Determination of humeral inclination in stemless shoulder arthroplasty using plain radiographs

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Abstract

Plain radiographs of the shoulder are routinely used to assess implant orientation after shoulder arthroplasty. Recently, humeral inclination has come into focus especially in reverse stemless shoulder arthroplasty. But, in X-ray projections not exactly parallel to the base of the humeral component, the humeral inclination angle cannot be determined precisely. Therefore, we established a mathematical algorithm to calculate the humeral neck shaft angle and counterchecked the formula using plain radiographs of a sawbone model containing a humeral head prosthesis. With increasing angles of retroversion, the base of the humeral component forms an ellipse in plain radiographs. Knowing the width and length of the ellipse as well as the inclination angle in a plain radiograph, the exact inclination angle can be determined using the equation reported below. Thus, independent from the viewing angle or angle of retroversion, the inclination angle of a stemless humeral head implant can be estimated with an accuracy of ±1.5-degree deviation. The algorithm proposed may be the basis for further research on the impact of humeral inclination in stemless shoulder arthroplasty.

Materials and Methods

Theoretical mathematical deliberations were undertaken for determination of the humeral neck shaft angle (humeral inclination) when looking at a prosthetic humeral head implant at an angle. The angle \( \theta \) between the orthogonal plane of the head component base (circle) and the viewing direction is given by

\[
\theta = \arccos \left( \frac{a}{b} \right),
\]

where \( a \) and \( b \) denote the radii of the minor and major axes of the projected ellipse. An equivalent formula was previously given by McLaren for the angle \( \beta \) between the bounding plane of the hemisphere and the viewing axis (Figure 2). Consider an orthogonal coordinate basis \( \{e_x, e_y, e_z\} \) with the unit vectors \( e_x \) and \( e_y \) pointing in distal direction of the humerus and in the viewing direction, with the unit vector \( e_z \) chosen to comply with the right-hand rule. Let \( x \) denote the unit vector in direction orthogonal to the plane of the prosthetic head’s base. Then the inclination is the angle \( \alpha \) between \( x \) and \( e_z \) as visualized in Figure 3.

In terms of corresponding spherical coordinates, the azimuth \( \phi \) of \( x \) is the projected angle between the base of the humeral component and the humerus pointing in distal direction, which is the apparent inclination measured in the radiograph, whereas the polar angle of \( x \) is exactly the angle \( \theta \) between the viewing axis and the joint axis computed in (1). In particular, the first component \( x_x \) of the unit vector \( x \) is given by \( x_x = x \cdot e_z \) for the dot product between \( x \) and the basis vector \( e_z \).
\[
\cos(\alpha) = \cos(\theta) = x \cdot e_1 = x_1 = \sin(\theta) \cos(\phi) = \sin \left( \arccos \left( \frac{a}{b} \right) \right) \cos(\phi) \\
= \sqrt{1 - \left( \frac{a}{b} \right)^2} \cdot \cos(\phi).
\]

Thus, the inclination \( \alpha \) is given by
\[
\alpha = \arccos \left( \sqrt{1 - \left( \frac{a}{b} \right)^2} \cdot \cos(\phi) \right). 
\tag{2}
\]

If the x-ray beam is perpendicular to the humeral shaft axis, the above formula (2) can be applied to calculate the inclination of a prosthetic humeral component on plain radiographs.

The accuracy of the theoretical calculation of humeral inclination was counterchecked by a radiographic model of the humerus. A sawbone model of a left humerus was used for the radiographic study. The humeral head of the sawbone was resected and a stemless humeral head prosthesis was inserted at the anatomical neck (Affinis short, Mathys AG, Bettlach, Switzerland). The sawbone model was installed on a tray using the distal part of the humeral canal for fixation. A wooden peg was positioned onto the distal humerus serving as a pointer for measuring rotation, parallel to the retroversion of the implant (Figure 4). The plane parallel to the humeral cut was determined under fluoroscopic control, when the base of the humeral head implant projected as a line. This position was defined as 0 degrees. Starting at 0 degrees, inclination angles were calculated from the humeral head prosthesis. A prosthetic humeral component was inserted at the anatomical neck (b) Total Evolutive Shoulder System (TESS), Biomet, Warsaw, IN, USA.

**Table 1. Aberration of calculated inclination angle (CIA) using the formula in (3) from real inclination angle (RIA).**

| Retroversion angle | Width of ellipse (a) | Length of ellipse (b) | Measured inclination angle (MIA) | Real inclination angle (RIA) | Calculated Inclination angle (CIA) | Aberration from real inclination angle |
|-------------------|---------------------|----------------------|---------------------------------|------------------------------|-----------------------------------|-------------------------------------|
| 0                 | 0                   | 7.94                 | 129.6                           | 129.6                        | 129.6                             | -                                   |
| 5                 | 0.56                | 7.84                 | 129.7                           | 129.6                        | 129.57                            | -0.02                               |
| 10                | 1.29                | 7.84                 | 130.0                           | 129.6                        | 129.35                            | -0.25                               |
| 15                | 2.12                | 7.99                 | 130.4                           | 129.6                        | 128.67                            | -0.93                               |
| 20                | 2.68                | 7.93                 | 131.0                           | 129.6                        | 128.30                            | -1.30                               |
| 25                | 3.02                | 8.00                 | 131.4                           | 129.6                        | 127.76                            | -1.84                               |
| 30                | 3.49                | 7.97                 | 133.3                           | 129.6                        | 128.07                            | -1.53                               |
| 35                | 3.98                | 7.93                 | 134.7                           | 129.6                        | 127.47                            | -2.13                               |
| 40                | 4.36                | 7.95                 | 137.7                           | 129.6                        | 128.21                            | -1.39                               |
| 45                | 4.68                | 7.93                 | 139.9                           | 129.6                        | 128.13                            | -1.47                               |
| 50                | 4.82                | 7.93                 | 140.2                           | 129.6                        | 127.59                            | -2.01                               |
| 55                | 5.10                | 7.93                 | 141.8                           | 129.6                        | 127.00                            | -2.60                               |
| 60                | 5.28                | 7.95                 | 145.6                           | 129.6                        | 128.09                            | -1.51                               |
| 65                | 5.46                | 7.95                 | 149.3                           | 129.6                        | 128.68                            | -0.92                               |
| 70                | 5.64                | 7.57                 | 158.0                           | 129.6                        | 130.30                            | +0.70                               |

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degrees, x-rays of the sawbone model were taken with increasing angles of retroversion. An x-ray was taken every 5 degrees between 0 and 70 degrees of retroversion.

**Results**

At 0 degrees of retroversion the ‘real inclination angle’ (RIA) of the sawbone model measured 129.6 degrees. With increasing angle of retroversion, the base of the humeral head prosthesis projected as an ellipse on plain radiographs (Figure 4). The ellipse with its two axes was delineated in each x-ray projection. Humeral inclination was measured using one axis perpendicular to the base of the ellipse and the other axis parallel to the humeral shaft. The angle formed between the two axes was named ‘measured inclination angle’ (MIA). With increasing angles of retroversion, the ellipse gained in width, whereas the length did not significantly change. With higher angles of retroversion, the MIA was found to increase up to 158.0 degrees at 70 degrees of retroversion (Table 1).

Knowing the width $a$ and $b$, length of the projected ellipse as well as the MIA ($\phi$), the RIA could be calculated using the following formula:

$$\arccos\left(\frac{1 - \left(\frac{a}{b}\right)^2}{\cos(\phi)}\right). \quad (3)$$

**Discussion**

Plain radiographs of the shoulder are routinely used to assess implant positioning in total shoulder arthroplasty, but measuring humeral inclination may be inaccurate due to projectional error. This poses a real challenge when stemless humeral implants are used, which enable placement of the humeral component independent from the humeral shaft axis. In contrast to stemmed humeral implants the surgeon is now free to choose inclination of the humeral implant.\(^{1,9-14}\) The described method for measuring anteversion of an acetabular cup from standard anteroposterior radiographs\(^{15-17}\) could not be easily transferred to the shoulder, since the base of the humeral component forming an ellipse is affected in two planes when the humeral head is rotated.

In our study, we demonstrate that the measured humeral inclination angle depends on the viewing- and retroversion angle of the implant on x-rays and the estimated value erroneously increases with advancing retroversion angle. We observed, that the apparent humeral inclination, as measured on plain radiographs, corresponds to the true humeral inclination when humeral retroversion does not exceed 25 degrees. Humeral inclination only increased from 129.6 degrees in neutral rotation to 131.4 degrees at 25 degrees of retroversion.

![Figure 3. Spherical coordinates used to compute the inclination $a$, showing the azimuth $\phi$ and the polar angle $\theta$ as well as the head’s circular base and its projection to the viewing plane.](image)

![Figure 4. a) Radiographic setup: sawbone with Affinis short humeral head replacement installed on a tray with a pointer for measurement of rotation. b) Anteroposterior radiographs of the sawbone in 20 degrees (b) and 45 degrees of retroversion (c). The base of the prosthetic component projects as an ellipse (blue), orange dotted lines demonstrate measured humeral inclination (MIA).](image)
Variability amounted to less than 2 degrees and could also be due to inaccuracy when measuring humeral inclination. However, for exact determination of humeral inclination on plain radiographs, an algorithm is required which generates the real inclination angle (RIA) independent of the viewing angle/retroversion angle. With varying angles, the base of the humeral component forms an ellipse with two axes. Knowing the minor and major axes of the ellipse as well as measuring humeral inclination (MIA), the real inclination angle (RIA) can be calculated accurately. In our sawbone model the calculated inclination angle (CIA) varied between 127.00 and 130.30 degrees. Thus, the maximum aberration of the CIA from the RIA was 2.6 degrees. This variation can be attributed to inaccuracy when determining the axes of the ellipse and the MIA. With the formula given (3) the mean deviation of the CIA was less than 1.5 degrees (1.32±0.71 degrees).

Our algorithm was counterchecked using an anatomical humeral head prosthesis. The basis for calculating the real inclination angle consists of measuring the apparent humeral inclination and the axes of the ellipse in plain radiographs. These principles do not only apply to anatomical humeral head components, but also for reverse implants since the base of a reverse humeral head prosthesis in plain radiographs. These forms an ellipse with two axes. Knowing the minor and major axes of the ellipse as well as measuring humeral inclination (MIA), the real inclination angle (RIA) can be calculated accurately. In our sawbone model the calculated inclination angle (CIA) varied between 127.00 and 130.30 degrees. Thus, the maximum aberration of the CIA from the RIA was 2.6 degrees. This variation can be attributed to inaccuracy when determining the axes of the ellipse and the MIA. With the formula given (3) the mean deviation of the CIA was less than 1.5 degrees (1.32±0.71 degrees).

Our algorithm was counterchecked using an anatomical humeral head prosthesis. The basis for calculating the real inclination angle consists of measuring the apparent humeral inclination and the axes of the ellipse in plain radiographs. These principles do not only apply to anatomical humeral head components, but also for reverse implants since the base of a reverse implant also forms an ellipse with increasing angles of retroversion (Figure 1).

Thus, using the algorithm introduced, the inclination angle of the humeral component in anatomic and reverse shoulder arthroplasty can be determined precisely.

Our algorithm may be the basis for further research on the effect of humeral inclination in stemless shoulder arthroplasty.

Limitations

We are aware that it is not possible to distinguish retroversion from anteverision of the humeral head prosthesis in plain radiographs. Nevertheless, assuming correct patient positioning and x-ray projection as well as correct implant positioning anteverision is very unlikely since anatomical studies showed that humeral head retroversion averages around 30 degrees. Furthermore, differentiation of retroversion vs. anteverision has no adverse effect on the calculated inclination angle.

Conclusions

The mathematical algorithm introduced (3) can serve as an important tool for precise determination of humeral inclination in stemless shoulder arthroplasty. Independent from the viewing angle or angle of retroversion the humeral neck shaft angle can be calculated ±1.5-degree deviation.

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