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Attachments of muscles as landmarks for implantation of shoulder hemiarthoplasty in fractures

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Background: The attachments of muscles and the position of the humeral head are important for a good functional outcome of shoulder hemiarthroplasties after displaced fractures of the proximal humerus. Deviations in the attachments and changes in their spatial position with respect to the humeral head during surgical reconstruction change the biomechanics and reduce the range of motion of the should joint postoperatively.
Methods and Results: We used 198 humerus preparations and using 3-dimensional analysis measured the angular relationships between the humeral head axis and medial margin of the greater tuberosity (11.9° ± 9.1°), lateral margin of the lesser tuberosity (48.0° ± 7.8°), and the crest of the greater tuberosity (27.1° ± 9.6°).
Conclusion: This study provides average values of the positions of the greater and lesser tuberosities with respect to the humeral head axis. We show that the greater and lesser tuberosities are more reliable than the transepicondylar line for reconstruction of humeral head retroversion.
Level of Evidence: Basic Science.

Keywords: Shoulder arthroplasty; humeral head retroversion; transepicondylar line; greater tubercle; lesser tubercle; crest of greater tubercle

The accuracy of reconstruction of a severe fracture of the upper humerus has a significant impact on the resulting function of the shoulder joint. For example, fractures requiring arthroplasty of the shoulder joint followed by reconstruction of fragments with rotator cuff attachments often lead to angular deviations of fragment position, limiting the range of motion of the shoulder joint.

The positions of the humeral head and the attachments of the rotator cuff are essential for the proper function of the shoulder joint implant. Currently, the transepicondylar line of the distal humerus is most often used to adjust position of the humeral implant shaft. Retroversion of the humeral head during implantation usually ranges from 20° to 35°. However, the variability of the actual humeral head retroversion is rather extensive (-8°-50°),[5,17,18] which can lead to significant deviation of the implant from the original values.

Anatomical landmarks of the proximal humerus could guide reconstruction efforts after fractures. The bicipital groove is an often used landmark; its anatomical position, course, and use in adjusting the retroversion of the head of implant were repeatedly described.[2,3,8,11,14] The groove is defined as the ‘‘deepest’’ part, ie, the area closest to the axis of the proximal humerus. However, identification of the groove during trauma is often difficult, when fragments of

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metaphysis are dislocated and the part of the groove suitable for stem positioning is distal to the surgical neck.

In trauma with multiple fragments of the proximal humerus, it is necessary to reconstruct fragments of the greater and lesser tuberosities with attachments of the rotator cuff. Achieving precise and strong reconstruction is important for a good functional outcome of the shoulder joint.

In this study, we provide statistical analysis of the positions of the greater and lesser tuberosities and the crest of greater tuberosity with respect to the humeral head axis. Our goal was to determine whether positions of tuberosities and crest of greater tuberosity correlate better with the position of humeral head than the transepicondylar line, and, therefore, should be more suitable for adjustment of the prosthesis during reconstruction of the humeral head retroversion.

Materials and methods

For the purpose of this study, we used 198 dry preparations of humeral bones (99 left, 99 right) from the collection of the Institute of Anatomy, Charles University, Prague. Only bones with closed growth plates, no morphological deviations, and no signs of degenerative or post-traumatic alterations were included in the study. No information about sex or age of the preparations was available.

Bone measurements were conducted in a custom made steel frame with a movable slider. Bones were positioned in the frame with the proximal axis of the diaphysis parallel to the longer axis of the frame and the transepicondylar line (EP) parallel to the table surface (x axis). Positions of landmarks on the bones were determined using pointers attached to the slider in a manner similar to orthopaedic navigation systems. The surface of each bone was copied gradually by moving the slider in the proximo-distal direction with pointers marking specific anatomical landmarks (see below). Thus the measurements were obtained in a manner similar to measurements obtained from axial MRI or CT scans.

The structures of interest were identified in transverse sections in points that either described the spatial location of the structure well or were easily identifiable during a standard (deltoideopectoral) approach to the shoulder joint.

Pointer positions were photographed with as digital camera (Canon 350D, Lens Sigma). The axis of the camera was aligned with the axis of the frame and the focal length was set to 70 mm. The camera was positioned 3 m away from the frame to avoid refractive errors. Scanned photographs were further evaluated using methods described below.

Several structures of interest were identified on each bone (Figures 1, 2).

Greater tuberosity (GT) was defined by its medial margin, ie, the margin that continues into the bicipital groove. Three points were identified on the greater tuberosity (in the upper, middle, and lower thirds) so that they included the whole metaphyseal portion of the tuberosity.

Lesser tuberosity (LT) was defined by its lateral margin, which continues into the bicipital groove. Here we identified 2 points in the upper and lower halves, such that the positions of the points corresponded to the middle and lower parts of the head in transverse sections.

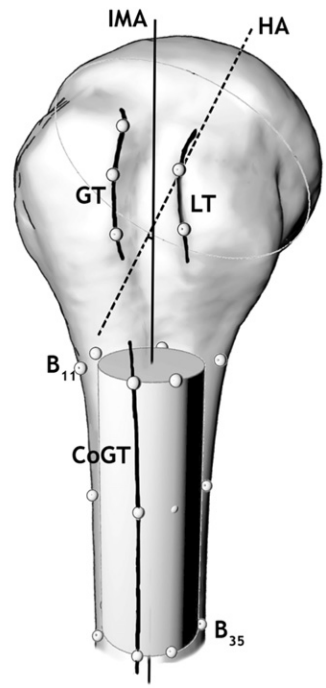

Figure 1 Regions of interest on a right proximal humerus. GT, greater tuberosity; LT, lesser tuberosity; IMA, intramedullary axis; HA, axis of the humeral head; CoGT, crest of the greater tuberosity; B11,…,B35, points defining the proximal shaft of the humerus.

Proximal shaft of humerus was demarcated using 3 groups of 5 points (Figure 1) in the proximo-distal direction from the area where metaphysis changed into the proximal diaphysis all the way towards the deltoid tuberosity. Locations of the points were selected outside muscle attachments (the crest of greater and lesser tuberosities) in regular intervals on the diameter of the humerus. Three points (1 from each group) were located in the bicipital groove. The length of the demarcated proximal diaphysis was approximately 45-55 mm. Three points were identified on the crest of the greater tuberosity (CoGT): on the surgical neck, in the middle third, and in the distal part of the crest, respectively. Anatomical neck of the humeral head was first marked by pencil in the area where spongiform bone changes into smooth subchondral bone. Then, 6 points were identified on the anatomical neck at regular intervals, so that pairs of points were situated in the upper, middle, and lower thirds of the head (Figure 2).

Coordinates of all points were expressed in the Cartesian coordinate system with x and y axes in transverse planes (coordinate origin corresponded to the upper left corner of the picture), and z axis in proximo-distal direction parallel with the long axis of the frame. Afterwards, 2 virtual axes defining positions of humeral head and proximal diaphysis for shoulder hemiarthroplasty were calculated.

Intramedullary axis of the proximal shaft (IMA) was defined as the longitudinal axis of a cylinder defined by the 15 points identified distally from the surgical neck (see above). The cylinder was fit to an array of the 15 points, such that no points were inside the cylinder.

Axis of the humeral head (HA) was defined as the line perpendicular to the anatomical neck plane and passing through the central point of the anatomical neck. The 6 points identified on the anatomical neck were fit with the anatomical neck plane, so as

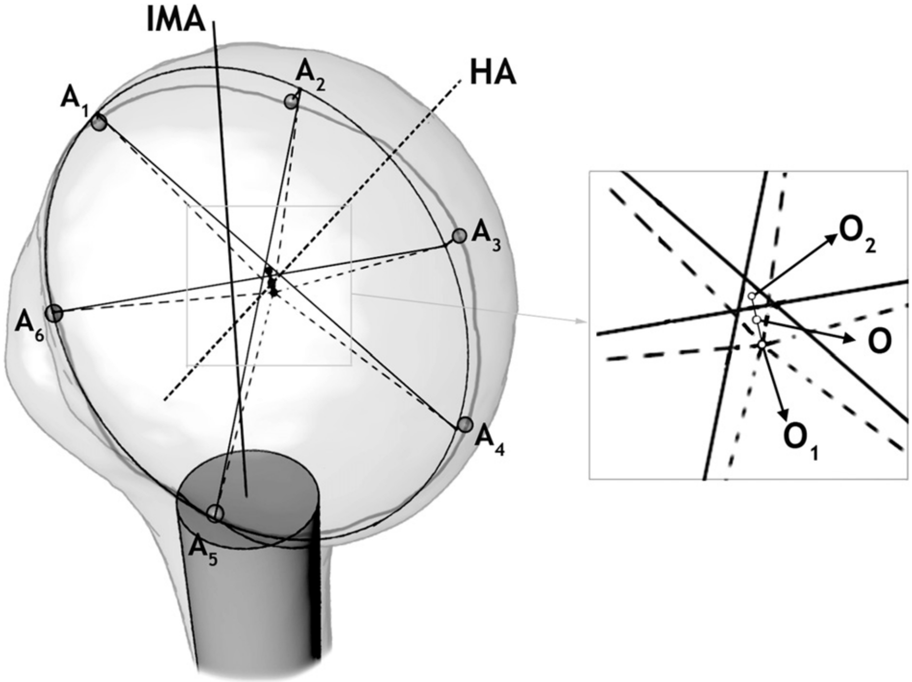

Figure 2 Six demarcating points on the anatomical neck (A1-A6) and central point (O) were used to determine the humeral head axis (HA). *IMA*, intramedullary axis.

to minimize the distance between the points and the plane. Projections of the six points on this plane were further used to compute the position of the central point. The central point was computed using 2 independently determined points due to irregular shape of the anatomical neck.

The central point was computed using 2 independently determined points. The first point (O_1) at the anatomical neck plane was computed as having the minimal distance from the 6 projections. To compute the second point (O_2), opposite projections (A'_1-A'_4, A'_2-A'_5, A'_3-A'_6) were connected, and the intersecting connecting lines formed a triangle in the middle of the anatomical neck plane. The O_2 point was then computed as the center of the triangle. The central point was then determined as the midpoint of the line connecting O_1 and O_2 (Figure 2).

Axis of the humeral head was defined as a line perpendicular to the anatomical neck plane and passing the central point (O). The axis defined the axis of the head of an implant in our model.

Finally, we determined spatial relationship between the basic axes (IMA, HA) and the identified anatomical landmarks (GT, LT, and CoGT). Angular measurements were performed in 2 transverse planes (humeral head and surgical neck planes) and used the projection of humeral head axis (PoHA) onto these planes.

To define the humeral head plane, a point P on intramedullary axis (IMA) having the shortest distance from the humeral head axis was first computed. The humeral head plane was then defined as the transverse section perpendicular to IMA and containing the point P (see below for details). In this plane, we measured 3 angles. GT and LT angles were defined as the angles between PoHA and lines connecting IMA and GT or LT, respectively; analogously, we measured EP angle (‘‘head retroversion angle’’) between PoHA and the transepicondylar line (Figure 3).

Surgical neck plane was defined as the transverse plane perpendicular to IMA where the metaphysis changes into the diaphysis (the most proximal point of GoGT). CoGT angle was defined as the angle between PoHA and the line connecting CoGT and IMA (Figure 3).

To control for accuracy of our measurements, we calculated 2 control parameters. The first parameter was computed as the spatial distance between IMA and HA (ie, the length of the line segment perpendicular to both axes) and corresponded to the offset of the neck of an implant at the point of anchoring. The second parameter evaluated the precision of bone position, and was computed as the angle between IMA and the longitudinal axis of the measuring frame.

All measurements are shown as means and standard deviations unless stated otherwise.

Statistical method

We used ratios of variances of angular measurements to compare the accuracy of the head axis position estimates. The ratios were first computed for left and right side separately and then pooled together.

The variance σ_A^2 (A = EP angle, GT angle, LT angle or CoGT angle) estimates the random deviation of the head axis position (the real position of the head axis is unknown during surgery) from the position expected (mean) in the population. The σ_A^2/σ_B^2 (A,B = EP angle, GT angle, LT angle or CoGT angle) ratio estimates the reduction of variance when estimating the position based on indicator B compared to indicator A.

Statistical significance of improvement for each pair of indicators (LT angle vs EP angle, GT angle vs EP angle, CoGT angle vs EP angle) was calculated using the χ^2 test for ratio of variances. Based on χ^2 distribution we calculated a 95% confidence interval for each ratio.

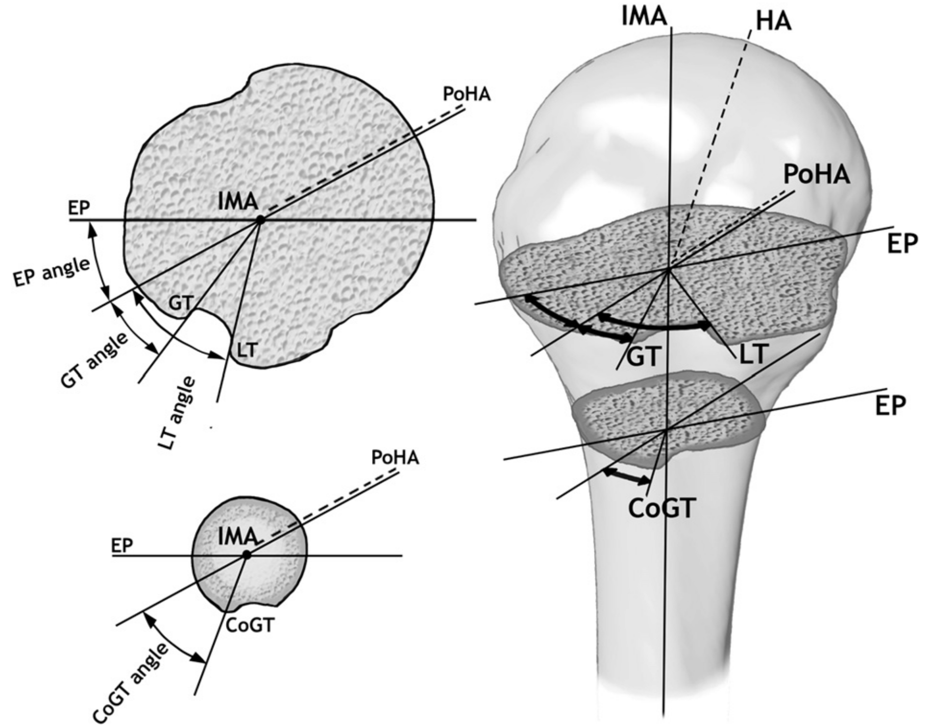

Figure 3 Angles of interest in proximal humerus were measured in the humeral head plane (top left) and in the surgical neck plane (bottom left). *EP*, axis parallel to the transepicondylar line; *PoHA*, projection of the humeral head axis; *LT*, lateral margin of the lesser tuberosity; *GT*, medial margin of the greater tuberosity; *CoGT*, center of the crest of the greater tuberosity.

Results

We measured angles of anatomical landmarks (greater tuberosity, GT; lesser tuberosity, LT; and crest of greater tuberosity, CoGT; see Methods) in 2 transverse planes in 97 left and 98 right humeral bones. In the humeral head plane, the angle between GT and projection of the humeral head axis (HA) was 11.9° ± 9.1°, and the angle between LT and the projection of the HA was 48.0° ± 7.8°. In the surgical neck plane, the angle between CoGT and the HA projection was 27.1° ± 9.6°.

The angle of retroversion, ie, the angle between transepicondylar line and the HA projection was 29.7° ± 10.6°. We did not find any statistically significant differences between right and left sides for any of the measured parameters. Results are summarized in Table I.

We wondered whether the anatomical landmarks could be used for reconstruction of the version of humeral head as reliably as the commonly used transepicondylar line. We compared angular deviations of individual angles (GT, LT, and CoGT angles) for an average spatial position of the humeral head to angular deviation of transepicondylar line (EP).

The position of the humeral head can be calculated more precisely using the LT landmark, when compared with the EP angle (1.85x, $P < .001$, Table II). The GT landmark was still better than the EP line (1.66x, $P < .001$), while the CoGT landmark was as reliable as the EP line in calculating the version of humeral head (1.23x, $P = .144$).

An important control parameter was the shortest spatial distance (offset)[5,18] of intramedullary axis from the humeral head axis (1.20 ± 1.18 mm). Offset distribution was symmetrical, with most values placing HA axis ventral to IMA. Another control parameter was the angle between IMA and the z axis of the measurement frame (3.46° ± 1.71°), which measured the accuracy of anchoring the humeral bone in the frame.

Discussion

Results of shoulder arthroplasty after traumatic injuries are usually worse than arthroplasty for osteoarthritis or rheumatoid arthritis. This is a result of the complicated reconstruction of the morphology of proximal humerus with rotator cuff attachments and the position of the humeral head replacement,[4,5,12,13,17,18,20, 21] required for proper biomechanics of shoulder joint. The accuracy necessary for proper reconstruction of the proximal humerus in displaced fractures is still not known.[6,7,10,22]

In the first phase of arthroplasty, which are because of proximal humerus fractures, it is necessary to identify anatomical structures that would serve as reference points during the reconstruction. The original position of such landmarks is rarely preserved in the metaphysis above surgical column. Free fragments of tuberosities with rotator cuff attachments can often be found, and the fracture line

Table I Angles between landmarks of proximal humerus and axis of humeral head

	Left	Right	Both
GT angle*	10.9° ± 9.1° (-16.3° - 30.2°)	12.9° ± 9.1° (-8.7° - 33.3°)	11.9° ± 9.1° (-16.3° - 33.3°)
LT angle*	46.5° ±7.8° (25.1° - 64.3°)	49.5° ± 7.6° (27.8° - 68.7°)	48.0° ± 7.8° (25.1° - 68.7°)
CoGT angle**	27.0° ± 9.6° (2.7° - 53.6°)	27.2° ± 9.6° (-3.3° - 50.6°)	27.1° ± 9.6° (-3.3° - 53.6°)
EP angle (retroversion of head)	30.9° ± 11.7° (3.8° - 53.6°)	28.6° ± 9.4° (-0.9° − 47.1°)	29.7° ± 10.6° (-0.9° − 53.6°)

See Materials and Methods for details.
* GT and LT angles were calculated in the humeral head plane.
** CoGT angle were calculated in the surgical neck plane.

Table II Comparison of angular deviations of angles to angular deviation of trans-epicondylar line for reconstruction of humeral head position

	Left	Right	Both
LT angle vs. EP angle	2.25 ($P < .001$) CI = (1.51, 3.37)	1.53 ($P = .035$) CI = (1.03, 2.28)	1.85 ($P < .001$) CI = (1.40, 2.46)
GT angle vs. EP angle	1.66 ($P = .013$) CI = (1.11, 2.48)	1.08 ($P = .069$, ns) CI = (0.73, 1.61)	1.66 ($P < .001$) CI = (1.26, 2.20)
CoGT angle vs. EP angle	1.47 ($P = .059$, ns) CI = (0.98, 2.19)	0.96 ($P = .859$, ns) CI = (0.65, 1.44)	1.23 ($P = .144$, ns) CI = (0.93, 1.63)

CI, 95% confidence interval for ratio of variances.

often runs along the bicipital groove. Only the smooth surface of the bicipital groove or its fragments running into the tuberosities are usually recognizable. Under the surgical neck, the crest of greater tuberosity with the pectoralis major attachment can be found more easily than the distal part of the bicipital groove. Flat attachment of the muscle is separated from the bone on a narrow crest, which can be seen after releasing the short upper portion of the attachment.

Anatomical landmarks of the proximal humerus or, traditionally, the transepicondylar line can be used as a reference for adjustment of retroversion of the humeral head after fractures. Some authors are skeptical when using landmarks during the surgical approach,[3] especially after fractures. Retroversion can be adjusted based on the transepicondylar line or the forearm axis; however, estimating the transepicondylar line is difficult without a special targeting device. Without such a device, it is also difficult to estimate transepicondylar line and its projection onto transverse plane in proximal humerus; moreover, settings and use of such devices can be quite complicated.

Some authors have shown that the bicipital groove can be used as a reference for reconstruction of version of the humeral head implant after fractures.[2,11,14] Angibaud et al[2] documented the procedure and demonstrated that it was applicable in adjusting the version of an implant. Their results can also be used for implantation of a humeral head replacement after traumatic injuries. The retroversion angle of the humeral head, with respect to the bicipital groove at a transverse plane at the surgical neck, was 43.7° ± 9.9°. This corresponds to our results, which considers the crest of the greater tuberosity at the surgical neck, ie, the position which delineates the groove laterally. In our experience, the CoGT landmark is much easier to identify during surgery.

Kontakis et al[14] measured the distance of the bicipital groove from the axis of the prosthesic head on CT scans of cadavers. Their results, when expressed as an angle in the transverse plane between tuberosities, corresponded to 19.7° ± 10.7° (range, -6.3°-41.7°), similar to our results. Values for the greater tuberosity (which is more lateral) were 11.9° ± 9.1° (range, -16.3°-33.3°).

Kummer et al.[15] measured the angle between the groove at the metaphysis and humeral head axis on 420 humeral bones. They measured the angle at the metaphysis to be 27.3° ± 14.2°. Their result is interesting when compared with our study, as the variability of margins of the groove in our sample was considerably smaller. On the other hand, Kummer et al and Balg et al[3] used the anatomical axis of the entire humerus, and it is difficult compare their results with ours, which used the intramedullary axis of the proximal diaphysis.

We conclude that the crest of the greater tuberosity can be used to estimate the position of a humeral head replacement during surgery after surgical neck fractures. Adjusting the rotation of the stem at the surgical neck using the crest of the greater tuberosity is as reliable as using the transepicondylar line (Table II). During surgery, the position of this landmark is apparent between tuberosities; distally, however, the position is harder to identify. There, the sulcus is flat and wide, and its position can be estimated only from cortical bone thickness or the surrounding

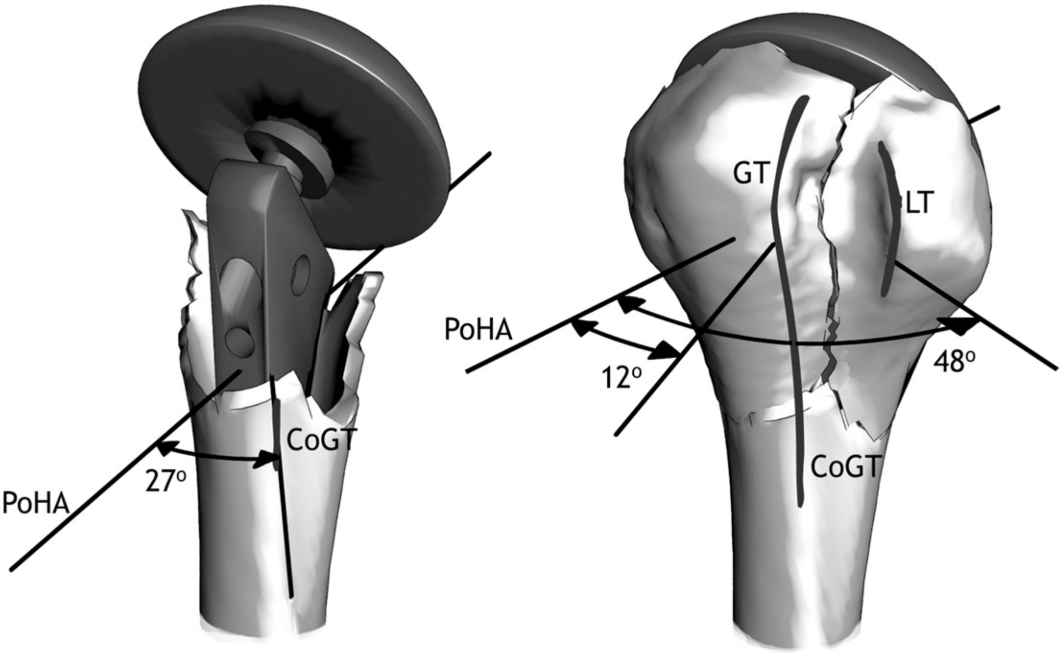

Figure 4 Stem rotation, including the head, in the diaphysis of the humeral bone based on the crest of the greater tuberosity (CoGT), projection of the axis of the head (PoHA) and an average position of the greater (GT) and lesser (LT) tuberosities based on the projection of the axis of the head (PoHA) on right side.

muscle attachments. The average value of stem rotation (in the diaphysis canal) based on the crest of the greater tuberosity (CoGT landmark) was 27° (Figure 4).

An important phase of reconstructing the rotator cuff attachments follows the prosthetic stem implantation. The attachments should be reconstructed and affixed to the proximal part of the implant, so as to form a functional unit with the head. If the original position of the attachments is not known, the lesser and greater tuberosities can be affixed at the usual location of attachments on the proximal part of the humeral bone. The position is important as the stem is usually set by the surgeon into a standard retroversion position, and individually adjusted stems are seldom used. We defined the muscle attachments by the margins of the greater (medial margin) and lesser (lateral margin) tuberosities, and found the average GT angle to be 12° and the LT angle 48° (Figure 4).

Statistically smallest angular deviation from the original position can be achieved using average angles for individual landmarks. For example, if the LT angle is set to 48°, the average angular deviation is approximately 8°, but grows to 13° when the LT angle is set to 60°. Selecting an angle different than the average (eg, 20°, 30°, etc.) causes a significantly greater angular deviation from the original position.

We think that the position of the rotator cuff attachments is more important for the final function of the shoulder joint than the rotation of the prosthetic stem in the proximal diaphysis, or with respect to the transepicondylar line. It is not necessary to fix the stem in the diaphysis precisely and the method using the transepicondylar line at the level of surgical neck can be used for stem adjustment. An accurate and stable fixation of the tuberosities with rotator cuff attachments is much more important.[1,9,16,19]

Conclusion

We described positions of the margins of tuberosities with respect to the axis of the humeral head. We assumed that surgeons may make rather large angular deviations during the procedure which can lead to a poor clinical outcome. We expect better estimates of position of tuberosities to lead to better clinical outcomes, even when estimating the positions during surgical reconstruction might be technically more challenging.

Our results can also be used in nontraumatic indications for shoulder joint arthroplasty. In this case, the rotation of the stem and the head can be based on the position of the margins of tuberosities, with LT and GT landmarks providing more accurate values than the transepicondylar line (Table II).

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ORIGINAL ARTICLE

Lesser tuberosity is more reliable than bicipital groove when determining orientation of humeral head in primary shoulder arthroplasty

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Abstract
Purpose The objective of the study was to provide statistical evaluation of position of bone landmarks of proximal humerus in relation to transepicondylar line and find out which one is the most suitable for setup of the head retroversion in case of humeral head destruction.
Methods We measured 185 dry humeral preparations (92 left, 93 right). Structures of interest on the proximal humerus were marked with pointers of custom made steel frame. Angular relationships between the humeral head axis and medial margin of the greater tuberosity, lateral margin of the lesser tuberosity, bicipital groove, and crest of the greater tuberosity were evaluated with respect to intramedullary axis of the proximal humeral shaft.
Results The angle between the humeral head axis and medial margin of greater tuberosity was 11.5 ± 9.0°, the angle between the lateral margin of the lesser tuberosity and the axis was 47.5 ± 7.4°, the angle between the bicipital groove and the axis was 31.6 ± 8.8° at the level of the humeral head. The angle between the crest of the greater tuberosity and the axis was 26.6 ± 9.6° in plane of the surgical neck.
Conclusions We statistically proved that the lateral margin of lesser tuberosity is more reliable than the bicipital groove; medial margin of the greater and transepicondylar line for reconstruction of humeral head retroversion. We suggest that the lesser tuberosity should be used to determine the retroversion, especially in cases when the margin of humeral head was destructed.

Keywords Shoulder arthroplasty · Humeral head retroversion · Bicipital groove · Greater tuberosity · Lesser tuberosity · Crest of greater tuberosity

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Introduction

Position of the head of the prosthesis in case of shoulder arthroplasty is essential for a satisfactory outcome as well as postoperative range of motion. One of the most important parameter is its retroversion. The retroversion is defined as the angle between the transepicondylar line of the distal humerus and an axis of the humeral head in the transversal plane. Regarding the high variability between the proximal and distal humerus, the angle is between −6 and 50° [4, 17].

The anatomical neck, i.e., humeral head margin is the best landmark for setting version of the humeral head implant in case of primary shoulder arthroplasty. However, in case when retroversion cannot be set based on anatomical neck (for example, when humeral head was destructed), surgeon has to use different humeral landmarks. Several authors showed that different parts of the proximal humerus can be used as a reference for setting up the position in primary arthroplasty [6, 14, 18] or in case of fracture [1, 2, 9, 11, 13, 15, 19]. Most authors used the bicipital groove for adjusting the version [1, 2, 6, 9, 13, 14, 18]. Anatomical studies using the groove are quite old, but many surgeons are still skeptical of this idea.

In this study we provide a statistical analysis of landmarks position (bicipital groove, margins of greater and lesser tuberosities, crest of greater tuberosity, and transepicondylar line) with respect to the humeral head axis. For this purpose a single method was used which analyzed the angular correlation of structures to the humeral head axis in dependence on axis of the proximal humeral shaft.

Our goal was to determine with uniform methodology whether these anatomical landmarks of the proximal humerus correlate better with the position of the humeral head as opposed to the transepicondylar line, i.e., forearm axis, and, therefore, should be more suitable for adjusting the prosthesis during reconstruction of the humeral head version in case of destructed humeral head.

Materials and methods

For the purpose of the study we used 185 dry preparations of humeral bones (92 left, 93 right) from the collection of our Institute of Anatomy, 1st Faculty of Medicine, Charles Faculty in Prague. Only bones with closed growth plates and no signs of degenerative or post-traumatic alterations were measured from incipient group of 190 humeri. No information about sex or age of the preparations was available.

Bone measurements were conducted in a custom made steel frame with a movable slider (Fig. 1). Bones were positioned in the frame with the proximal axis of the diaphysis parallel to the longer axis of the frame, and the transepicondylar line (EP) parallel to the table surface (X-axis). Positions of the anatomical structures on the bones were determined using pointers attached to the slider. The surface of each bone was gradually copied by moving the slider in the proximo-distal direction with pointers marking specific anatomical landmarks (see below).

Pointer positions were scanned with a digital camera (Canon 350D, Lens Sigma 35–70 mm, F3.5). The axis of the camera was aligned with the long axis of the frame as well as the anatomical axis of each humerus and the focal length was set to 70 mm. The camera was positioned in at distance (3 m) from the frame to avoid refractive errors of

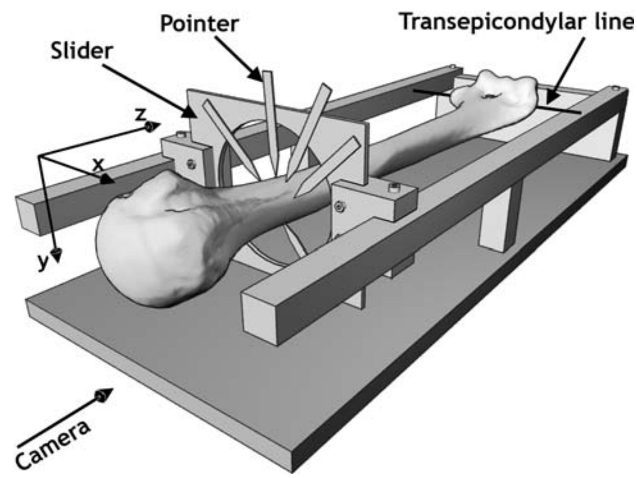

Fig. 1 Measuring frame with designated basic axes

the lens. Twenty-nine points were identified on each bone and pointers were scanned by 7–10 photographs. Positions of pointers on each picture were further evaluated using custom made software. Coordinates of all points were expressed in the Cartesian coordinate system with X- and Y-axes in transversal planes (coordinate origin corresponded to the upper left corner of the picture), and Z-axis in proximo-distal direction parallel with the long axis of the frame. The software was developed at the Department of Evolution Biology, Faculty of Science, Charles University in Prague specifically for the study and uses the mathematical methods described below.

Three muscle attachments of proximal humerus, bicipital groove, anatomical neck, and proximal shaft of humerus were identified and marked by points that well described spatial location of the structure. The software used for mathematical approximation of their spatial positions not only marked points but also virtual connection between them, e.g., the whole margin of greater tuberosity was described by three points and two lines (Fig. 2). Afterwards, two virtual axes (intramedullary axis of the proximal shaft, axis of the humeral head) and two virtual planes (humeral head plane, surgical neck plane) were calculated for further measurements.

Greater tuberosity (GT) was defined by its medial margin, i.e., the part of the tuberosity that continues into the bicipital groove. Three basic points were identified on the margin (in the upper, middle and lower thirds) so that they included the whole metaphyseal portion of the tuberosity.

Bicipital groove (BG) was defined by its "deepest place", i.e., with points that are closest to an intramedullary axis of proximal humeral shaft. Three points were identified inside of the metaphyseal part of the groove (in the upper, middle and lower thirds) so that they described the whole portion above the surgical neck.

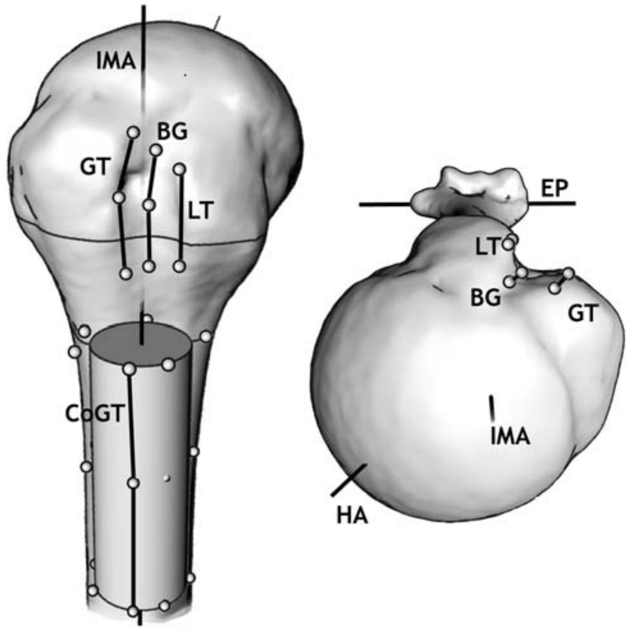

Fig. 2 Points of interest on a right proximal humerus (left-anterior view, superior view). *GT* greater tuberosity, *BC* bicipital groove, *LT* lesser tuberosity, *IMA* intramedullary axis, *HA* axis of the humeral head, *EP* transepicondylar line, *CoGT* crest of the greater tuberosity and points defining the proximal shaft of the humerus

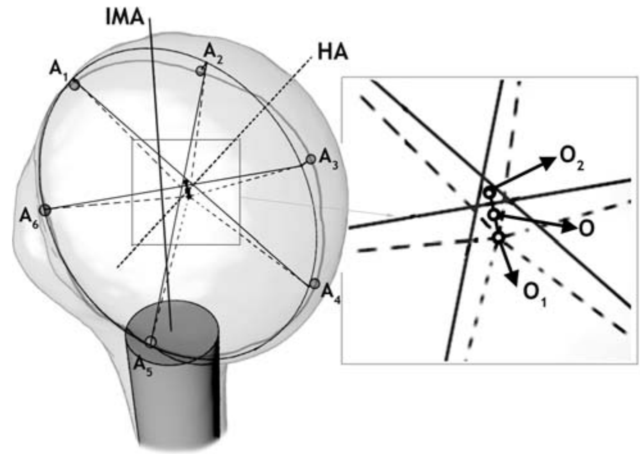

Fig. 3 Six demarcating points on the anatomical neck (A_1–A_6) and central point of the anatomical neck plane (O) computed as a midpoint of a line connecting O_1–O_2. O_1 and O_2 are temporal centers determined from two independent mathematical methods. *IMA* intramedullary axis of the proximal humeral shaft, *HA* axis of humeral head

Lesser tuberosity (LT) was defined by its lateral margin, which continues into the bicipital groove. Here we identified two points in the upper and lower halves, such that the positions of the points corresponded to the middle and lower parts of the head in transversal sections.

Crest of the greater tuberosity (CoGT) was defined by three points. The proximal one lies on the crest at the level of the surgical neck, the second one in the middle third, and distal one on the distal part of the crest, respectively.

Proximal shaft of the humerus was demarcated using three groups of five points (Fig. 2) in the proximo-distal direction from the level of the surgical neck distally to the deltoid tuberosity. Locations of the points were selected outside muscle attachments (crest of greater and lesser tuberosities) in regular intervals on the diameter of the humerus. Three points (one from each group) were located in the bicipital groove. The mean length of the demarcated diaphysis was 48 mm (39–52 mm).

Anatomical neck of the humeral head was first marked by pencil in the area where cancellous bone changes into smooth subchondral bone. Then, six points were identified on the anatomical neck at regular intervals, so that pairs of points were situated in the upper, middle, and lower thirds of the head (Fig. 3).

Intramedullary axis of the proximal shaft (IMA) was defined as the longitudinal axis of a cylinder inserted among the 3 × 5 points identified distally from the surgical neck. The software computed the greatest cylinder (biggest diameter) which fit inside the 15 points, such that all points were outside the cylinder. The axis defined the axis of the stem of an implant in our model.

Axis of the humeral head (HA) was defined as a line perpendicular to the anatomical neck plane and passing through the central point of the anatomical neck. The six points identified on the anatomical neck were fit with the anatomical neck plane, so as to minimize the distance between the points and the plane. Projections of the six points on this plane were further used to compute the position of the central point.

The central point was computed using two independently determined points due to irregularity of the anatomical neck shape. The first point (O_1) at the anatomical neck plane was computed as having the minimal distance from the six projections. To compute the second point (O_2), opposite projections (A'_1–A'_4, A'_2–A'_5, and A'_3–A'_6) were connected, and the intersecting connecting lines formed a triangle in the middle of the anatomical neck plane. The point O_2 was then computed as the center of the triangle. The central point was then determined as the midpoint of the line connecting O_1 and O_2 (Fig. 3).

The axis of the humeral head was then defined as a line perpendicular to the anatomical neck plane and passing the central point (O). The axis defined the axis of the head of an implant in our model.

The *humeral head plane* was defined as the transversal section perpendicular to IMA at a level, where the axis of the humeral head (HA) intersects the intramedullary axis (IMA). Because axes usually do not interfere, the plane contains the shortest distance between the humeral head axis and IMA. The *surgical neck plane* was set as a plane perpendicular to IMA at a level of the most proximal point of the crest of greater tuberosity (Fig. 4).

Finally, we determined the spatial relationship between axes (IMA, HA) and identified anatomical landmarks (GT, LT, and BG) in the humeral head plane and CoGT in the surgical neck plane. For the purpose of angular measurements a projection of humeral head axis (PoHA) onto the planes was used.

We measured four angles (*GT angle*, *BG angle*, *LT angle* and *CoGT angle*), which were defined as the angles between the projection of the humeral head axis (PoHA) and lines connecting IMA and GT, BG, LT or CoGT landmarks, respectively. Analogously, we measured *EP angle* ("head retroversion angle") between PoHA and the transepicondylar line in both planes (Fig. 4).

Mathematical methods, which were used to calculate the angles:

$EP\ angle = \pm (n_1) arccos(n_1/\sqrt{(n_1^2 + n_2^2)})$; n_1, n_2, n_3 were coordinates of the normal vector of the anatomical neck plane.

$GT\ angle = \pm\ arccos(n_{12}\mathrm{u}/(|n_{12}||\mathrm{u}|)$; $n_{12} = (n_1, n_2)$; u = G–P, G is a GT projection to the humeral head plane and P is a point of intersection of IMA with the plane of the humeral head.

$LT\ angle = \pm\ arccos(n_{12}\mathrm{v}/(|n_{12}||\mathrm{v}|)$; $n_{12} = (n_1, n_2)$; v = L–P, L is the projection of LT into the humeral head plane and P is an intersection of IMA with the plane of humeral head.

$CoGT\ angle = \pm\ arccos(n_{12}\mathrm{w}/(|n_{12}||\mathrm{w}|)$; $n_{12} = (n_1, n_2)$; w = C–P, C is the projection into the plane of the humeral head plane and P is an intersection of IMA with the plane of humeral head.

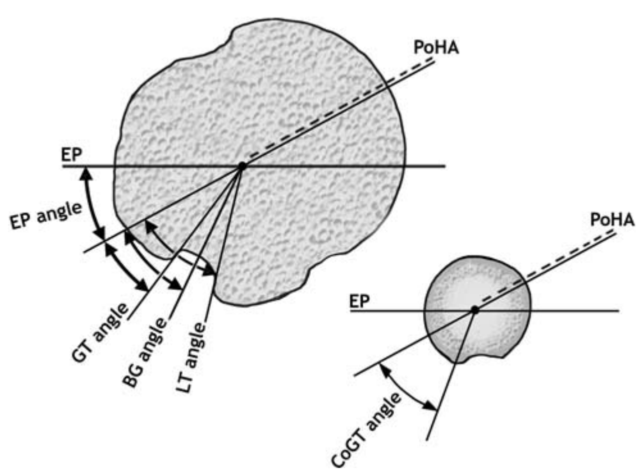

Fig. 4 Angles of interest in proximal humerus were measured in the humeral head plane (*left*) and in the surgical neck plane (*right*). EP, axis parallel to the transepicondylar line; *PoHA* projection of the humeral head axis on planes, *LT* lateral margin of the lesser tuberosity, *GT* medial margin of the greater tuberosity, *BG* bicipital groove, *CoGT* center of the crest of the greater tuberosity

$BG\ angle = \pm\ arccos(n_{12}\mathrm{x}/(|n_{12}||\mathrm{x}|)$; $n_{12} = (n_1, n_2)$; x = B–P, B is the projection of BG into the humeral head plane and P is an intersection of IMA with the plane of the humeral head.

Statistical method

The variance σ_A^2 (A = EP angle, GT angle, LT angle, BG angle, or CoGT angle) determined the random deviation of the head axis position from the position expected (mean) in the population. The σ_A^2/σ_B^2 (A, B = EP angle, GT angle, LT angle, BG angle or CoGT angle) ratio estimated the reduction of variance when estimating the position based on indicator B compared to indicator A.

Statistical significance of improvement for each pair of indicators (LT angle versus EP angle, GT angle versus EP angle, BG angle versus EP angle and CoGT angle versus EP angle) was calculated using the χ^2 test for ratio of variances. Based on χ^2 distribution we calculated a 95% confidence interval for each ratio.

Results

We measured the angles of anatomical landmarks (greater tuberosity, GT; lesser tuberosity, LT; crest of greater tuberosity, CoGT; bicipital groove, BG; transepicondylar line, EP) in defined transversal planes in 92 left and 93 right humeral bones. The angle between GT and projection of the humeral head axis (PoHA) was 11.5 ± 9.0° (mean ± STD), the angle between LT and PoHA was 47.5 ± 7.4°, the angle between BG and PoHA was 31.6 ± 8.8° in the humeral head plane. The angle between CoGT and PoHA was 26.6 ± 9.6° in the surgical neck plane (Fig. 4).

The angle of retroversion, i.e., the angle between transepicondylar line and projection of humeral head axis was 29.9 ± 11.2°. We did not find any statistically significant differences between right and left sides for any of the measured parameters. Results are summarized in Table 1.

Finally, we statistically evaluated the data as to whether the anatomical landmarks could be used for reconstruction of the version of humeral head as reliably as the commonly used transepicondylar line, i.e., forearm axis. We compared angular deviations of individual angles (GT, LT, BG, and CoGT angles) for an average spatial position of the humeral head to the angular deviation of the transepicondylar line (EP).

The position of the humeral head can be calculated more precisely using the LT landmark, when compared with EP angle (2.27×, $P < 0.001$). GT landmark (1.56×, $P = 0.003$) was still better than EP line while CoGT landmark (1.37×,

Table 1 Angles of interest on proximal humerus and angle of retroversion in angular degrees

	Left	Right	Both
GT angle	11.1 ± 8.8° (−15.3 to 31.1°)	12.0 ± 9.1° (−9.7 to 32.4°)	11.5 ± 9.0° (−15.3 to 32.4°)
LT angle	46.9 ± 7.4° (25.5 to 64.7°)	48.2 ± 7.4° (26.8 to 64.7°)	47.5 ± 7.4° (25.5 to 64.7°)
BG angle	30.5 ± 8.4° (7.0 to 49.6°)	32.7 ± 9.1° (9.2 to 53.4°)	31.6 ± 8.8° (7.0 to 53.4°)
CoGT angle	27.0 ± 9.2° (3.5 to 54.6°)	26.2 ± 9.9° (−4.4 to 49.6°)	26.6 ± 9.6° (−4.4 to 54.6°)
EP angle (retroversion of humeral head)	30.8 ± 11.7° (2.9 to 53.2°)	30.0 ± 10.6° (−5.5 to 48.2°)	29.9 ± 11.2° (−5.5 to 53.2°)

Mean ± standard deviation (range)

GT greater tuberosity, *LT* lesser tuberosity, *BG* bicipital groove, *CoGT* crest of greater tuberosity, *EP* transepicondylar line

GT, BG, LT angles were calculated in the humeral head plane, CoGT angle at a level of surgical neck; see "Materials and methods" for details

Table 2 Angular deviations of angles on proximal humerus compare to angular deviation of transepicondylar line for reconstruction of humeral head position

	Left	Right	Both
LT angle versus EP angle	2.47 ($P < 0.001$)	2.08 ($P < 0.001$)	2.27 ($P < 0.001$)
GT angle versus EP angle	1.75 ($P = 0.008$)	1.36 ($P = 0.14$, ns)	1.56 ($P = 0.003$)
BG angle versus EP angle	0.51 ($P = 0.002$)	0.72 ($P = 0.013$)	0.61 ($P = 0.001$)
CoGT angle versus EP angle	1.61 ($P = 0.024$)	1.15 ($P = 0.51$, ns)	1.37 ($P = 0.035$)

Ratio of variances (*P* value)

For definition of GT angle, LT angle, BG angle, CoGT angle, and EP angle see "Materials and methods" section

$P = 0.035$) as well as BG landmark (0.61×, $P = 0.001$) was as reliable as the EP line in setup version of the humeral head. Results of statistical evaluation are summarized in Table 2.

Discussion

Retroversion of shoulder arthroplasty head and its setup is one of the most important parameters in implantation [1–10, 12–14, 16]. In case of primary arthroplasty surgeons should use the margins of humeral head for setting of the version. Although the margin itself can be found in virtually every case, its deformity (for example after a severe posttraumatic destruction of humeral head, or in rheumatoid arthritis), or osteophytes can lead to incorrect osteotomy. If the implantation can not be guided by the margin of the destructed humeral head, surgeons have to set the version according to different reference landmarks. The axis of forearm and the transepicondylar line are usually used for this purpose. For example, a fixed angle of retroversion is set between 30 and 40° relative to the transepicondylar line [4], or an appropriate angle relative to the axis of the forearm.

Several authors show that landmarks of the proximal humerus, especially the bicipital groove, which can be used as a reference for reconstruction of version of the humeral head in case of fracture [1, 2, 9, 13, 16] or primary arthroplasty [6, 14, 18]. The groove is the dominant anatomical structure of the proximal humerus, and can be found above the surgical neck, between the greater and lesser tuberosities. Despite the fact that the distal part of the groove can be easily identified, it is rather flat and too wide to serve as a reliable and representative landmark. Instead, the crest of the greater tuberosity should be used as a surgical landmark. The crest can be identified easily based on the attachment of the pectoralis major muscle. The narrow attachment of the muscle is separated from the bone crest, which can be seen after releasing the short upper portion of the attachment during operation.

It does not matter, which landmark a surgeon uses, but a fixed angle of head version (e.g., 30–40° according to transepicondylar line) causes an angular deviation from an unknown original position. Statistically, the smallest angular deviation from the original position can be achieved using average angles for each landmark. It means that we can expect a larger angular deviation from the original position if the head is set to a different angle than the average one thus affecting the postoperative outcome.

Our study is based on angular measurements at a defined section of the proximal humerus. We believe it's important to use the intramedullary axis of the proximal shaft because in this line the surgeon turns the stem of the implant. We applied the uniform method to all mentioned landmarks which were described in the literature. Except for the bicipital groove itself, we used its margins (medial margin of

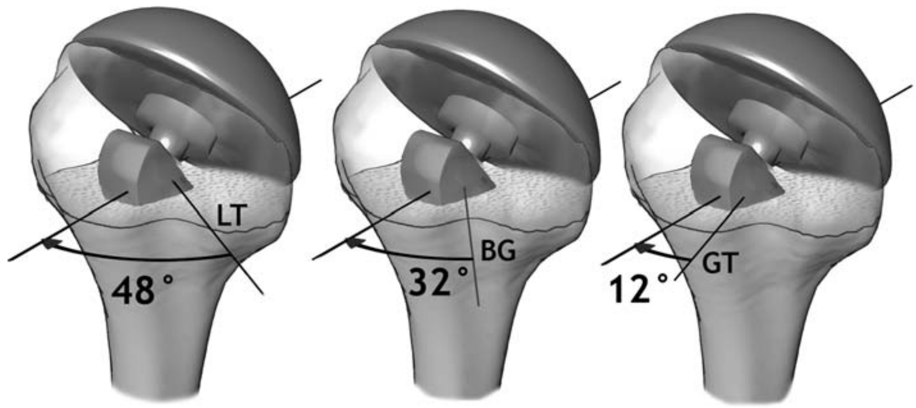

Fig. 5 Stem rotation during the procedure inside the proximal shaft of humerus based on the projection of the axis of humeral head at a level of the humeral head plane. *LT* lateral margin of the lesser tuberosity, *GT* medial margin of the greater tuberosity, *BG* bicipital groove

greater and lateral margin of lesser tuberosities) and the crest of the greater tuberosity. The spatial position of the crest was previously published especially as a landmark suitable for reconstruction in case of severe fractures of the proximal humerus [15, 19], but no data was previously published in correlation to the intramedullary axis.

We compared the angular deviation of associated angles to find out which mentioned landmark is most suitable for setup of implant version. Statistical evaluation showed that all mentioned landmarks can be used as landmarks for setup of implant retroversion. Data showed that the most suitable landmark is the lateral margin of the lesser tuberosity, more so than the "deepest" part of the bicipital groove, medial margin of the greater tuberosity and crest of the greater tuberosity (Table 2). The crest is functionally accurate as the transepicondylar line in restoration of the head version.

The average angle (LT angle) for the lesser tuberosity landmark is 48°. To setup the version of the head a surgeon has to turn the prosthesis backwards about 48° (Fig 5). The exact area of the landmark is on the lateral margin of the lesser tuberosity at a level where the axis of the implant head intersects an axis of the implant stem. Analogously, we found the average BG angle to be 32° and the GT angle 12° at the level of the humeral head plane. The CoGT angle, measured at the level of the surgical neck, can be applicable in case of fractures, when no suitable landmark above the surgical neck can be found.

The margins of tuberosities and bicipital groove provide more accurate values of restoration of the humeral head retroversion than does the transepicondylar line. Statistically, the smallest angular deviation from the original position can be achieved using average angles for individual landmarks. For example, if the LT angle is set to 48°, the average angular deviation is approximately 8°, but grows to 13° when the LT angle is set to 60°. Selecting an angle different than the average one (e.g., 40°, 60°, etc.) causes a significantly greater angular deviation from the original position. Figure 6 shows the dependency of angular deviation on average angles of individual landmarks.

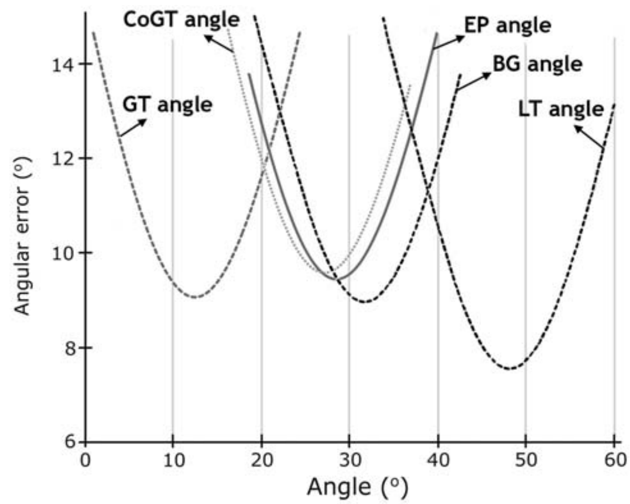

Fig. 6 Graph showing the dependency of angular error from original position of humeral head on setting angle of implant version. For example: if the version is set with respect to lesser tuberosity (LT angle) to 48°, the average angular deviation from original position of humeral head is approximately 8°, but grows to 13° when the surgeon sets LT angle to 60°. *GT* greater tuberosity, *CoGT* crest of greater tuberosity, *EP* transepicondylar line, *BG* bicipital groove

Our study is based on visual definition of anatomical structures and the mathematical method was designed for that purpose. We tried to avoid imaging methods such as CT or MRI scans for this study in order to define the position of structures more naturally as during the surgical procedure. The main reasons for using landmarks on the proximal humerus are that it is difficult to accurately define the distal ones (the transepicondylar line or axis of forearm) during the operation and their inconvenient reproduction at the level of the proximal humerus. The lateral margin of lesser tuberosity (medial margin of bicipital groove) is more reliable landmark than bicipital groove itself and lateral margin of greater tuberosity to set humeral head version. The application of them should be limited to cases with destructed humeral head or posttraumatic deformity.

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Třídimenzionální anatomie proximálního humeru a úponů rotátorové manžety a její uplatnění při aloplastice ramenního kloubu

Three-Dimensional Geometry of the Proximal Humerus and Rotator Cuff Attachment and Its Utilization in Shoulder Arthroplasty

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ABSTRACT

PURPOSE OF THE STUDY

The aim of the study was to provide a method of measurement and data collection, based on morphologic analysis of the proximal humerus, that would facilitate precise placement of the humeral stem and would be easy to apply in clinical medicine in patients requiring shoulder arthroplasty.

MATERIAL

Three groups of materials were used. Materials for the first and second groups were provided by the Department of Anatomy, First Faculty of Medicine, Charles University. The first group included 10 specimens (five left and five right humeral bones) obtained at routine anatomical dissection. The second group contained 110 so-called dry preparations from the collections of the Department of Anatomy and the third group comprised nuclear magnetic resonance (NMR) scans of 20 patients. To show spatial relationships between the proximal and the distal humerus, another coil was applied to the epicondylar region in addition to the one placed over the proximal humerus.

METHODS

The first group material was used to study proximal humerus morphology and to determine reference points for the other two groups. The points were constructed to make seven planes perpendicular to the axis of the proximal humeral metaphysis. Based on the reference points, parameters of the proximal humerus were assessed in the defined planes also in the other two groups. We measured angles between the reference points and the transepicondylar line or the humeral head axis. The vertex of each angle was always placed in the point of intersection of the metaphyseal axis and the given transverse plane. Reference points of the greater tubercle were marked on the medial margin continuous with the intertubercular groove, on the lateral margin of the lesser tubercle and in the "deepest" place of the intertubercular groove. We also measured humeral head retroversion and the position of maximal bony mass of both the greater and the lesser tubercle (this parameter can be used with advantage for optimal insertion of screws in proximal humerus reconstruction).

RESULTS

The angle between the medial margin of the greater tubercle and the humeral head axis was on average 164.8° on the left side and 163.2° on the right side; the angle between the great tubercle margin and the transepicondylar line was 137.0° on the left humerus and 137.7° on the right humerus. The lateral margin of the lesser tubercle and the humeral head axis formed on average an angle of 124.4° and of 122.6° on the right and the left side, respectively. The intertubercular groove/humeral head axis relationship was 143.4° and 144.8° for the left and the right humerus, respectively, and the intertubercular groove/transepicondylar line angle was 115.6° for the left and 119.5° for the right humerus. The humeral head axis and the transepicondylar line made an angle of 27.8° for the left and 25.3° for the right humerus. These values corresponded to the angle of the humeral head retroversion. The reference point of maximal bony mass of the greater tubercle and the humeral head axis made an angle of 181.1° and of 180.2° for the left and the right humerus, respectively; between this point and the lesser tubercle was an angle of 120.2° for the left and 126.9° for the right humerus.

DISCUSSION

One of the most important parameters in restoring shoulder function by alloplasty is humeral head retroversion. If this is not correct, ventral or, less frequently, dorsal instability of the shoulder may result. The correct setting of retroversion is guided by the transepicondylar line or several specific landmarks on the greater and the lesser tubercle of the humerus. Another important factor is the correct reconstruction of anatomic position of the greater and the lesser tubercle in relation to the insertion of rotator cuff muscles into the humeral head. Relationships of diaphyseal, metaphyseal and humeral head axes have been reported in the relevant literature dealing with proximal femoral morphology. None of the reports, however, has dealt with tubercular angles and position of the maximal body mass, which is a decisive factor for insertion of screws fixing the prosthetic stem.

CONCLUSIONS

The values provided here can be used for a more precise construction of implants for shoulder replacement. The method of three-dimensional presentation of the proximal humerus may aid in a more exact implantation procedure during shoulder arthroplasty. An optimal position of the implant can also be based on parameters obtained from the healthy contralateral shoulder joint.

Key words: rotator cuff, humeral alloplasty, greater tubercle, lesser tubercle, proximal humerus.

ÚVOD

Prostorové charakteristice horního konce pažní kosti je v anatomické literatuře věnována relativně malá pozornost. Proto především na podnět klinických ortopedů, zabývajících se náhradou ramenního kloubu, vzniklo v posledních 10 letech několik prací, popisujících tvar proximálního humeru (1, 2, 3, 4, 5, 9, 10, 11).

Boileau a Walch v roce 1997 (1) publikovali první obsáhlý rozbor základních parametrů geometrie vnějšího povrchu horního konce humeru na 65 suchých kostních preparátech. Tvarová charakteristika pažních kostí byla zjednodušena a na základě jednoduchých prostorových útvarů digitálně zpracována. Díky digitálnímu zpracování bylo definováno několik geometrických parametrů, které byly pak proměřeny. Cílem bylo definovat v 3D prostoru tvar proximálního humeru s ohledem na jeho respektování při následné implantaci endoprotézy.

Na uvedenou práci navázali Robertson, Yuan a spol. (11). Poukázali na fakt, že při implantaci endoprotézy je rozhodující především tvar dřeňové dutiny a nikoliv vnějšího pláště kosti. Proto použili při charakterizaci kostní architektury humeru CT data se softwarovou 3D rekonstrukcí. Měření se uskutečnilo na suchých kostních preparátech. Sledována byla retroverze hlavice, inklinace hlavice, poloměr a výška hlavice, mediální a dorzální ofset, dále poloha sulcus intertubercularis a vzdálenost baze velkého hrbolu od mediální kontury hlavice v přesně sagitální rovině. Současně byl charakterizován tvar dřeňového kanálu proximální poloviny humeru.

Cílem naší experimentální práce bylo:

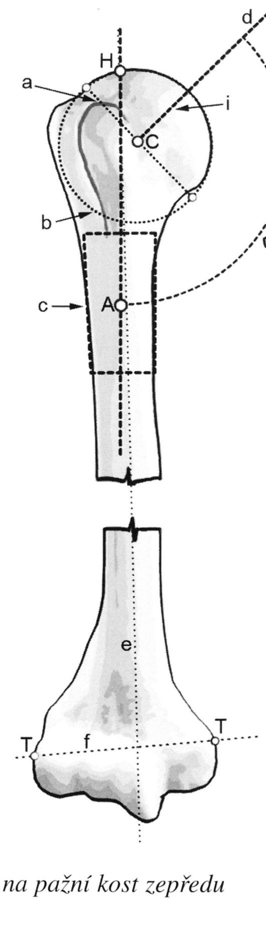
- vytvoření metodiky měření a získávání digitálních dat o prostorové konfiguraci proximálního humeru, která by byla snadno použitelná i v klinické praxi u pacientů;
- přesnost této metody ověřit přímým měřením na kostních preparátech;
- ze získaných dat od pacientů pomocí počítačového zpracování vytvořit virtuální 3D model humeru;
- na podkladě získaných údajů vypracovat doporučení k zdokonalení konstrukce implantátů pro náhradu ramenního kloubu v různých indikacích, zvláště v indikacích traumatických.

PROSTOROVÉ VZTAHY DIAFÝZY, METAFÝZY, HLAVICE PAŽNÍ KOSTI, VELKÉHO A MALÉHO HRBOLU

Při studiu geometrie proximálního humeru jsme vycházeli z definovaných parametrů, které jsou v literatuře obecně uváděny.

Určeny jsou tedy následující parametry (obr. 1, 2):

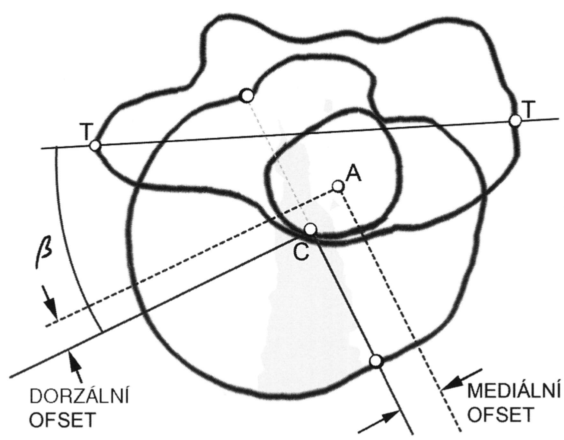
1. **Rovina anatomického krčku** je definována jako rovina, proložená bazí kloubní plochy (a);
2. **Epifyzární koule** je koule (b), odpovídající kloubnímu povrchu s definovaným centrem (C);
3. **Metafyzární válec** je pomyslný válec (c), který je pro možnost studia tvaru proložen oblastí proximál-



Obr. 1. Pohled na pažní kost zepředu

ní metafýzy humeru s geometricky definovaným středem (A) **a podélnou osou**;

4. **Osa hlavice humeru** je osa (d) epifyzární koule kolmá na rovinu anatomického krčku a procházející vrcholem kloubní plochy;
5. **Diafyzární osa** je osa vlastní diafýzy pažní kosti (e);
6. **Transepikondylární osa** je přímka spojující hroty epikondylů (T-T);
7. **Průměr zakřivení kloubního povrchu hlavice**;
8. **„Hindge point"** bod (H), průsečík mezi osou metafyzárního válce a povrchem hlavice;
9. **Výška kloubního povrchu** (i)
10. **Úhel inklinace** α je úhel mezi osou metafyzárního válce a osou hlavice;
11. **Úhel retroverze** β je úhel mezi osou hlavice a transepikondylární čárou;
12. **Mediální ofset** je vzdálenost mezi body **A-C** v rovině frontální;
13. **Dorzální ofset** je vzdálenost mezi body **A-C** v rovině sagitální.



Obr. 2. Pohled na pažní kost shora v ose metafýzy

MATERIÁL A METODA

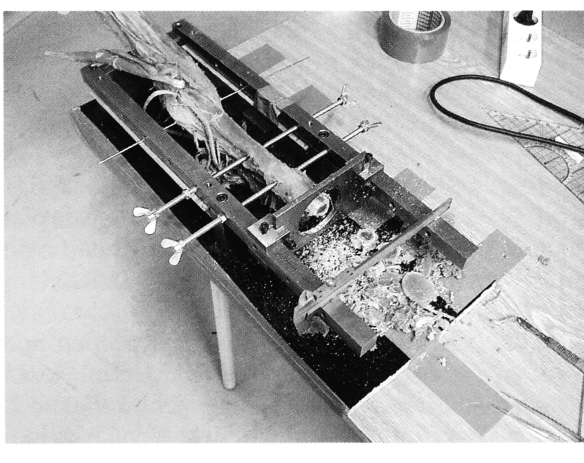
V naší studii jsme vycházeli ze tří skupin preparátů.

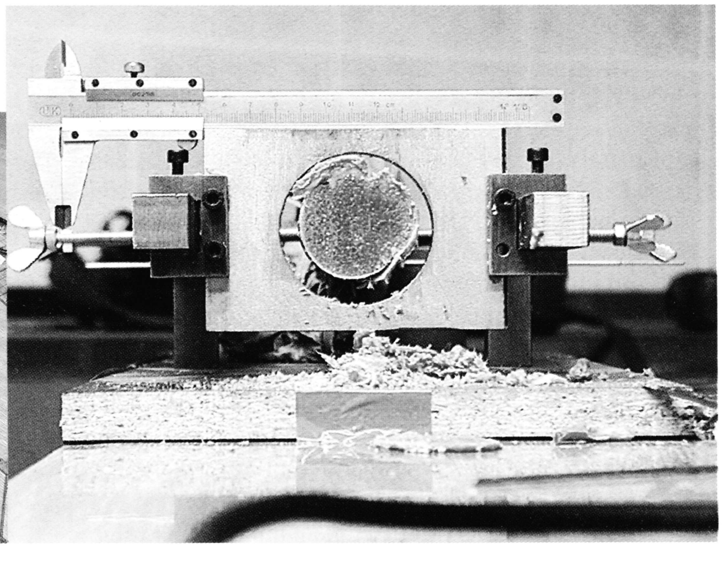
Pro studium prostorové architektury horního konce pažní kosti jsme si nejdříve potřebovali detailně objasnit morfologii. Měření byla provedena na preparátech Anatomického ústavu 1. LF UK. Pro první skupinu jsme použili deset preparátů (vždy obě pažní kosti z 5 těl), které jsme získali při anatomické pitvě. Tyto byly zbaveny veškerých měkkých tkání v oblasti proximálního humeru, kromě krátkých úponů svalů, které byly posléze použity k upřesnění úponu při měření. Chrupavka hlavice byla rovněž ponechána. Pažní kosti byly poté upnuty do ocelového rámu, který byl speciálně vyroben pro naši studii. Osa proximální metafýzy byla paralelní s dlouhou osou rámu a transepikondylární linie paralelní s rovinou stolu. V několika případech byla transepikondylární linie distálního humeru ozřejmena zavrtáním Kirschnerova drátu přes epikondyly. Drát byl následně upnut do rámu. Digitální fotoaparát byl instalován ve vzdálenosti 3000 mm, tj. vzdálenosti, která minimalizuje vadu čočky objektivu a umožňuje zhotovení snímku, kde 1 pixel = 0,2 mm. Poté byla provedena kalibrace soustavy pomocí měřítka. První snímek byl pořízen při pohledu na vrchlík hlavice. Dále byla pažní kost rozřezána oscilační pilou na plátky po 3 mm, provedeno postupné fotografování a kalibrace každého snímku pomocí měřítka (obr. 3a, b). Fotografie byly ukládány v blocích po sobě jdoucích snímků a digitálně vyhodnocovány.

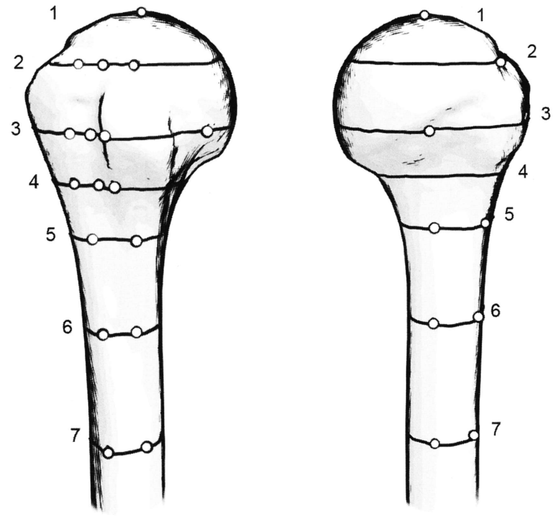
Tímto způsobem jsme detailně zobrazili morfologii proximálního humeru a stanovili jsme si referenční body pro určování parametrů, které byly zmíněny v úvodu. Tyto body byly uspořádány do 7 rovin (obr. 4).

- Rovina 1 procházela vrchlíkem hlavice, na rovině byl zvolen jediný bod.
- Rovina 2 protíná pažní kost v místě, kde prochází velkým hrbolem a proximální hlavicí a neprochází masou malého hrbolu. Byly označeny okraje kloubního povrchu hlavice ventrálně a dorzálně, mediální okraj velkého hrbolu a „nejhlubší" místo sulcus intertubercularis.

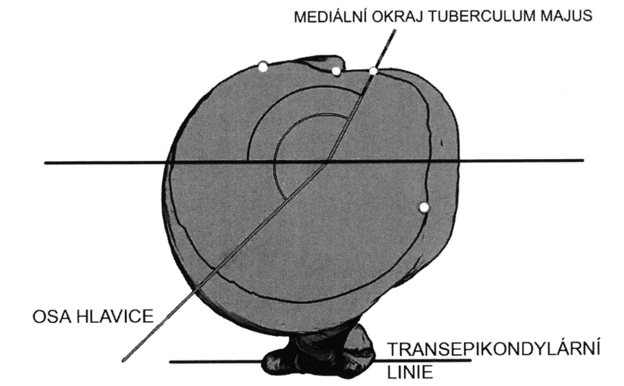
Obr. 3a, b. Pohled na resekované pažní kosti v první skupině



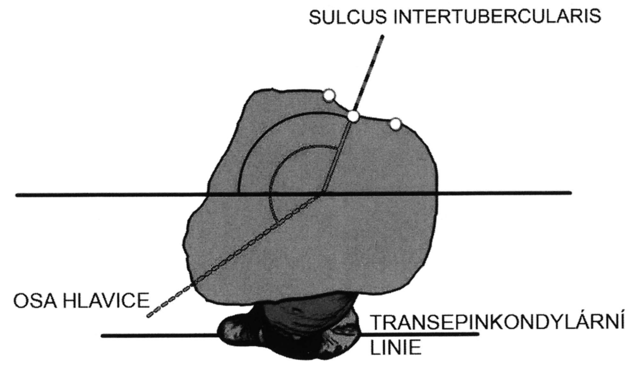




Obr. 4. Schéma znázorňující roviny řezů a na nich hodnocených bodů při pohledu zpředu (vlevo) a zezadu (vpravo)



Obr. 5. Schéma měření pozice mediálního okraje tuberculum majus v 2. rovině



Obr. 6. Schéma měření vztahu sulcus intertubercularis ve 4.rovině (osa hlavice je zobrazená jako průměr z měření ve druhé a třetí rovině)

- Rovina 3 protíná pažní kost v úrovni hrbolů a hlavice. Byly označeny okraje hlavice ventrálně a dorzálně, mediální okraj velkého hrbolu, laterální okraj malého hrbolu a sulcus intertubercularis.
- Rovina 4 protíná oba hrboly a prochází distálně pod hlavicí humeru. Byl označen mediální okraj velkého hrbolu, laterální okraj malého hrbolu a sulcus intertubercularis.
- Rovina 5 je definovaná chirurgickým krčkem. Body byly zvoleny na kompaktě pažní kosti, a to v těchto místech: crista tuberculi minoris, protilehlá kortikalis, crista tuberculi majoris a protilehlá kortikalis.
- Rovina 6 je uprostřed mezi pátou a sedmou rovinou, přičemž byly zvoleny stejné body jako u páté roviny, tj. crista tuberculi minoris, protilehlá kortikalis, crista tuberculi majoris a protilehlá kortikalis.
- Rovina 7 protíná pažní kost v místě proximálního začátku tuberositas deltoidea, kde byla možná identifikace crista tubercularis majoris a v ní byly zvoleny čtyři body po obvodu kompakty.

Měření a následné vyhodnocování probíhalo podle označených bodů v jednotlivých rovinách. Určené body v páté až sedmé rovině sloužily k vytvoření osy proximální metafýzy pažní kosti, tj. osy, ve které je zaváděn dřík endoprotézy. Body v první až čtvrté rovině sloužily k popisu morfologických útvarů proximálního humeru.

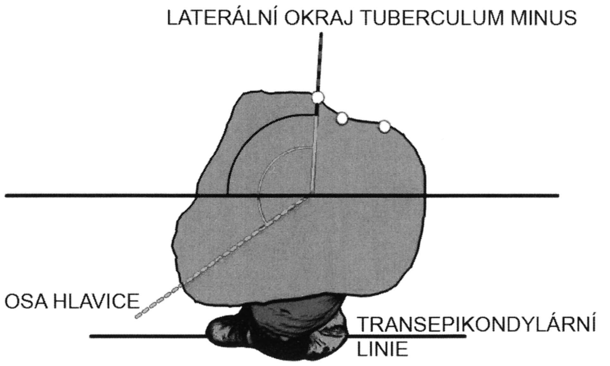
Dále byly postupně v jednotlivých rovinách na proximálním humeru popsány tyto útvary:

Tuberculum majus bylo prostorově definováno jeho mediálním okrajem, tj. okrajem, který přechází v sulcus intertubercularis. Tato ostrá hrana je většinou snadno identifikovatelná na úlomku zlomeniny. Původně bylo zamýšleno hodnotit vrchol, resp. nejvíce prominující bod hrbolu. Při analýze geometrické variability tvaru hrbolu jsme však došli ke značným diferencím. Tím by měření bylo zcela zavádějící. Zmíněný mediální okraj je naopak tvarově velmi konstantní. Byly změřeny úhly, které svírá tuberculum majus s transepikondylární linií a osou hlavice (obr. 5). Vrchol tupého úhlu se nacházel v ose metafýzy pažní kosti. Na obrázku 5 jsou pro příklad vyznačeny úhly v rovině 2.

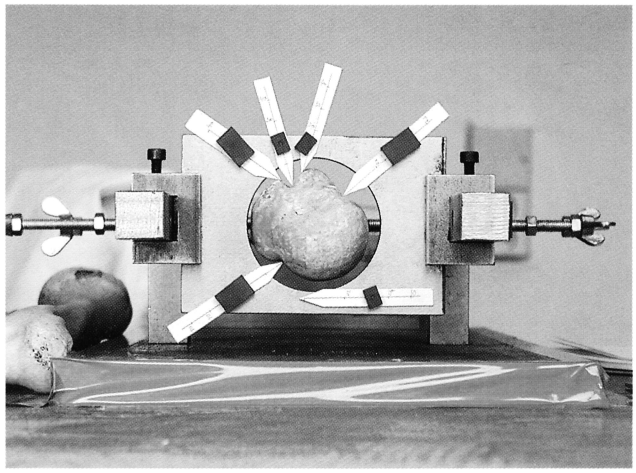
K popisu **sulcus intertubercularis** bylo zvoleno „nejhlubší“ místo, tj. místo, kde je kortikalis nejblíže k ose metafýzy. V daném místě dochází při zlomeninách často k oddělení malého a velkého hrbolu. Pokud je sulcus intertubercularis zachován, lze jej použít k upřesnění pozice úlomku. Rovněž jsme změřili úhly, které toto místo svírá s transepikondylární linií a osou hlavice. Na obrázku 6 jsou pro příklad vyznačeny úhly v čtvrté rovině.

Na **tuberculum minus** byl označen laterální okraj, tj. okraj, který prochází v sulcus intertubercularis. Zde platí obdobně jako u velkého hrbolu možnost tuto hranu identifikovat při zlomenině. Opět nás zajímal vztah hrany k transepikondylární linii a k ose hlavice (obr. 7).

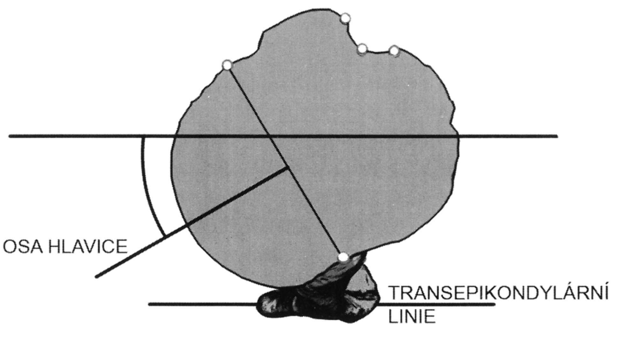
Postavení **caput humeri** v prostoru bylo definováno **osou hlavice a rovinou anatomického krčku**, která vycházela z označeních bodů anatomického krčku ve 2. a 3. rovině. V obou rovinách byla vyznačená osa, kte-



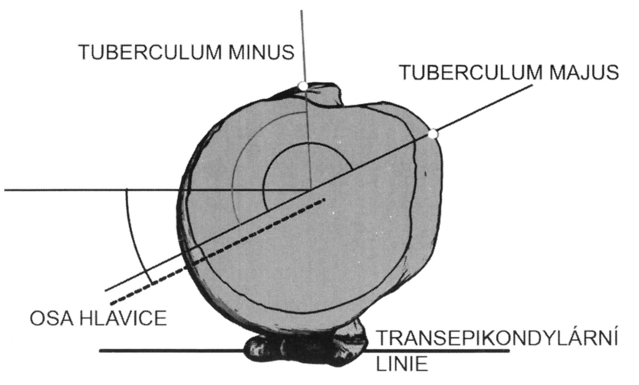
Obr. 7. Schéma měření laterálního okraje tuberculum minus ve 4. rovině (osa hlavice je zobrazená jako průměr z měření ve druhé a třetí rovině)



Obr. 10. Označování bodů v 2. rovině



Obr. 8. Schéma měření retroverze hlavice ve 3. rovině



Obr. 9. Schéma měření maxima kostěné masy velkého a malého hrbolu

rá byla kolmá na spojnici označených bodů anatomického krčku a procházela vrcholem hlavice daného řezu. Retroverze hlavice byla pak definována úhlem mezi osou hlavice a transepikondylární linií (obr. 8).

Dále nás v naší studii zajímalo místo největší kostěné masy v oblasti velkého a malého hrbolu. Tyto hodnoty lze využít pro určení polohy šroubů při fixaci fragmentů hrbolů na dřík endoprotézy (obr. 9).

Naše poznatky jsme aplikovali při samotném měření u druhé a třetí skupiny. V obou metodách jsme volili shodné roviny a na nich shodně definované body pro dobrou reprodukci výsledků a možnost porovnání.

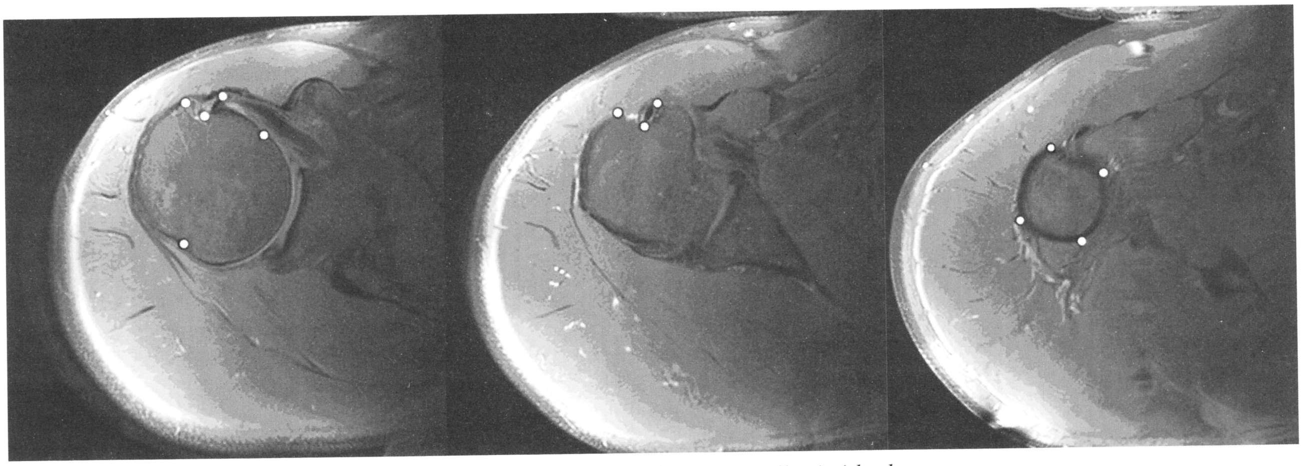
Přímé měření na kostních preparátech

Měření na kostních preparátech jsme opět prováděli v Anatomickém ústavu 1. LF UK. Celkem bylo v **druhé skupině** použito sto deset pažních kostí. Soubor preparátů se skládal z 55 levých a 55 pravých pažních kostí; jednalo se o tzv. suché preparáty. Tyto byly vybírány zcela náhodně mezi těmi, které nevykazovaly zjevné morfologické odchylky, známky degenerativních změn a měly uzavřené růstové chrupavky. Pažní kosti byly posléze upnuty do již zmíněného ocelového rámu. Osa proximální metafýzy byla paralelní s dlouhou osou rámu a transepikondylární linie byla paralelní s rovinou stolu. Postupně byly označovány body na kosti v sedmi rovinách (průřezech), kolmých na proximální metafýzu a snímány digitálním fotoaparátem (obr. 10). Digitální fotoaparát byl instalován opět ve vzdálenosti 3000 mm jako v počáteční skupině. Po kalibraci měřítkem byly pořizovány série snímků, které byly ukládány v blocích.

Digitální rekonstrukce NMR řezů vybraných pacientů

Digitální rekonstrukce NMR řezů jsme provedli u 20 pacientů **(třetí skupina)**, u kterých bylo indikováno NMR vyšetření ramenního kloubu v rámci klinického vyšetření.

NMR vyšetření probíhalo na přístroji Philips (Gyroscan, Medical System Eindhoven). Pacient byl uložen na lůžko přístroje, ramenní kloub ve středním postavení, přiloženy dvě cívky přístroje, jedna v oblasti proximálního humeru druhá v oblasti epikondylů loketního kloubu. Zhotovené bloky T1 vyvážených průřezů zabíraly celou pažní kost, tj. z výsledného stacku (bloku) je možné určit rotaci pažní kosti v prostoru kolem osy Z. Bloky pak byly uchovávány pouze v digitální podobě ve formátu DICOM (obr. 11).



Obr. 11. NMR řezy jednotlivými rovinami horního konce pažní kosti s označenými body

Snímky byly upravovány pomocí programu ImageJ. Tento software jsme vybrali pro jeho nenáročnost k hardwaru a pro jeho jednoduché ovládání. Dále je možné z internetu získat velké množství pluginů pro doplnění funkcí programu, zejména zásuvný modul pro import DICOM snímků, pro zobrazování stacků DICOM formátu, pro měření úhlů a vzdáleností v rovině a zhotovení přímek v prostoru. Získané výsledky byly zpracovány programem Statistica6.

VÝSLEDKY

Výsledky měření jsou shrnuty do následujících tabulek.

Tab. 1. Levá pažní kost: postavení vzhledem k transepikondylární linii (v úhlových stupních), průměrně hodnoty (tučně) a naměřené rozmezí

	Rovina č. 2	Rovina č. 3	Rovina č. 4	Průměr
Tuberculum majus	**136,6** 107,2–164,6	**137,1** 109,2–165,1	**137,3** 115,1–169,9	**137,0**
Sulcus intertubercularis	**119,4** 86,7–148,5	**116,2** 87,7–143,1	**111,1** 82,0–139,3	**115,6**
Tuberculum minus	–	**98,1** 78,7–114,2	**86,5** 58,8–107,4	**96,6**

Tab. 2. Levá pažní kost: postavení vzhledem k ose hlavice (v úhlových stupních)

	Rovina č. 2	Rovina č. 3	Rovina č. 4	Průměr
Tuberculum majus	**164,4** 142,9–184,5	**164,9** 143,8–184,3	**165,1** 144,1–189,0	**164,8**
Sulcus intertubercularis	**147,2** 124,8–172,7	**144,0** 118,6–162,2	**138,9** 117,2–159,0	**143,4**
Tuberculum minus	–	**125,9** 107,0–145,0	**114,3** 95,4–126,5	**124,4**

Tab. 3. Pravá pažní kost: postavení vzhledem k transepikondylární linii (v úhlových stupních)

	Rovina č. 2	Rovina č. 3	Rovina č. 4	Průměr
Tuberculum majus	**139,7** 120,0–168,5	**135,1** 44,1–166,5	**138,9** 120,6–169,9	**137,9**
Sulcus intertubercularis	**124,6** 101,7–152,2	**119,4** 96,8–147,8	**114,4** 98,1–139,3	**119,5**
Tuberculum minus	–	**98,8** 72,0–122,4	**85,2** 37,5–108,2	**97,3**

Tab. 4. Pravá pažní kost: postavení vzhledem k ose hlavice (v úhlových stupních)

	Rovina č. 2	Rovina č. 3	Rovina č. 4	Průměr
Tuberculum majus	**164,9** 148,2–188,3	**160,4** 167,3–184,3	**164,2** 143,9–189,2	**163,2**
Sulcus intertubercularis	**149,9** 125,9–172,0	**144,7** 125,4–167,6	**139,7** 118,8–161,8	**144,8**
Tuberculum minus	–	**124,1** 107,1–145,0	**110,5** 62,9–136,1	**122,6**

Tab. 5. Retroverze hlavice, oboustranně (v úhlových stupních)

	Rovina č. 2	Rovina č. 3	Průměr
Pravá pažní kost	**24,1** 5,2–55,2	**26,6** 9,4–53,7	**25,3** 7,3–54,4
Levá pažní kost	**27,2** 4,9–48,9	**28,4** 9,2–53,6	**27,8** 7,3–45,9

Za zcela zásadní hodnotu pro konstrukci doplňkových fixačních prvků pro fixaci fragmentů velkého a malého hrbolu považujeme vztah osy hlavice humeru (resp. implantátu) k velkému a malému hrbolu (k místu maxima kostní hmoty).

Tab. 6. Maximum kostní hmoty velkého a malého hrbolu vzhledem k ose hlavice (v úhlových stupních)

	Levá pažní kost	Pravá pažní kost	Průměr
Tuberculum majus	**181,1** 165,2–194,5	**180,2** 165,8–196,4	**180,7**
Tuberculum minus	**120,2** 97,1–136,2	**126,9** 105,2–147,8	**123,6**

DISKUSE

Je všeobecně známo, že výsledky náhrad ramenního kloubu při traumatické destrukci jsou podstatně horší než v indikacích osteoartrózy či revmatoidní artritidy (6, 7, 8, 12). Příčinou je problém rekonstrukce komplexně poškozené rotátorové manžety a obnovení adekvátních biomechanických poměrů svalstva ramenního kloubu.

Míra přesnosti, jakou má být rekonstruován proximální humerus při tříštivém poranění, není dosud plně objasněna.

Jedním z rozhodujících parametrů, které je třeba obnovit při aloplastice, je retroverze (3, 11). Chybné nastavení retroverze hlavice endoprotézy může vést k velmi nepříjemné komplikaci – ventrální (méně často dorzální) instabilitě operovaného ramena.

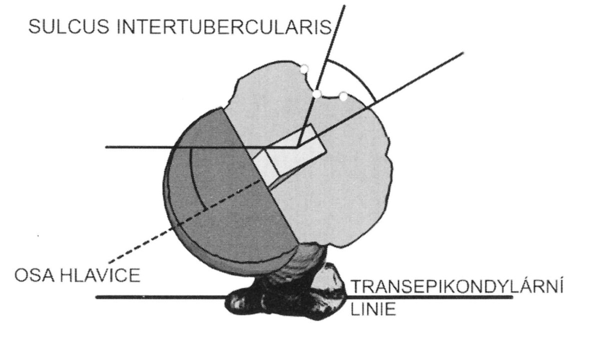
Orientaci při nastavení retroverze poskytuje transepikondylární linie. Podle autorů (2, 3, 5) se pohybuje v rozpětí od +4° až do –50° vzhledem k této linii. Při implantaci většinou volíme střední hodnotu, za kterou autoři považují cca 23° retroverze vzhledem k transepikondylární linii. V naší studii, ve které jsme vycházeli z měření vzhledem k ose metafýzy, se retroverze pohybovala v rozmezí 4,9° až 54,4° s průměrnou hodnotou 26,6° pro obě strany.

Pokud je při zlomenině zachována a při rekonstrukci patrná oblast sulcus intertubercularis, vycházejí někteří autoři při určování retroverze hlavice z jeho pozice. V naší studii jsme měřili tupý úhel svírající „nejhlubší" část rýhy s osou hlavice (vrchol úhlu se nachází na ose metafýzy). Kummer (5) ve své práci rovněž zjišťoval na 420 pažních kostech úhel, který svírá rýha s osou hlavice. Na rozdíl od naší studie vycházel z osy celé pažní kosti a zjišťoval vedlejší úhel. Jeho výsledky ukazují, že osa hlavice je pootočená přibližně 27° dorzálně (obr.12). V naší práci jsme vycházeli z osy proximální metafýzy a naše hodnota je 36,6° pro levou pažní kost a 35,2° pro pravou pažní kost.

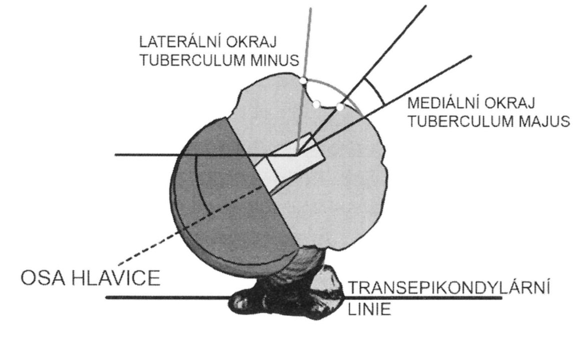
Střední část rýhy je ve svém průběhu daleko variabilnější než „ostřejší" hrany okrajů hrbolů a z našeho pohledu je lépe určovat pozici retroverze hlavice vzhledem k mediálnímu okraji velkého hrbolu anebo podle laterálního okraje malého hrbolu. Výsledky v našem souboru preparátů vycházejí z tabulek 1 a 3 a jsou to vlastně vedlejší úhly pro průměrnou hodnotu postavení velkého a malého hrbolu vzhledem k ose hlavice. Pro malý hrbol je to 55,6° a 57,4° a pro velký hrbol 15,2° a 16,8° (obr. 13).

Doyle (2) měřil ve své studii vzdálenost laterálního okraje sulcus intertubercularis, která odpovídá našemu mediálnímu okraji velkého hrbolu, od osy hlavice u kadaverů i pacientů po implantaci endoprotézy. Jeho výsledek byl 11,8 mm (±3,5mm). Uvedené hodnoty lze použít pro zpřesnění natočení dříku protézy při implantaci endoprotézy v netraumatologických indikacích náhrady ramenního kloubu, kdy si operatér může přímo změřit vzdálenost mediálního okraje velkého hrbolu a nástroje k zavádění dříku protézy (nástroj se musí nacházet v ose hlavice).

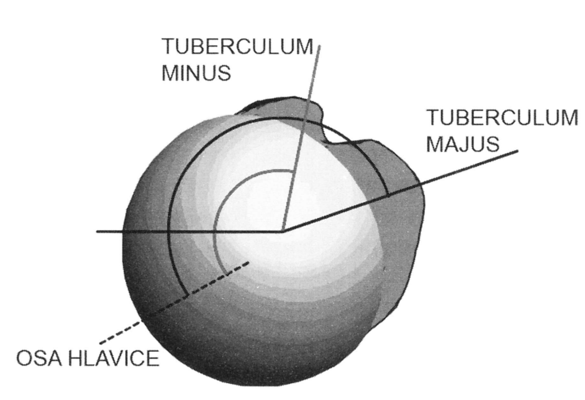
Dále nás v naší studii zajímalo nejen postavení hrbolů, ale také místo největší kostěné masy v oblasti velkého a malého hrbolu. Výsledky jsou shrnuty v tabulce 6. Tyto hodnoty nám ukazují místo, kde je nejvhodnější zavádět šrouby fixující fragmenty hrbolů k dříku endoprotézy. Definice úhlového vztahu velkého a malého hrbolu k ose dříku endoprotézy by měla sloužit k optimalizaci polohy otvorů pro šrouby, které fixují doplňkové osteosyntetické prvky (např. drápková dlaha).



Obr. 12. Schéma zobrazující natočení dříku protézy podle sulcus intertubercularis



Obr. 13. Schéma zobrazující natočení dříku protézy podle okrajů velkého a malého hrbolu



Obr. 14. Schéma zobrazující maximum kostěné masy velkého a malého hrbolu

Výsledky ukazují, že osa proložená maximem kostěné masy velkého hrbolu svírá s osou hlavice v průměru úhel 180,7°. Mezi maximem kostní hmoty malého hrbolu a osou hlavice je úhel v průměru 123,6°. Kostěné masivy hrbolů svírají mezi sebou úhel v průměru 57,1° (obr. 14).

Vypracovanou metodu digitální 3D rekonstrukce pažní kosti lze využít u rekonstrukčních výkonů traumatických stavů proximálního humeru, kdy je vhodné při rekonstrukci respektovat původní prostorové vztahy. Ty zjistíme vyšetřením prostorové anatomie na nepostižené končetině. Jak z našeho měření vyplývá, diference mezi pravou a levou končetinou u stejného pacienta v určitých parametrech je minimální (11).

ZÁVĚR

Pro studium prostorové anatomie proximálního humeru autoři vyvinuli vlastní metodiku měření vztahů požadovaných bodů na pažní kosti jednak na anatomickém preparátu, jednak na virtuálně vytvořeném digitálním 3D modelu, který vychází ze NMR snímků.

Uvedené hodnoty je vhodné využít k zpřesnění konstrukce implantátů pro náhradu ramena. Navíc lze metodu digitálního prostorového modelu pažní kosti využít i pro správné nastavení pozice endoprotézy ramenního kloubu v klinické praxi.

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