A 3D comparison of humeral head retroversion by sex and measurement technique

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Abstract

Background: Accurate humeral head reconstruction during shoulder arthroplasty is partially dependent on correctly estimating and replicating native version. The present study evaluated the effects of sex and measurement technique on three-dimensional (3D) humeral version measurements made using the transepicondylar, forearm and flexion–extension axes.

Methods: Fifty-two full-arm computed tomography scans were converted to 3D models and geometry extracted to define landmarks and coordinate systems. An anatomic humeral head osteotomy plane was used to measure version relative to the three measurement techniques and compare between sexes.

Results: The measurement technique used had a significant affect ($p < 0.001$) on the resulting version measurement. The forearm axis technique consistently resulted in higher measured version compared to either the flexion–extension [mean (SD) males 9° (4°), females 13° (5°), $p < 0.001$] or the transepicondylar axes [mean (SD) males 8° (4°), females 11° (4°), $p < 0.001$]. Version in males was 7° greater than females when referencing either the flexion–extension [$p = 0.029$; mean (SD) males 37.7° (11°), females 30.4° (13°)] or transepicondylar axes [$p = 0.045$; mean (SD) males 39° (11°), females 32° (12°)].

Conclusions: The choice of measurement technique can affect the humeral version angle. These results are important because measuring version using the epicondyles pre-operatively, and subsequently the forearm intra-operatively, will result in approximately 10° under-retroverted osteotomy. For example, 0° neutral version cut during reverse arthroplasty measured referencing the forearm results in 10° anteverted osteotomy when referencing the distal humerus.

Keywords

3D measurement, cadaveric, computational, humeral head version

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Introduction

It has been suggested that, for the long-term success of anatomic shoulder arthroplasties, replication of the native anatomy, including version angle of the humeral head, is important. Intra-operatively, the angles dictate the orientation of the humeral head osteotomy, which is carried out via a manual free hand technique or with the use of a cutting guide. Both methods use the articular cartilage margin as a reference, with the aim of preserving the rotator cuff insertions. Deviation of the osteotomy plane from the native version and head–neck angles may result in non-anatomic humeral head reconstruction.

Native humeral head version has been previously reported with mean values in the range 18° to 33° .^{1,2}

The large variability of humeral head version has been associated with hand dominance,^{3,4} ethnicity,³ sports participation⁵ and age-related changes.⁶ Additionally, sex has been suggested to be a factor, although there is no consensus within the literature.^{3–5,7,8}

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Traditionally, version has been measured with two dimensional (2D) computed tomography (CT) slices or radiographic images.^{9–12} This has been shown to introduce errors as a result of a lack of standardized landmarks, as well as out-of-plane patient positioning that may cause projection errors.^{13–15} Three-dimensional (3D) version measurements have been shown to be more accurate and repeatable than 2D measurements.¹²

Three common measurement techniques exist to measure humeral head version: the transepicondylar axis, the forearm or ulnar axis and the anatomic elbow flexion–extension axis. The latter is commonly used in biomechanical studies and is defined as the line between the sphere-fit centre of the capitellum and the circle-fit centre of the trochlear groove.^{16,17} Pre-operatively, as in most anatomic studies, as well as the ISB standardized guidelines,¹⁸ the transepicondylar axis is most often used to measure version by selecting the medial and lateral distal humeral epicondyles. Intra-operatively, however, the forearm axis is most commonly referenced for version by surgeons.^{19–24} As such, most intra-operative humeral surgical cutting guides use an outrigger that references the forearm axis. However, it has been shown that the transepicondylar axis differs significantly from the forearm axis,¹⁰ which conceivably could lead to a discrepancy between pre-operative and intra-operative version measurements. Notably, there are no manufacturer technical manuals for the use of cutting guides in arthroplasty that reference the transepicondylar axis.^{19,21,22,24} Moreover, none of the aforementioned anatomic studies have considered version following humeral head osteotomy. Thus, the present study aimed to determine the differences in version by sex and by measurement technique, as it relates to prosthetic humeral head replacement.

Materials and methods

CT scans of 52 complete upper extremity cadaveric specimens (26 females: 17 left, nine right; 26 males: 14 left, 12 right) with all soft tissue intact were converted to 3D models using medical imaging software^{15,25} (Mimics, version 17.0; Materialise, Leuven, Belgium). Only specimens with clear demarcation of the anatomic head–neck junction were utilized; specimens with pathology, trauma and severe osteoarthritis were excluded. The bony geometry of the humerus, ulna and radius was extracted and separated using semi-automated segmentation. All elbows were placed at 90° of flexion using 3-Matic, version 9.0 (Materialise) to replicate the arm position during intra-operative version assessment. An anatomic humeral head osteotomy plane was virtually oriented by an experienced shoulder arthroplasty

surgeon (GSA) to coincide with the head–neck junction as previously reported.²⁶ This plane was used as the baseline for anatomic version angle. This technique has been shown to have very good repeatability and reproducibility; a previous study using the same landmarks had a minimum intraclass correlation of 0.87.²⁷

Coordinate systems

Each measurement technique used different anatomical features for reference. Thus, landmarks were located for defining a reference coordinate system specific to each measurement technique. However, because all three techniques define humeral version as being axial rotation about the humeral axis, the origin and humeral canal axis were common to all three coordinate systems. The centre of the trochlea circle fit defined the common origin as previously reported.²⁸ The humeral canal geometry was estimated as a circle fit using a least-squares algorithm (MATLAB 2015b; MathWorks; Natick, MA, USA) based on points placed on the inner cortical boundary at 20% and 45% of the length of the humerus, is also based on the approximate depth of an implanted humeral stem component. The vector joining the centres of these two circle fits, directed proximally, defined the common +Z-axis (canal axis). All three coordinate systems are shown in Figure 1. The placement of coordinate systems illustrated in Figures 1 and 2 represents the average male.

Transepicondylar coordinate system

The transepicondylar coordinate system was defined as reported previously.² Points were placed on the medial²⁹ and lateral epicondyles with placement verified by one of the senior authors (GSA). Using the same technique, Roberts et al.³⁰ found the SD was within 4% of the mean, producing a high degree of reproducibility. Previous studies have also found a high degree of repeatability using these landmarks.^{9,31} The vector from the lateral to the medial epicondyle was projected orthogonally to the canal axis, and defined as the +Y-axis (directed medially). The +X-axis was defined as the orthogonal cross product of the epicondylar and canal axes (Figure 1).

Anatomic flexion–extension coordinate system

The anatomic flexion–extension coordinate system was defined as reported previously.^{32–34} Points were placed on the articular surface of the capitellum and used to calculate a sphere fit. The +Y-axis was defined as the vector from the centre of the trochlea circle fit to the centre of the capitellar sphere fit (directed medially).

Figure 1. Coordinate systems for retroversion measurement. The origin and Z-axis were common to all three measurement techniques.

Figure 2. Retroversion angle defined by angle between projected osteotomy normal axis and Y-axis. Green, transepicondylar technique; blue, anatomic flexion–extension technique; red, forearm technique.

The +X-axis was defined as the orthogonal cross product of the flexion–extension and canal axes.

Ulnar coordinate system

The forearm coordinate system was defined as previously reported¹⁷ to replicate intra-operative arm positioning with the elbow flexed at 90°. The forearm long axis was defined by a vector from the centre of the proximal olecranon process (as defined previously)²⁹ to the most distal point on the ulnar styloid at the wrist (+X-axis directed distally). The +Y-axis was defined as the orthogonal cross product of the canal and ulnar axes.

Version measurement and calculation

Within each measurement coordinate system, the osteotomy plane normal vector (orthogonal to the osteotomy plane) was projected to the X-Y plane located at

the elbow (MATLAB). The angle between this projected osteotomy normal vector and the Y-axis was defined as the version measurement about the humeral canal axis (Figure 2).

Statistical analysis

Version measurements were statistically analyzed for overall effects using a two-way mixed-measures analysis of variance (ANOVA) with pairwise comparisons (SPSS, version 23; IBM; Armonk, NY, USA). The measurement technique was set as the within-subjects factor, with three levels (forearm, flexion–extension, and transepicondylar axes). Sex was a between-subjects factor.

Differences between sexes were analyzed using unpaired t-tests (SigmaPlot, version 11.0; Systat Software Inc., Erkrath, Germany) for each measurement technique. Within-sex differences were evaluated using a one-way repeated-measures ANOVA (SPSS) for each sex.

Results

The measurement technique used was found to have a significant effect on measured retroversion angle ($p < 0.001$) (Figure 3). Humeral head version measured referencing the forearm axis was a mean (SD) of 11° (5°) higher than the version measured using the flexion–extension axis ($p < 0.001$) and a mean (SD) of 10° (5°) higher than version measured using the transepicondylar axis ($p < 0.001$). Humeral head version measured by referencing the transepicondylar axis was a mean (SD) of 1° (3°) ($p = 0.001$) higher than referencing the

Figure 3. Humeral head version by measurement technique analyzed by two-way mixed measures analysis of variance for all 52 specimens. *Statistically significant ($p < 0.05$).

flexion–extension axis. Sex was found to have no significant effect on measured version ($p = 0.086$).

When males and females were analyzed separately (Figure 4), the effects of measurement technique on measured version persisted, with the exception of the flexion–extension axis and forearm axis techniques within the male group. For females, forearm version was a mean (SD) of 11° (4°) higher than transepicondylar version ($p < 0.001$) and a mean (SD) of 13° (5°) higher than flexion–extension version ($p < 0.001$). Version measured by the flexion–extension axis was a mean (SD) of 2° (2°) higher than the transepicondylar version ($p < 0.01$). Within the male group, ulnar version was a mean (SD) of 9° (4°) higher than flexion–extension version ($p < 0.001$) and a mean (SD) of 8° (4°) higher than the transepicondylar axis ($p < 0.0005$). There was no difference between the version measured by the flexion–extension axis and transepicondylar axis ($p = 0.256$).

The trends in Figure 4 are consistent with the relative differences among measurement techniques from nearly all individual specimens. In almost every specimen, version referencing the anatomic flexion–extension axis was lowest, and version referencing the forearm was highest (Figures 5 and 6).

Between sexes, when referencing the flexion–extension axis, the version in males [37.7° (11°)] was 7° greater than females [mean (SD) 30.4° (13°)] ($p = 0.029$). When referencing the transepicondylar axis, the version in males [mean (SD) 39° (11°)] was 7° greater than females [mean (SD) 32° (12°)] ($p = 0.045$). Interestingly, version measured by the forearm axis was not significantly different ($p = 0.376$) between males [mean (SD) 47° (11°)] and females [mean (SD) 44° (13°)].

Figure 4. Mean humeral head version by measurement technique within-sex analyzed by one-way analysis of variance. *Statistically significant ($p < 0.05$).

Figure 5. Male humeral head version by measurement technique. Version measured with the forearm technique was significantly greater than with the flexion–extension or transepicondylar axes ($p < 0.0005$), and this trend was demonstrated in all but three specimens.

Figure 6. Female humeral head version by measurement technique. Version measured with the forearm technique was significantly greater than with the flexion–extension or transepicondylar axes ($p < 0.0005$), and this trend was demonstrated in all but one specimen.

Discussion

The present study of humeral head version compared measurement techniques that are commonly used in clinical practice, as well as one that is typically used in biomechanics (i.e. the flexion–extension axis), in the context of a clinically relevant humeral head osteotomy for arthroplasty.

Version measurements made by the transepicondylar and flexion–extension axes were found to be within a mean (SD) 2° (2°) of each other, in agreement with the literature which indicates that these axes differ within 2° .^{28,35} Because 2° is small for a clinically relevant difference in version, we refer to the transepicondylar and flexion–extension axes together as the ‘distal humerus axis’. The version angle, as measured between the

osteotomy normal vector and the distal humerus axis, was 7° higher in males [mean (SD) 38° (11°)] than females [mean (SD) 31° (12°)] using a one-way ANOVA ($p=0.035$), as indicated by the blue–green markers in Figures 5 and 6. We found that version of the humeral head osteotomy plane was significantly greater when measured by the forearm axis than by the distal humerus axis; on average, 12° for females and 8° for males on a within-subject basis ($p=0.002$) (Figure 7). Additionally, the carrying angle, defined between the ulnar long axis and the vector perpendicular to the distal humerus axis, was 4° higher for females [mean (SD) 12° (4°)] than males [mean (SD) 8° (4°)] ($p=0.001$).

These results have implications on the use of osteotomy cutting guides, many of which rely on the forearm axis for reference.^{21–24} On average, and combining sexes, our forearm-based versions measured 10° higher (i.e. more retroverted) than when based on the distal humerus (as in some computer-based pre-operative planning software). This can cause a notable disagreement depending on whether one begins measuring at the pre-operative or intra-operative stage.

Recognizing that most reported native humeral version measurements reference the distal humerus, a sex-specific correction offset should be added to the distal humerus based version measure to translate into a forearm-based version value. For example, if a surgeon wishes to replicate a 30° native version (relative to the distal humerus) in a male patient, an 8° correction

offset should be added to the 30°, resulting in a 38° humeral head osteotomy referenced off the forearm. Likewise, for a female patient, a 12° correction offset should be added to the distal humerus version to achieve the true version measured relative to the forearm.

With the high variability of reported humeral version, an osteotomy performed at the population average value, even if it has been corrected to the forearm based value, may not match a patient's native version and may lead to poorer outcomes. Although it is not typical to image the entire humerus, if surgeons wish to measure their patients' true version, a CT scan of the shoulder that includes a few limited axial slices at the epicondyles is all that is required to perform a patient-specific version measurement.

Also, as it pertains to reverse total shoulder arthroplasty, many surgeons recommend conducting a 'neutral' cut of the humeral head. If the method used to determine 'neutral' intra-operatively is the forearm axis, as it is in most technical manuals and surgical guides, this results in a true humeral version cut of approximately 10° of anteversion. Additionally, many clinical outcome studies on reverse and anatomic shoulder arthroplasty report the version that the humeral component was implanted in, although they do not mention the measurement method used to determine version. We recommend that, if studies report humeral component version, they should also report the method used to determine the version (i.e. transepicondylar axis or forearm axis).

Our results showed significant sex differences in some measurements. Measuring version relative to the distal humerus revealed that males have greater native axial torsion of the humerus compared to females, which manifests as 7° greater version. This result agrees with the 5° difference found by Matsumura et al.,⁷ who also used a CT-based measurement referencing the transepicondylar axis. It should be noted that the absolute torsion measurements observed by Matsumura et al.⁷ were significantly lower than those observed in the present study. This is likely a result of the fact that their proximal humerus definition was different than ours (because they were not measuring osteotomy version) and also because those authors utilized 2D within-slice measurements, in contrast to our full 3D measurement methods. Still, the similar measured sex difference using the same reference axis definition is confirmation of our result because it was a relative measure in both studies, and thus independent of the datum definition.

Although our results showed that males have significantly greater retroversion as a result of the increased humeral torsion when measured by the distal humerus techniques, it is interesting that we observed no sex

Figure 7. Male and female humeral head version discrepancy between forearm and distal humerus axis techniques. Axial view of the humerus (grey) with the ulna (yellow) flexed at 90° (right arm shown). All axes and lines are projected onto the two-dimensional transverse plane as viewed, in which also lies the forearm long axis. Placement of axes is based on the mean male and female specimens, and shaded fan regions represent 1 SD.

*Statistically significant ($p < 0.05$).

difference in version measured by the forearm axis (Figure 7). Indeed, humeral head cutting guides, which reference the forearm axis, are sex neutral, and there is no literature indicating that sex is a factor in version resulting from a cutting guide. From our observations, it is apparent that this paradox is the result of a balanced relationship between humeral torsion (males > females) and carrying angle (females > males). Our results indicate that, at 90° of elbow flexion, a greater carrying angle in females was matched by a reduced humeral torsion, and vice versa for males, which results in a balance when measuring version from the humeral head to the forearm axis. This conclusion is in stark contradiction with the established understanding that carrying angle is zero at 90° elbow flexion;^{17,36,37} however, it is important to also regard the biomechanics and anatomy studies that have measured carrying angle using the distal humerus as reference, rather than the forearm axis.^{28,32,38,39} It is known in the biomechanics community that carrying angle measurement is affected by the choice of reference axis; first reported by An et al.³⁹ Ferreira et al. confirmed experimentally that carrying angle, when measured as forearm relative to the humeral flexion axis, is 6° valgus at 90° of elbow flexion, even though it is near 0° when measured relative to the humeral long axis.⁴⁰ This supports our observations that a valgus carrying angle sex difference, in concert with the sex-specific humeral torsion, is responsible for the apparent lack of a sex effect on humeral head version when measured relative to the forearm axis. Thus, even though male and female version is a similar magnitude, they are apparently shifted relative to one another, as illustrated in Figure 7. This shift is not apparent if only using a cutting guide, and thus can lead to an unexpected version, especially in females, which have a greater carrying angle.

The 3D measurement method employed in the present study is a strength because it eliminates projection errors inherent with 2D studies.^{2,4,5,7,8,10,41,42} Also, clinical relevance was improved by basing the coordinate systems on common clinical landmarks and replication of the surgical humeral head osteotomy technique. Limitations included uncertain hand dominance and an imbalance of left–right arms in the female group. Males are 1.25 times more likely (by a mean weighted odds ratio) to be left-handed than females,^{43,44} and so the female group likely had a lower proportion of dominant arms compared to the male group. *In vitro* scans were obtained and 90° elbow flexion was produced manually, thus it is possible that *in vivo* scans with active joint position may have produced a more congruous ulnohumeral placement.⁴⁵ Additionally, some bony landmarks are subjective to operator selection. Moriguchi et al.⁴⁵ showed that inter-rater

measurements for the ulnar styloid were within 5 mm and lateral humeral epicondyles were within 7 mm.

When version is measured through imaging using the distal humerus, then this is a measure of humeral torsion. Because of the variations in humeral version between measurement techniques, a correction offset to convert between techniques is recommended when evaluating patients. The results of the present study indicate that the magnitude of the correction offset should be different for males and females.

The use of axis definitions primarily used in biomechanics studies, together with a clinically relevant humeral version measurement, has led to an interesting observation. Our interpretation is that there may be an elegant morphological relationship between carrying angle and humeral torsion (consequently version), which may play an important role in upper extremity function and range of motion. Our results indicate that this relationship is sex-specific.

Declaration of Conflicting Interests

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Ethical Review and Patient Consent

None required because all specimens were cadavers.

Level of evidence

Anatomic Study.

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