p < 0.001$) and age at trauma ($W = 0.966$, $p < 0.001$) departed significantly from normality; continuous variables are therefore summarized as median and interquartile range (IQR) and were compared using non-parametric methods.

Descriptive statistics. Continuous variables are reported as median (IQR); categorical variables are reported as absolute and relative frequencies.

Interrater reliability. Agreement between the two raters was quantified using Cohen's κ for the nominal Walch and Neer classifications and weighted Cohen's κ with quadratic weights for the ordinal AO classification. Reliability was additionally computed for the dichotomized exposure (Walch B) and outcome (tuberculum involvement). Ninety-five percent confidence intervals (CI) for κ were obtained by bootstrap resampling (1000 iterations). κ values were interpreted according to the benchmarks of Landis and Koch [35]. To test the a priori hypothesis that interrater disagreement is concentrated at the A1↔B1 boundary—where posterior decentring is most difficult to adjudicate in the fractured shoulder—all discordant Walch cases were dichotomized into A1↔B1 disagreements versus all other disagreements, and the observed proportion was tested against the null expectation of an equal contribution from each of the 21 possible disagreement pairs ($p = 1/21$) using an exact one-sided binomial test.

Univariate analysis. The primary univariate association between Walch B morphology and tuberculum involvement was assessed using the χ^2 test, with the crude odds ratio (OR) and its 95% CI derived from the 2×2 table; the minimum expected cell frequency was verified to justify the χ^2 approximation. The distribution of Walch subtypes across Neer types was examined using the χ^2 test on the full 7×6 contingency table, with standardized residuals used to identify cells contributing disproportionately to the association; because several cells had low expected frequencies, this global test was interpreted descriptively. The association between Walch B morphology and AO complexity (ordinal rank) was tested using the Mann–Whitney U test, with the rank-biserial effect size r reported; differences in AO complexity across the four principal Walch classes were tested using the Kruskal–Wallis test with Dunn's post-hoc comparisons under Bonferroni correction.

Confounder selection. Each candidate covariate was screened for its association with both the outcome and the exposure. Variables associated with both at a liberal threshold of $p < 0.20$ were retained as confounders in the multivariable model, consistent with established epidemiological practice for confounder identification.

Multivariable analysis. The primary model was a multivariable binary logistic regression of tuberculum involvement on Walch B morphology, adjusted for the retained confounders (age at trauma, sex, osteoarthritis). Prior to fitting, multicollinearity was assessed using the variance inflation factor (VIF), with $VIF < 5$ considered acceptable. Adjusted odds ratios (aOR) with 95% CI are reported for all model

terms. Model performance was evaluated using the Hosmer–Lemeshow goodness-of-fit test, McFadden, Cox–Snell, and Nagelkerke pseudo- R^2 , the likelihood-ratio test against the null model, and the area under the receiver operating characteristic curve (AUC).

Secondary analyses. Three pre-specified secondary models were fitted. First, the primary logistic model was repeated with the full Walch subtype as a categorical predictor (reference A1) to determine whether the effect was specific to the B subtypes. Second, a multinomial logistic regression of the complete Neer classification (I–VI; reference Neer I) was fitted to confirm that the effect was not an artefact of the binary outcome definition. Third, an ordinal logistic regression was fitted to assess whether Walch B morphology was associated with a general fracture-severity gradient; because the nine-level AO model failed to converge owing to sparse cells, the three-level AO type (A/B/C) was used, and the proportional-odds assumption was examined by comparing coefficients across threshold-specific binary logistic models.

Sensitivity analyses. The robustness of the primary estimate was examined through a series of pre-specified subgroup exclusions, each targeting a specific potential source of bias. First, Neer VI fracture-dislocations were excluded to address a potential circularity between exposure and outcome: because Walch type B is defined by posterior humeral head decentring and Neer VI denotes fracture-dislocation, an acute traumatic dislocation could in principle be misclassified on post-traumatic CT as pre-existing posterior subluxation, spuriously inflating the association. Second, the rare Walch D subtype was excluded to confirm that the estimate was not distorted by unstable coefficients arising from its very small cell count, and both exclusions were additionally applied in combination. Third, the analysis was restricted to patients without osteoarthritis to test whether the association held independently of degenerative change (the osteoarthritis term, being constant in this subgroup, was removed from the model). Finally, the primary model was re-estimated using the fully independent classifications of Rater 2 (cross-rater replication) to verify that the finding was not driven by the assessments of a single observer.

Multiplicity. The primary hypothesis test was not adjusted for multiplicity, having been specified a priori as the single primary comparison. All secondary and exploratory p values were corrected for multiple comparisons using the Benjamini–Hochberg false discovery rate (FDR) procedure.

Use of artificial intelligence tools. During the preparation of this study, the large language model Claude (Anthropic, 2025) was used in a supportive capacity for two methodological tasks: (i) assistance with the development, debugging, and verification of the Python code used for the statistical analyses described above, and (ii) assistance with the generation and formatting of data visualisations. In all cases, the authors independently verified the correctness of the generated code, the plausibility of the statistical output, and the accuracy of the visual representations against the source data. The final analytic decisions, the interpretation of all results, and the scientific conclusions remain entirely the responsibility of the authors.

3. Results

3.1 Study population

The cohort comprised 919 patients. The median age at trauma was 69 years (IQR 58–80; range 19–97); the median age at data collection was 79 years (IQR 66–88). The cohort was predominantly female (667/919, 72.6%; male 252/919, 27.4%). Glenohumeral osteoarthritis was present in 547 patients (59.5%) (Table 1). The age distribution of the cohort is shown in Fig. 3.

Table 1 Baseline characteristics of the study population (<i>n</i> = 919)	
Characteristic	Value
Age at trauma, years – median (IQR)	69 (58–80)
Age at data collection, years – median (IQR)	79 (66–88)
Female sex – <i>n</i> (%)	667 (72.6)
Male sex – <i>n</i> (%)	252 (27.4)
Osteoarthritis present – <i>n</i> (%)	547 (59.5)
Tuberculum involvement, Neer IV/V – <i>n</i> (%)	586 (63.8)

3.2 Distribution of fracture and glenoid classifications

The distribution of Walch glenoid morphology, AO/OTA fracture type, and Neer fracture type for the primary rater is summarized in Table 2. Walch B morphology was present in 500 of 919 cases (54.4%). The most frequent Neer type was type IV (440/919, 47.9%); tuberculum involvement (Neer IV or V) was present in 586 cases (63.8%). The most frequent AO type was type B (455/919, 49.5%).

Table 2
Distribution of glenoid and fracture classifications (Rater 1;
n = 919)

Classification	Category	n	%
Walch	A1	238	25.9
	A2	154	16.8
	B1	243	26.4
	B2	216	23.5
	B3	41	4.5
	C	25	2.7
	D	2	0.2
Walch (dichotomised)	B (B1–B3)	500	54.4
	Non-B	419	45.6
AO/OTA	A1	142	15.5
	A2	97	10.6
	A3	46	5.0
	B1	350	38.1
	B2	92	10.0
	B3	13	1.4
	C1	104	11.3
	C2	39	4.2
	C3	36	3.9
AO/OTA (type)	A	285	31.0
	B	455	49.5
	C	179	19.5
Neer	I	104	11.3
	II	68	7.4
	III	100	10.9
	IV	440	47.9
	V	146	15.9

Classification	Category	n	%
	VI	61	6.6
Tuberculum involvement	Present (IV/V)	586	63.8
	Absent	333	36.2

3.3 Interrater reliability

Interrater agreement was moderate for the nominal Walch ($\kappa = 0.53$, 95% CI 0.49–0.57) and Neer ($\kappa = 0.59$, 95% CI 0.55–0.63) classifications, and almost perfect for the ordinal AO classification using quadratic-weighted κ ($\kappa_w = 0.81$, 95% CI 0.77–0.85). Dichotomisation improved the reliability of the clinically decisive variables: agreement on tuberculum involvement was substantial ($\kappa = 0.67$, 95% CI 0.62–0.72), whereas agreement on the dichotomized Walch B exposure remained moderate ($\kappa = 0.52$, 95% CI 0.46–0.57) (Table 3).

Table 3
Interrater reliability between Rater 1 and Rater 2 ($n = 919$)

Classification	κ	95% CI	Interpretation
Walch (7 categories)	0.53	0.49–0.57	Moderate
Neer (6 categories)	0.59	0.55–0.63	Moderate
AO/OTA (quadratic-weighted κ)	0.81	0.77–0.85	Almost perfect
Walch B (dichotomous)	0.52	0.46–0.57	Moderate
Tuberculum involvement (dichotomous)	0.67	0.62–0.72	Substantial

Of 336 cases in which the two raters disagreed on the Walch classification, 71 (21.1%) were A1↔B1 disagreements, a proportion substantially exceeding the 4.8% expected under a uniform distribution across all possible disagreement pairs (exact binomial test, $p < 0.001$). This confirms the a priori expectation that the principal source of interrater disagreement is the adjudication of posterior decentring in the fractured shoulder.

3.4 Univariate association between Walch B morphology and tuberculum involvement

Tuberculum involvement occurred in 360 of 500 Walch B cases (72.0%) versus 226 of 419 non-B cases (53.9%). The association was highly significant ($\chi^2 = 31.41$, $df = 1$, $p < 0.001$; minimum expected cell count 151.8), corresponding to a crude OR of 2.20 (95% CI 1.67–2.89).

The distribution of Walch subtypes across Neer types differed significantly ($\chi^2 = 135.83$, $df = 30$, $p < 0.001$); because several cells had low expected frequencies (minimum 0.13), this global test is interpreted descriptively. Analysis of standardized residuals showed that Walch A1 was strongly

overrepresented among Neer I fractures (standardized residual + 6.18) and that Walch B2 was markedly underrepresented among Neer I (− 4.14) and overrepresented among Neer V fractures (+ 2.17), consistent with a shift towards tuberculum-involving patterns in the presence of posterior decentring (Fig. 4). Among Neer VI fracture-dislocations, the proportion of Walch B cases (30/61, 49.2%) did not differ materially from the overall Walch B rate (54.4%), arguing against a systematic distortion of the morphology assessment by the dislocation pattern.

Walch B morphology was associated with greater AO fracture complexity (Mann–Whitney U test, $p < 0.001$), although the effect size was small ($r = 0.15$); the shift was driven by a higher proportion of AO type B fractures in the Walch B group (56.4% vs. 41.3%) at the expense of type A fractures (23.0% vs. 40.6%). Across the four principal Walch classes, AO complexity differed significantly (Kruskal–Wallis $H = 22.03$, $p < 0.001$); in post-hoc testing, only the comparison between classes A and B reached significance after Bonferroni correction ($p < 0.001$), with all other pairwise comparisons non-significant.

3.5 Multivariable analysis

All three candidate covariates satisfied the confounder criterion (association with both exposure and outcome at $p < 0.20$) and were retained: age at trauma ($p = 0.004$ with outcome; $p < 0.001$ with exposure), sex ($p = 0.002$; $p = 0.014$), and osteoarthritis ($p = 0.020$; $p < 0.001$). Multicollinearity was negligible (all VIF < 1.7).

In the primary multivariable logistic regression, Walch B morphology remained independently associated with tuberculum involvement after adjustment for age at trauma, sex, and osteoarthritis (aOR 2.07, 95% CI 1.56–2.74, $p < 0.001$). Female sex was modestly associated with the outcome (aOR 1.44, 95% CI 1.05–1.97, $p = 0.023$), whereas age at trauma (aOR 1.01, 95% CI 0.99–1.02, $p = 0.262$) and osteoarthritis (aOR 1.01, 95% CI 0.71–1.44, $p = 0.951$) were not (Table 4). Notably, the univariate association of osteoarthritis with the outcome did not persist after adjustment, indicating that the effect of glenoid morphology on tuberculum involvement is not explained by coexisting osteoarthritis.

Table 4
Primary multivariable logistic regression for tuberculum involvement
($n = 919$)

Variable	aOR	95% CI	<i>p</i>
Walch B (vs. non-B)	2.07	1.56–2.74	< 0.001
Age at trauma (per year)	1.01	0.99–1.02	0.262
Sex (female vs. male)	1.44	1.05–1.97	0.023
Osteoarthritis (present vs. absent)	1.01	0.71–1.44	0.951

The model fitted the data adequately (Hosmer–Lemeshow $\chi^2 = 9.20$, $p = 0.326$) and was significant against the null model (likelihood-ratio $\chi^2 = 41.71$, $df = 4$, $p < 0.001$), with pseudo- R^2 values of 0.035 (McFadden), 0.044 (Cox–Snell), and 0.061 (Nagelkerke) and an AUC of 0.62.

3.6 Secondary analyses

Subtype-resolved model. When the full Walch subtype was entered as a categorical predictor (reference A1), the association was confined to the decentring subtypes B1 (aOR 1.98, 95% CI 1.33–2.93, $p < 0.001$) and B2 (aOR 2.40, 95% CI 1.57–3.67, $p < 0.001$). Subtypes A2 (aOR 1.07, $p = 0.777$), B3 (aOR 1.18, $p = 0.649$), and C (aOR 0.54, $p = 0.156$) were not significantly associated with the outcome; the estimate for the rare Walch D subtype was uninterpretable owing to quasi-complete separation ($n = 2$, both tuberculum-positive). The absence of a significant effect for B3 is most plausibly attributable to its small sample size ($n = 41$) rather than to a true null association.

Multinomial model. In the multinomial regression of the full Neer classification (reference Neer I), Walch B morphology was associated with significantly increased odds of Neer III (OR 4.07, 95% CI 2.17–7.66), Neer IV (OR 3.97, 95% CI 2.37–6.65), Neer V (OR 5.15, 95% CI 2.84–9.32; all $p < 0.001$), and Neer VI (OR 2.48, 95% CI 1.22–5.01, $p = 0.012$), but not of Neer II (OR 1.53, 95% CI 0.77–3.08, $p = 0.228$). This confirms that the effect is not an artefact of the binary outcome definition and indicates that posterior decentring is specifically associated with more complex, tuberculum-involving fracture patterns rather than with simple two-part fractures (Fig. 5).

Ordinal model. In the ordinal regression of AO type, Walch B morphology was associated with greater overall fracture severity (OR 1.60, 95% CI 1.24–2.07, $p < 0.001$). However, the proportional-odds assumption was not satisfied for the Walch B term (nor for sex or osteoarthritis), so this estimate is reported as a descriptive summary measure rather than as a structurally interpretable parameter. The smaller magnitude of this association relative to the primary model is consistent with the effect being specific to tuberculum involvement rather than to global fracture complexity.

3.7 Sensitivity analyses

The primary estimate was robust across all sensitivity analyses (Table 5; Fig. 6). Excluding Neer VI fracture-dislocations (aOR 2.15), excluding the rare Walch D subtype (aOR 2.09), restricting to cases without osteoarthritis (aOR 2.51, with the constant osteoarthritis term removed), and excluding both Neer VI and Walch D (aOR 2.18) all yielded estimates consistent with the primary model, with all confidence intervals excluding unity and all $p < 0.001$.

Cross-rater replication using the fully independent classifications of Rater 2 reproduced the association (aOR 1.87, 95% CI 1.39–2.51, $p < 0.001$); the difference between the rater-specific point estimates was small (Δ OR = 0.20), indicating that the finding is not driven by the classifications of a single observer, notwithstanding the moderate reliability of the Walch classification.

Table 5
Sensitivity analyses for the Walch B–tuberculum involvement association

Analysis	n	aOR (Walch B)	95% CI	p
Primary model (all cases)	919	2.07	1.56–2.74	< 0.001
Excluding Neer VI	858	2.15	1.59–2.91	< 0.001
Excluding Walch D	917	2.09	1.58–2.77	< 0.001
Without osteoarthritis ^a	372	2.51	1.60–3.92	< 0.001
Excluding Neer VI + Walch D	856	2.18	1.61–2.95	< 0.001
Cross-rater replication (Rater 2)	919	1.87	1.39–2.51	< 0.001

^a Osteoarthritis was omitted from this model as it was constant within the subgroup.

After Benjamini–Hochberg correction for multiple comparisons, all principal secondary findings—including the subtype effects for B1 and B2, the multinomial associations for Neer III–VI, the Walch-subtype × Neer distribution, and the AO complexity comparisons—remained statistically significant; the non-significant subtype terms (A2, B3, C, D) likewise remained non-significant after correction.

4. Discussion

4.1 Principal findings

This study demonstrates a robust, independent association between pre-existing Walch type B glenoid morphology and tuberculum involvement (Neer types IV and V) in proximal humeral fractures. After adjustment for age at trauma, sex, and osteoarthritis, Walch type B morphology was associated with a near-doubling of the odds of tuberculum involvement (adjusted OR 2.07, 95% CI 1.56–2.74, $p < 0.001$). The association persisted across every sensitivity analysis and was reproduced when the fully independent classifications of the second rater were substituted (adjusted OR 1.87, 95% CI 1.39–2.51; Δ OR 0.20). A secondary multinomial analysis localized the effect to the complex, tuberculum-involving fracture patterns: relative to minimally displaced fractures (Neer I), Walch B was associated with significantly increased odds of Neer types III, IV, V, and VI, but not of the two-part Neer type II pattern, confirming a category-specific rather than a uniform effect. In a separate ordinal analysis, Walch B was additionally associated with a higher AO/OTA fracture type (adjusted OR 1.60, 95% CI 1.24–2.07, $p < 0.001$); because the proportional-odds assumption was not satisfied, this estimate is interpreted descriptively and represents overall fracture complexity as a construct distinct from the primary tuberculum-involvement outcome [29, 30].

Within the adjusted model, female sex was independently associated with tuberculum involvement (OR 1.44, 95% CI 1.05–1.97, $p = 0.023$), whereas age at trauma (OR 1.01, $p = 0.262$) and osteoarthritis (OR 1.01, $p = 0.951$) were not. Age, which was associated with the outcome in unadjusted screening, lost

significance after adjustment, consistent with confounding by correlated factors rather than an independent effect of chronological age. Notably, osteoarthritis—although strongly associated with Walch B morphology at the group level—was not independently associated with tuberculum involvement once glenoid morphology was modelled. This dissociation suggests that the influence of glenohumeral degeneration on fracture pattern operates primarily through altered glenoid geometry—increased retroversion, biconcave or posteriorly eroded B-type glenoids, and posterior humeral head decentring—rather than through generalized changes in bone quality, an interpretation that is consistent with the conflicting evidence on whether bone density itself determines fracture complexity [21, 22, 27, 28, 29, 30].

The absence of a significant effect for Walch types C and D most plausibly reflects limited statistical power. For Walch type C ($n = 25$), a non-significant trend toward lower odds of tuberculum involvement was observed (OR 0.54, 95% CI 0.23–1.27, $p = 0.156$), which is hypothesis-generating and warrants verification in adequately powered cohorts. For Walch type D ($n = 2$), quasi-complete separation rendered the estimate uninterpretable, precluding any conclusion regarding this rare morphology.

4.2 Pre-existing morphology versus acute trauma

A legitimate concern is whether posterior humeral head decentring on post-traumatic CT reflects a pre-existing chronic glenoid abnormality or an acute, trauma-induced dislocation—an ambiguity that could introduce circularity, given that Walch type B is defined by posterior subluxation and Neer type VI denotes fracture-dislocation. Two findings argue against such an artefact. First, Walch B was not overrepresented among Neer VI fracture-dislocations: its prevalence in this subgroup (49.2%, 30/61) did not exceed the cohort-wide rate (54.4%) and did not differ from that in Neer I–V fractures (54.8%; $\chi^2 = 0.51$, $p = 0.474$). Second, excluding all Neer VI cases left the association essentially unchanged (adjusted OR 2.15, 95% CI 1.59–2.91, $p < 0.001$). Together, these results indicate that the Walch B–tuberculum involvement association is not an artefact of misclassifying acute dislocation as pre-existing posterior subluxation.

4.3 Mechanistic and biomechanical interpretation

Walch type B glenoids are characterized by posterior humeral head decentring with eccentric posterior wear and retroversion [17, 19, 20]. Beyond established osteoarthritic B patterns, a pre-osteoarthritic, posteriorly subluxated configuration (B0) has been described, attributed to asymmetric posterior glenohumeral contact forces and increased retroversion, supporting the concept that chronic posterior decentring alters local load transfer across the glenoid [23]. Three-dimensional imaging studies delineate a spectrum from minor posterior erosion (B1) to biconcave posterior deficiency with marked retroversion (B2/B3) [17, 19]. Mechanically, posteriorly eccentric glenoids impose asymmetric load across the posterior rim and shift rotator cuff and capsuloligamentous force vectors [17, 18, 19, 20, 24]; cadaveric data show that even modest posterior bone loss produces measurable posterior humeral head translation and altered joint contact, with significant translation arising from as little as five degrees of posterior resection in certain arm positions [24]. Although these alterations have been characterized

chiefly in the contexts of instability and arthroplasty [24], their contribution to acute fracture mechanics is unestablished. The present association is therefore best interpreted as evidence that chronic alterations in glenohumeral geometry may influence the fracture pattern produced by an external load—by analogy with bone-mechanics observations at other anatomical sites, where pre-existing deformity alters local stress distribution and failure mode [25, 26]—and does not establish causation. Prospective biomechanical work, using finite-element or cadaveric fracture modelling, would be required to test the proposed pathway linking retroversion, altered joint mechanics, and fracture pattern.

4.4 Risk factors for proximal humeral fractures

Risk-factor models for proximal humeral fractures have centred on osteoporosis, advanced age, and fall mechanism, but the type and energy of trauma and the patient's musculoskeletal history may also shape fracture occurrence and pattern [36, 37]. A systematic review identified moderate evidence for several shoulder-injury risk factors in overhead sport, including rotational strength deficits and scapular dyskinesia [36]; although focused on overuse injury rather than fracture, such chronic adaptations could alter glenohumeral biomechanics in ways that become relevant when acute trauma is superimposed. Sport-specific adaptations in overhead athletes, including altered humeral retroversion and capsular laxity, have likewise been described [37]. In the present study, prior sporting and occupational activity were unmeasured and could plausibly influence both glenoid morphology and fracture pattern; future work should capture trauma mechanism, activity history, and previous shoulder injury to disentangle these interrelated factors.

4.5 Imaging, measurement, and classification implications

Plain radiographs remain the initial triage tool, but reliable identification of glenoid subtype and quantification of posterior wear require computed tomography with three-dimensional reconstruction, on which glenoid version and morphology can be quantified reproducibly [38]. Three-dimensional analysis, validated for arthroplasty planning [39, 40] and applied to fracture assessment [29, 41], permits reproducible measurement of fragment translation and rotation that two-dimensional radiographs systematically underestimate [41]. Conventional systems such as the Neer classification address only the humeral side, were developed for radiographs, show only modest interobserver reliability, and do not encode premorbid joint morphology [10]. Reporting a fracture pattern without a standardized glenoid descriptor therefore omits a potentially relevant prognostic variable and a possible confounder for outcome studies. For operative planning, three-dimensional CT defines the configuration in all planes, allows adjudication of Walch subtype despite post-injury distortion, and quantifies features—tuberosity rotation and articular comminution—that alter fixation strategy and are frequently occult on radiographs [17, 41]. Representative examples of a centred (Walch A) and a posteriorly decentred (Walch B) glenoid in the setting of an acute proximal humeral fracture are shown in Fig. 2.

4.6 Clinical translation: fixation versus arthroplasty

The morphological association identified here has planning relevance. Posterior glenoid wear complicates glenoid preparation and guidewire positioning when arthroplasty is selected; the

arthroplasty literature shows that posterior wear increases version error, component malposition, and subsequent loosening with standard techniques [18, 42], and that glenoids with posterior wear exhibit greater version error and malposition for reverse arthroplasty when planned placement is reproduced without navigation or patient-specific guides [43]. In a borderline decision between internal fixation and arthroplasty in an elderly patient, a B2 or B3 glenoid is therefore relevant to the risk calculus, because reverse total shoulder arthroplasty is mechanically less dependent on a congruent native glenoid and intact cuff than hemiarthroplasty or internal fixation [44, 45], and meta-analytic data report more consistent function and lower reoperation rates for reverse arthroplasty than for hemiarthroplasty in elderly fractures [44]. Morphology alone should not mandate arthroplasty: a sound algorithm integrates patient factors, bone density, rotator cuff status, and anticipated functional demand. Where posterior bone loss and retroversion must be addressed, options include augmented glenoid components [17], corrective eccentric reaming (generally limited to retroversion < 15–20°) [42, 46], structural bone grafting [45], and computer-assisted navigation or patient-specific instrumentation to improve version correction [43].

4.7 Evidence gap and classification implications

Current proximal humeral fracture practice and research largely overlook the glenoid. These data indicate that a simple glenoid-morphology modifier, recorded from standardized preoperative CT using validated three-dimensional criteria, could refine prognostic models and stratify clinical trials. Incorporating a Walch-based modifier—including the Bercik three-dimensional modification—into prospective PHF registries [17, 19] would allow testing of whether posterior glenoid wear independently predicts fixation failure, instability, post-traumatic arthropathy, revision surgery, or inferior patient-reported outcomes.

4.8 Limitations

Several limitations apply. The retrospective, observational design precludes causal inference, and the temporal sequence between glenoid morphology and fracture cannot be established without pretraumatic imaging, which is not practically obtainable. Statistical power was limited for the rare Walch types C ($n = 25$) and D ($n = 2$), whose estimates are correspondingly unstable. Important variables were unavailable—trauma mechanism and energy, prior sporting and occupational activity, and previous shoulder injury—any of which could confound or modify the observed associations [36, 37]. Inclusion required CT, which may introduce selection bias if patients with minor, non-operatively managed fractures less frequently underwent CT, potentially enriching the cohort for more complex fracture patterns.

Classification reliability is a further consideration. All cases were classified independently by two blinded raters; interobserver agreement was moderate for the Walch ($\kappa = 0.53$) and Neer ($\kappa = 0.59$) systems and almost perfect for the AO/OTA system (quadratic-weighted $\kappa = 0.81$), values consistent with the fair-to-moderate ranges reported for these classifications [11, 12, 14, 15]. Agreement improved for the clinically decisive dichotomies (tuberculum involvement $\kappa = 0.67$; dichotomized Walch B $\kappa = 0.52$). The residual

Walch disagreement was concentrated at the A1↔B1 boundary—the distinction of pure posterior decentring from a centred glenoid—which accounted for a disproportionate share of all discordant cases (21.1%; $p < 0.001$), whereas structurally evident osseous defects were more readily adjudicated [47, 48]. Such morphological ambiguity introduces predominantly non-differential classification variability that would, if anything, attenuate rather than inflate the measured association; that the effect nonetheless persisted under cross-rater replication (OR 1.87, $p < 0.001$) argues against a spurious finding. Because each rater assessed exposure and outcome on the same images, observer-expectation bias cannot be entirely excluded, although the concordance of the two independent raters' adjusted estimates makes a substantial contribution from this source unlikely.

5. Conclusion

Pre-existing Walch type B glenoid morphology is independently associated with tuberculum-involving (Neer IV/V) and, secondarily, with more complex proximal humeral fractures, and this association is robust to extensive sensitivity testing and to independent cross-rater replication. Glenoid morphology—currently absent from all proximal humeral fracture classifications—therefore represents a pre-existing anatomical factor that merits systematic consideration during preoperative CT assessment and fracture-pattern evaluation. Prospective studies incorporating a standardised glenoid-morphology descriptor, together with dedicated biomechanical work, are needed to confirm these associations and to test their prognostic and therapeutic relevance.

Declarations

Author contributions

Conceptualization, H.Ö. and J.-D.C.; methodology, H.Ö., J.-D.C. and J.M.; validation, M.W., S.S. and J.-D.C.; formal analysis, H.Ö. and G.A.; investigation, H.Ö., J.M. and J.-D.C.; resources, S.O. and S.S.; data curation, H.Ö., J.M., A.G. and G.A.; writing—original draft preparation, H.Ö.; writing—review and editing, H.Ö., J.M., G.A., A.G., S.O. and J.-D.C.; visualization, H.Ö.; supervision, S.S., M.W. and J.-D.C. All authors have read and agreed to the published version of the manuscript.

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Consent to participate. Patient consent was waived due to the retrospective nature of the study.

Consent to publish. Not applicable. The figures contain only non-identifiable computed tomography images from which no individual participant can be identified.

Data availability. The datasets generated and/or analyzed during the current study are not publicly available due to patient privacy considerations but are available from the corresponding author on reasonable request.

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Figures

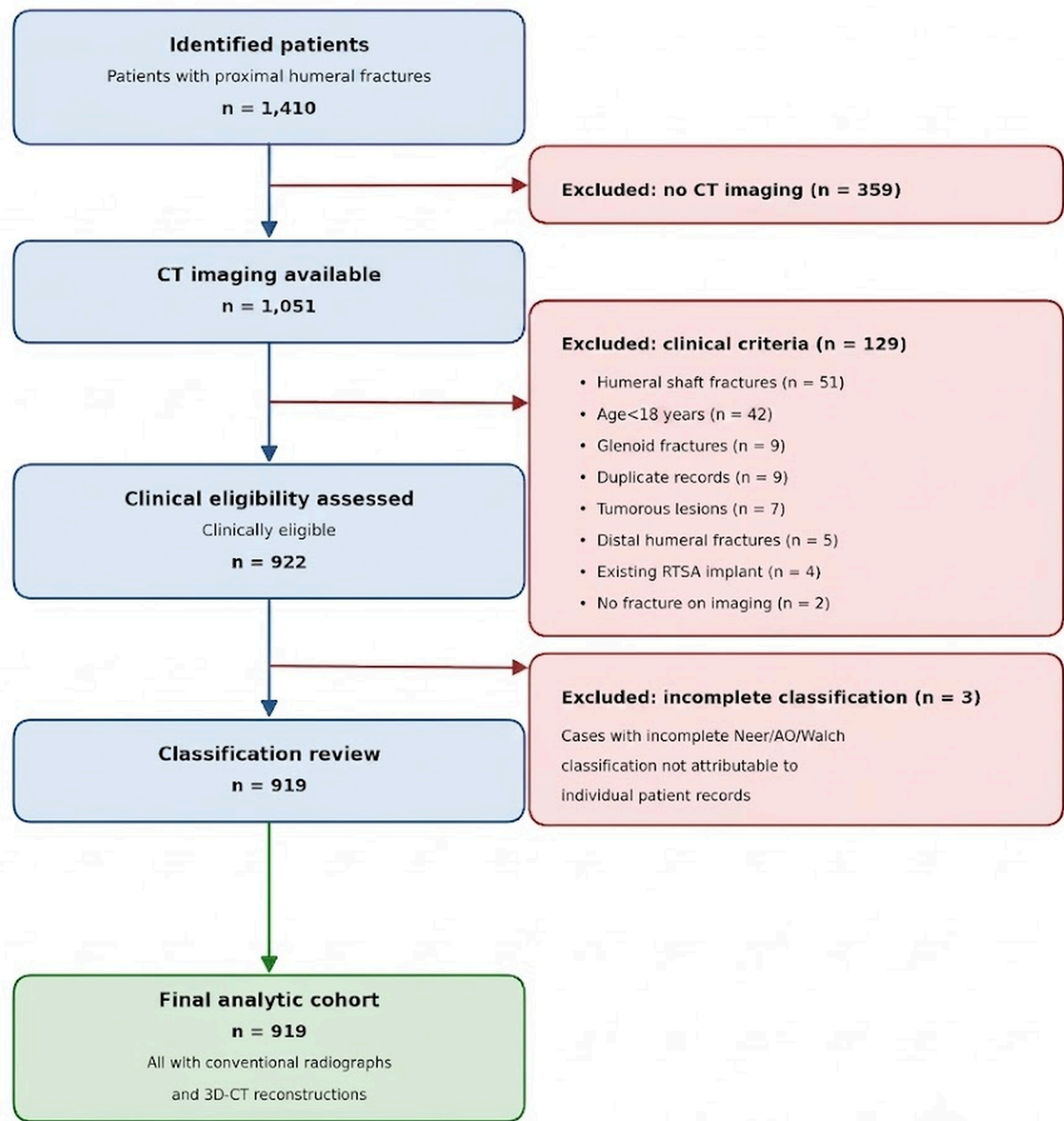


Figure 1

Flow diagram illustrating the patient recruitment and selection process. A total of 1410 patients initially identified with proximal humeral fractures were screened for eligibility. Patients were sequentially excluded based on the absence of requisite computed tomography (CT) imaging ($n = 359$) and predefined clinical criteria ($n = 129$), including concomitant shaft or distal humeral fractures, age under 18 years, pre-existing reverse total shoulder arthroplasty (RTSA), and pathological lesions. Following the exclusion of three further cases owing to incomplete classification data, the final analytic cohort comprised 919 patients, all with complete imaging datasets comprising both conventional radiographs and 3D-CT reconstructions suitable for comprehensive Neer, AO/OTA, and Walch classification

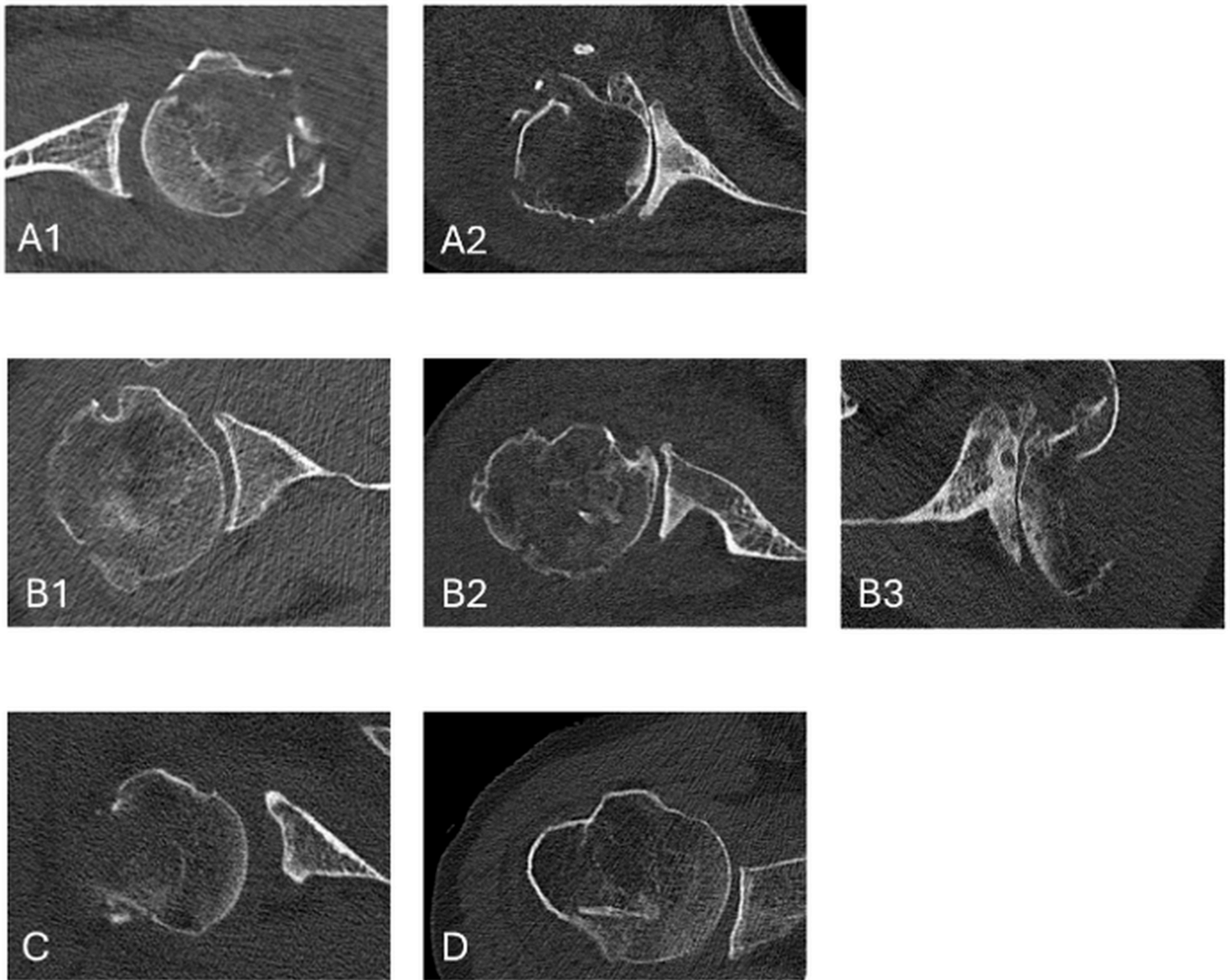


Figure 2

Representative axial computed tomography (CT) images illustrating the modified Walch classification (subtypes A1–D) in the setting of acute proximal humeral fractures

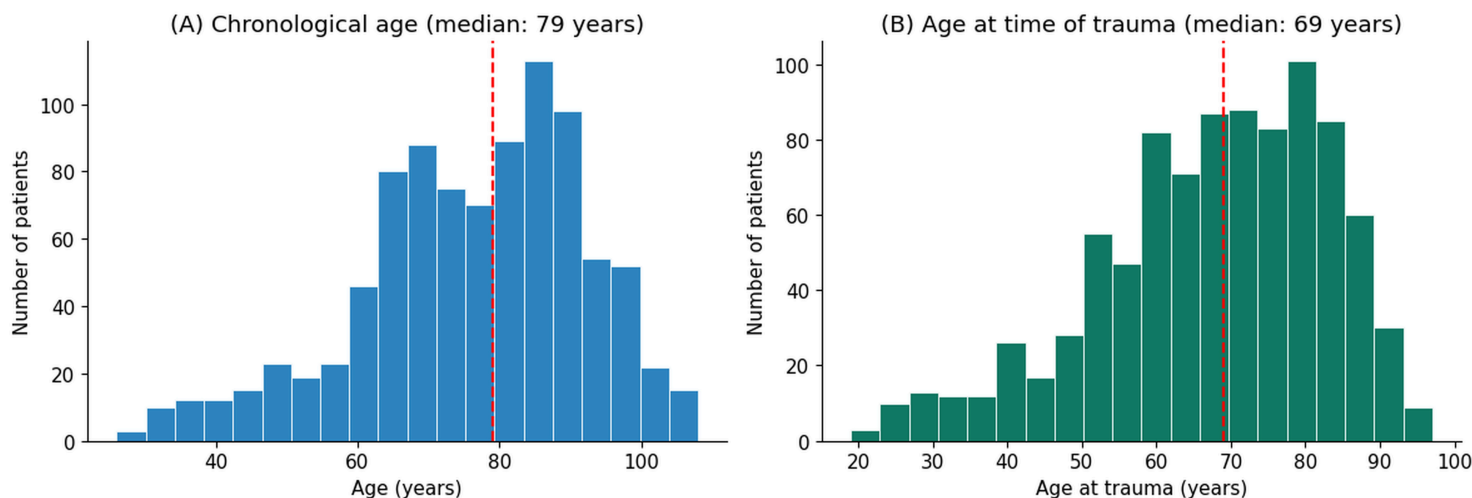


Figure 3

Age distribution of the study cohort. Histograms depicting (A) the distribution of chronological age (median: 79 years) and (B) the distribution of age at time of trauma (median: 69 years). Dashed red lines indicate median values

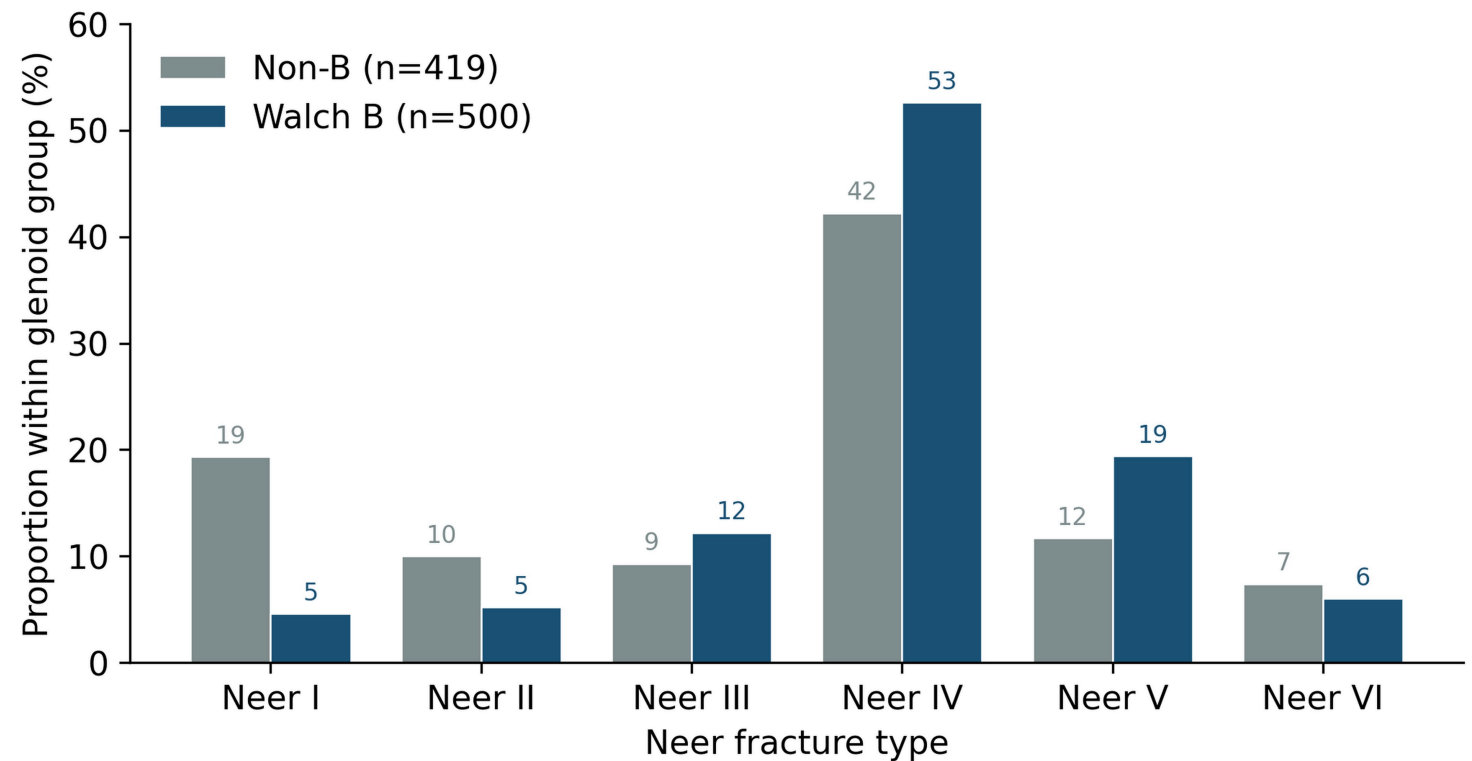


Figure 4

Distribution of Neer fracture types within the Walch B and non-B groups, expressed as the proportion (%) within each glenoid group. Posterior decentring (Walch B) is associated with a shift towards the tuberculum-involving patterns Neer IV and V

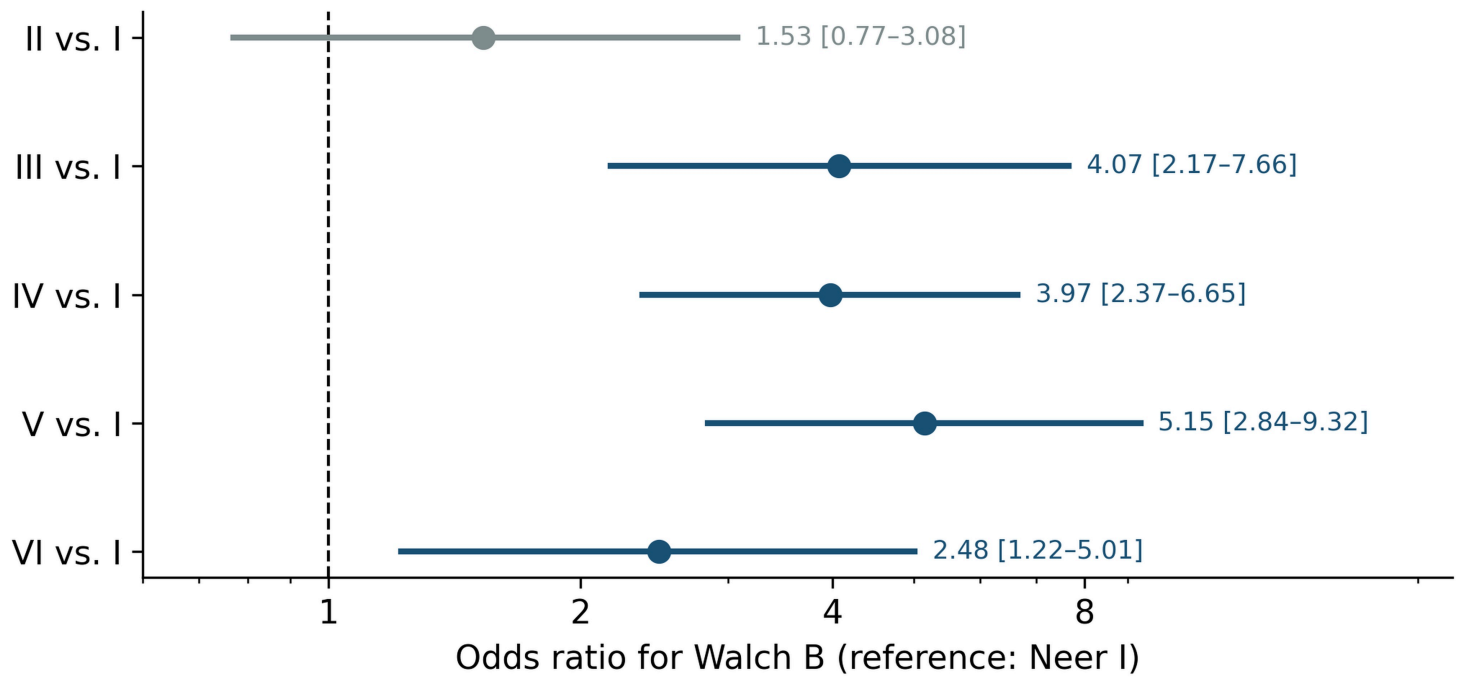


Figure 5

Multinomial logistic regression: adjusted odds ratios for Walch B morphology across Neer fracture types relative to Neer I (reference). Filled markers indicate $p < 0.05$. The effect is significant for the complex patterns Neer III–VI but not for the two-part Neer II pattern. Horizontal bars denote 95% confidence intervals; the dashed line marks an odds ratio of 1.0

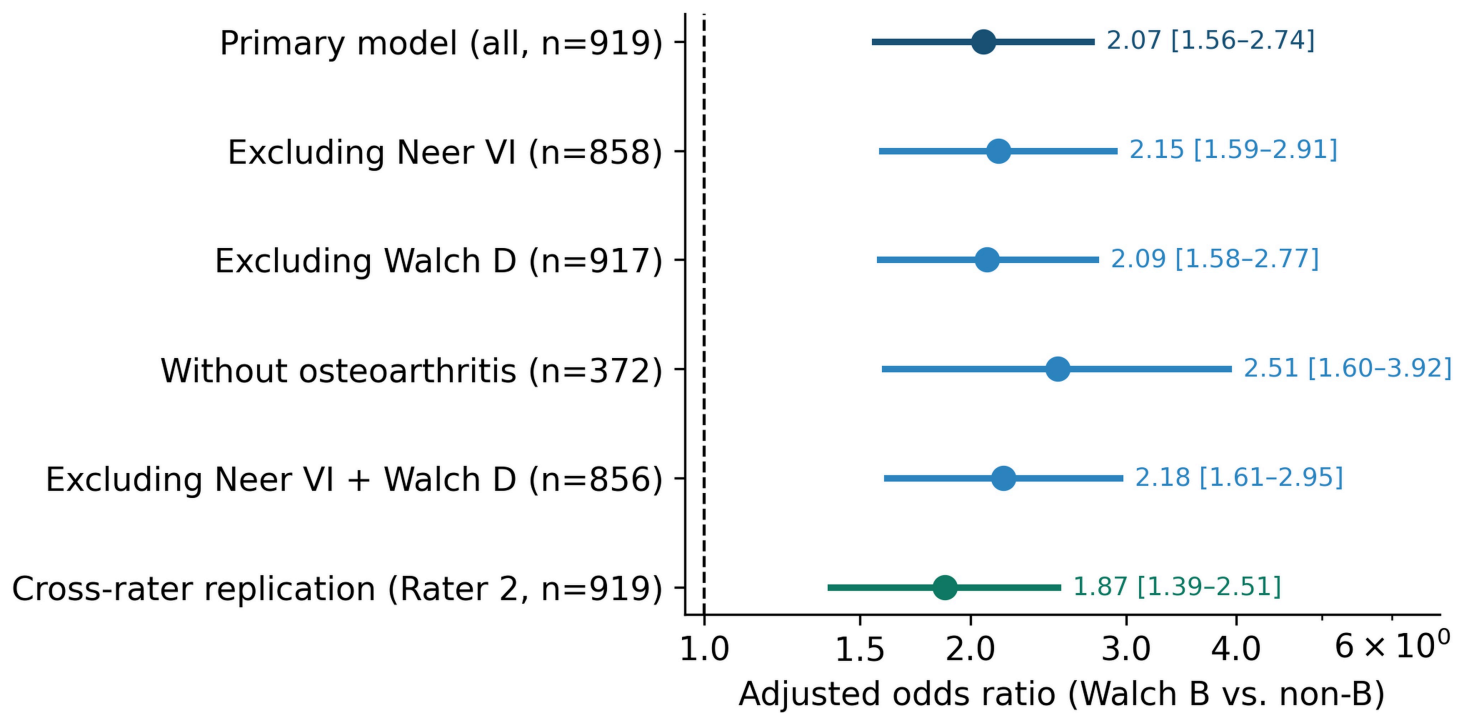


Figure 6

Forest plot of the adjusted odds ratio for Walch B morphology in the primary model, in each sensitivity analysis, and in the independent cross-rater replication. All estimates exclude an odds ratio of 1.0 (dashed line); horizontal bars denote 95% confidence intervals