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The shape match of the olecranon tip for reconstruction of the coronoid process: influence of side and osteotomy angle

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Background: The integrity of the coronoid process is critical to maintaining elbow stability. Unreconstructible fractures and chronic coronoid deficiency are challenging clinical problems with no clear solution. The purposes of this study were to investigate the shape match of the ipsilateral and contralateral olecranon tips as graft options and to determine the influence of the osteotomy angle on fitment.
Methods: Nineteen paired cadaveric elbow joints were investigated by 3-dimensional digital analysis of computed tomography DICOM (Digital Imaging and Communications in Medicine) data. After construction of an ulnar coordinate system, the ipsilateral and contralateral olecranon tips were digitally harvested at 10°, 20°, 30°, 40°, 50°, and 60° osteotomy angles. In an overlay analysis, we compared the shape match of the ipsilateral and contralateral grafts and the different angles.
Results: The ipsilateral grafts showed an average mismatch of 1.8 mm (standard deviation, 1.38 mm), whereas the contralateral grafts had a significantly lower ($P < .001$) mean mismatch of 1.3 mm (standard deviation, 0.95 mm). The 50° osteotomy plane showed the best shape match in comparison with the native coronoid—in both the ipsilateral and contralateral grafts. Evaluation of the intraclass correlation coefficient was calculated at $r = 0.944$, showing high repeatability of the measurements.
Conclusions: The contralateral olecranon tip graft showed significantly better shape matching to the native coronoid than the ipsilateral olecranon graft. Specifically, the contralateral graft more closely matched the biomechanically critical anteromedial coronoid facet. Finally, both the contralateral and ipsilateral olecranon grafts had better shape matching with the native coronoid when osteotomy was performed at higher angles, specifically 50°.
Level of evidence: Anatomy Study; Imaging

Keywords: Coronoid; graft; olecranon tip; instability; reconstruction; defect; fracture

The coronoid process of the proximal ulna has been shown to be of great importance for elbow stability and function. Experimental studies have highlighted the contribution of the coronoid to elbow biomechanics and have reported that it not

Ethical committee approval is not applicable to cadaveric studies.

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only provides varus stability but also resists posterior and rotational forces.[12,13,22]

Defects of the coronoid process can lead to acute and chronic elbow instability, resulting in subluxation or recurrent dislocation and, thereafter, rapid degeneration to post-traumatic arthritis.[6] To restore stability in unreconstructible coronoid fractures, prosthetic replacement is an option, but clinical experience is very limited and, presently, an implant is not commercially available.[7,11] Another option in acute and chronic coronoid deficiency is replacement with autografts or allografts.[9,21] Autograft donor sites that are available include the iliac crest, radial head, and ribs. Moreover, the navicular bone has been reported as a possible donor site for coronoid reconstruction.[9] In a previous study, good fitting accuracy was shown with grafts from the ipsilateral olecranon tip.[2] However, harvesting the osteoarticular olecranon graft from the injured elbow may adversely affect an already compromised elbow joint, as the olecranon is an important contributor to elbow varus and/or valgus stability.[3,5]

The contralateral olecranon tip, however, has not been investigated for its suitability as a graft for coronoid reconstruction. In addition, it has not been investigated to what extent the osteotomy angle at the base of the olecranon tip might influence its fitting capabilities to reconstruct the coronoid. By changing the angle of the osteotomy, the projection of the articular surface of the graft onto the trochlea might be optimized. Hence, the aim of this study was to compare the shape match of the contralateral and ipsilateral olecranon tips for coronoid reconstruction. In addition, the influence of variable osteotomy angles at the olecranon tip on the shape match was evaluated. It was hypothesized that osteotomy of the contralateral olecranon tip performed at a higher base angle offers a better shape match than the ipsilateral side and lower osteotomy angles.

Methods

Nineteen paired cadaveric elbow joints (14 male and 5 female cadavers; mean age, 69 ± 16 years) were available for analysis. All 38 elbows were imaged by computed tomography (CT) (Discovery CT750 HD [GE Medical Systems, New Berlin, WI, USA]; reconstruction matrix, 512 × 512; voltage, 120 kV [peak]; current, 200 mA). The CT images were taken with a slice thickness of 0.625 mm (voxel dimensions of 0.625 in the axial direction × 0.180-0.229 in the coronal direction × 0.180-0.229 in the sagittal direction). The DICOM (Digital Imaging and Communications in Medicine) data from the CT scans were imported into Mimics Software (version 17.0, Mimics Innovation Suite; Materialise, Leuven, Belgium), and 3-dimensional (3D) reconstructions of the isolated proximal ulna were constructed. According to the technique described by Gray,[10] a proximal ulnar coordinate system was generated to facilitate navigation of the 3D reconstructions in the transverse, coronal, and sagittal planes. The ulnar coordinate system was derived using the guiding ridge of the greater sigmoid notch and the flat spot of the dorsal aspect of the proximal ulna to align the axes with specimen-specific anatomic landmarks.

Olecranon tip graft

A 40% coronoid defect was simulated, randomly alternating between the left and right sides in the paired specimens, using the technique published by Gray.[10] A 40% defect of the coronoid was chosen as several previous studies defined this amount of bony defect as a threshold value for the generation of varus elbow instability.[2,4,11] To create the defect, the maximum height of each coronoid was measured in the sagittal plane and the 60% height, measured from the base, was marked. The virtual osteotomy was then conducted in the coronal plane at the 60% sagittal height, resulting in a 40% coronoid deficiency in 1 of each paired specimen. Hence, nineteen 3D models of a proximal ulna with a defined coronoid defect were available (Fig. 1).

After construction of the coronoid deficiency bone models, osteoarticular ipsilateral and contralateral olecranon tip grafts were created. To create the grafts, the length of the 40% coronoid defect was transferred in millimeters onto the respective olecranon tip as the radius of a circle, having its center point at the very tip of the olecranon (Fig. 2). The intersection of the circle with the articular surface of the olecranon tip served as the starting point for the osteotomy. For each ipsilateral and contralateral olecranon, 6 osteotomies in 10° increments were conducted. The angulation of the osteotomies was oriented to a plane parallel to the flat spot of the olecranon. The osteotomy plane was oriented orthogonal to the sagittal axis of each specimen, in concordance with the individual coordinate system.

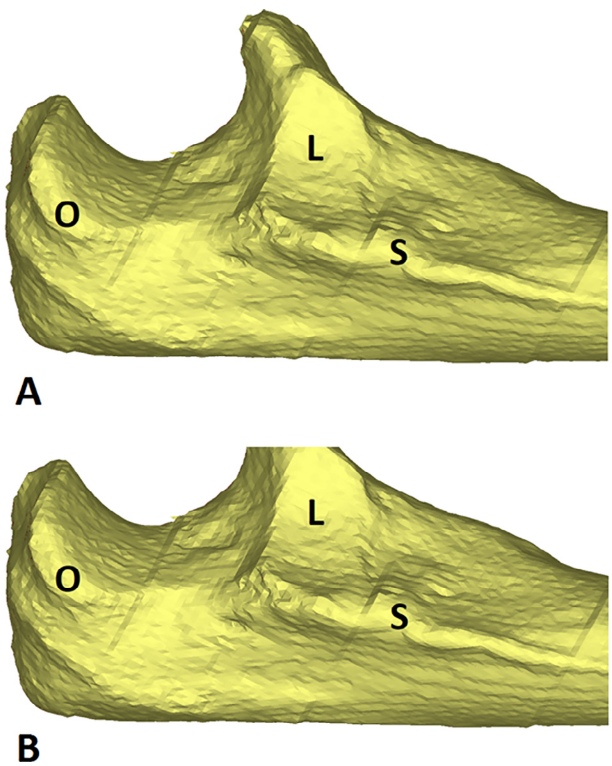

Figure 1 Three-dimensional models of proximal ulna before **(A)** and after **(B)** creation of 40% coronoid defect. *L*, lesser sigmoid notch; *O*, olecranon; *S*, supinator crest.

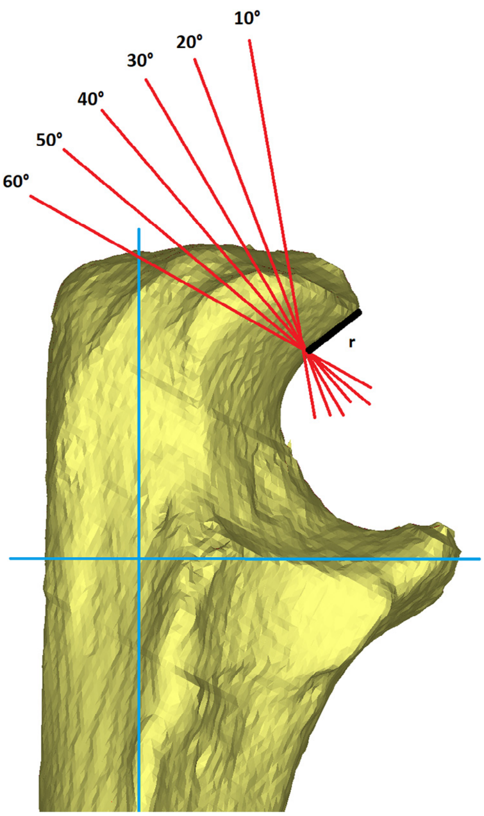

Figure 2 The length (*r*) equals the length (in millimeters) of the 40% coronoid defect that had been created. The *red lines* represent the 6 angles of the olecranon osteotomy that would be studied for fitment with the deficient coronoid. The 0° angle runs parallel to the flat spot of the corresponding olecranon, which is defined with the constructed coordinate system (*blue lines*).

The olecranon grafts were virtually removed from the contralateral or ipsilateral ulnae as 3D surface models stereolithographies (STLs) (Fig. 3). Each model retained an individual coordinate system that could be used to translate and rotate the graft to the desired position within the associated software (3-matic, Mimics Innovation Suite). Within the 3-matic software, the olecranon grafts were placed by a best-fit technique onto the coronoid defect (Fig. 4).

Measurement regions

The plane along the guiding ridge of the greater sigmoid notch was duplicated to create 2 identical planes (3-matic, version 11.0). These planes were translated to the most medial and lateral aspects of the native coronoid. The distance between these 2 planes was calculated using custom code (MATLAB; The MathWorks, Natick, MA, USA) to measure the medial-lateral length of the native coronoid. This distance was equally separated into 10 discrete regions in each of the cadaveric specimens (Fig. 5). This resulted in measurement regions approximately 2.5 mm in width (depending on specimen size) from the medial to lateral aspects of the native coronoid. These measurement regions allowed for a localized comparison of each graft with the native coronoid to determine the best-fitting graft.

Bone geometry comparison

The articular surfaces were re-meshed with a uniform 0.1-mm triangular surface mesh. The articular surface of the native coronoid and each contralateral or ipsilateral olecranon graft was separated using discrete surface marking (Fig. 6). To complete this, the articular surface of each graft was marked using the built-in surface-marking tools within the 3-matic software. This allowed for comparison of only the articular surfaces while removing the possibility of extraneous noise from points outside the articular regions. Each of the 13 bone geometries (coronoid and 10°, 20°, 30°, 40°, 50°, and 60° osteotomies for each contralateral and ipsilateral olecranon) were exported as STL files. After placement, an overlay analysis technique was used to identify the best-fitting graft in comparison with the native coronoid process.[16] To complete this, the vertices of each STL file were extracted using custom MATLAB code to generate a point cloud of the native coronoid and each of the olecranon grafts. The Euclidean distance between the nearest point on the native coronoid and each olecranon osteotomy model was measured and collected. This method provides a single value (distance in millimeters) for comparison of every point that represents the native coronoid and corresponding graft (Fig. 7). For localized measurements, points were separated into the 10 measurement regions (Fig. 5) and plotted.

The mean, standard deviation (SD), maximum, and minimum values of each parameter were calculated. A Welch 2-sample t test was performed to evaluate statistically significant differences. The level of significance was set at $P < .05$.

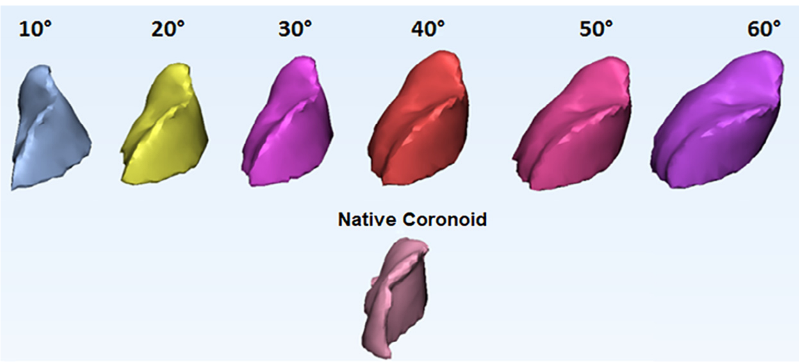

Figure 3 Variable base-angle olecranon grafts from 10° to 60° (*top row*) and post-osteotomy native coronoid process tip (*bottom row*) in a representative sample specimen.

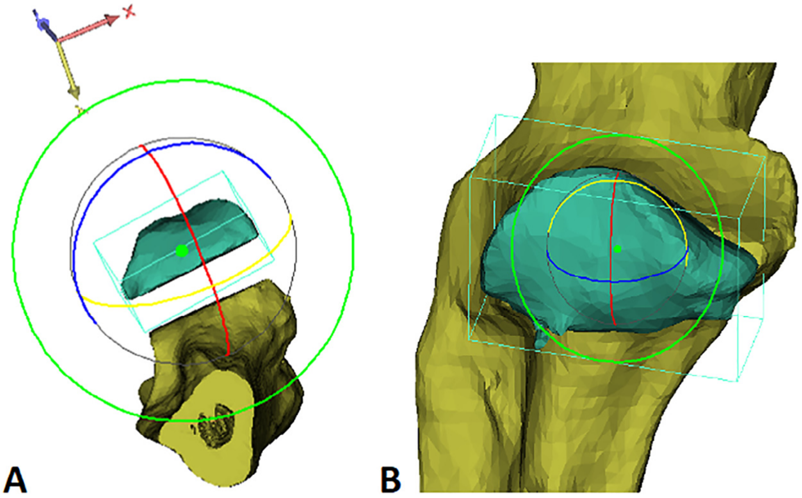

Figure 4 Placement of a 50° olecranon graft onto the 40% coronoid-deficient ulna as observed from distal **(A)** and ventral **(B)** vantage points.

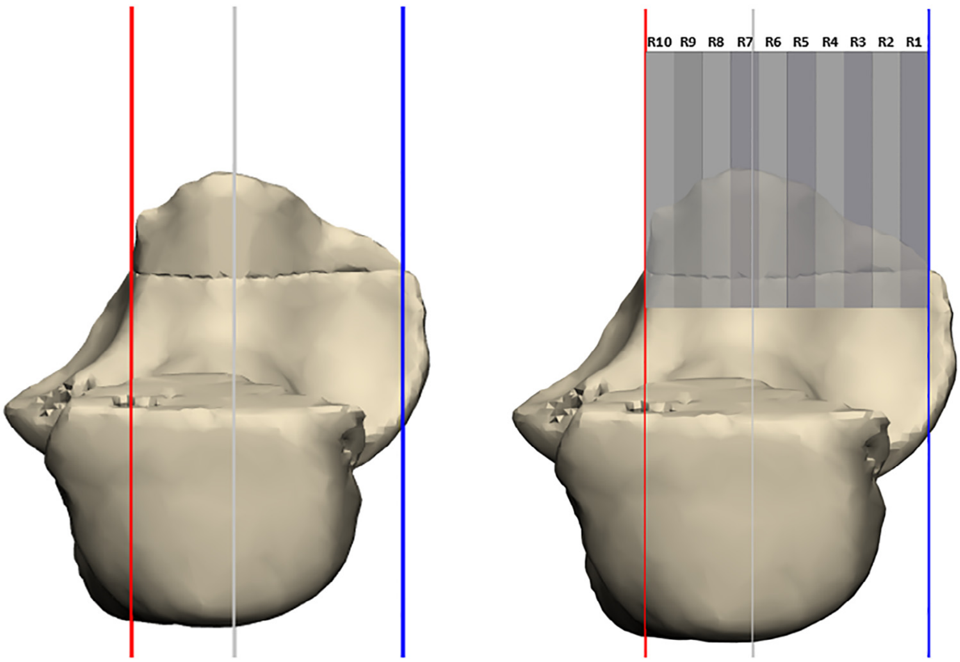

Figure 5 The greater sigmoid notch was separated into ulnar and radial segments. The ulnar and radial segments were each further subdivided into 5 discrete regions. By assessing and comparing at each discrete region, we were able to differentiate segmental and regional fitting characteristics of the measured grafts. *R*, region.

To develop a ranking within the different osteotomy angles, a single-step multiple comparison was performed using the Tukey range test. To investigate the intrarater reliability of the measurements, in 4 specimens, the measurements for the ipsilateral and contralateral grafts at the 6 different angles were repeated (K.W.) and the intraclass correlation coefficient was calculated.

Results

Overall, the measurements revealed that the contralateral osteoarticular olecranon tip grafts showed a better shape match as a coronoid replacement than the ipsilateral grafts (Figs. 8 and 9). The ipsilateral grafts showed an average deviation of 1.8 mm (SD, 1.4 mm; maximum, 0.1 mm; minimum, 7.9 mm), whereas the contralateral grafts had a statistically significantly lower ($P < .001$) mean deviation of 1.3 mm (SD, 1.0 mm; maximum, 5.4 mm; minimum, 0.2 mm).

The comparison of the medial to lateral regions (regions 1-4 [mean, 2.2 mm; SD, 1.7 mm; maximum, 7.9 mm; minimum, 0.1 mm] vs regions 7-10 [mean, 1.5 mm; SD, 1.0 mm; minimum, 0.1 mm; maximum, 5.1 mm]) within the

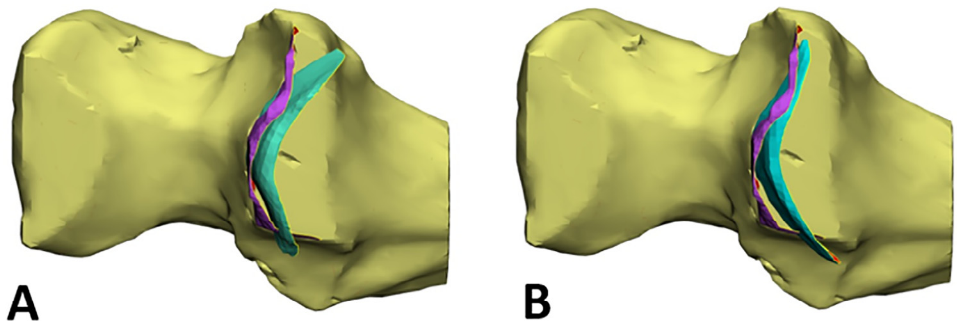

Figure 6 Native articular coronoid surface (*purple*) compared with ipsilateral 30° olecranon osteotomy (*green*) **(A)** and contralateral 30° (*green*) olecranon tip osteotomy fragment **(B)**.

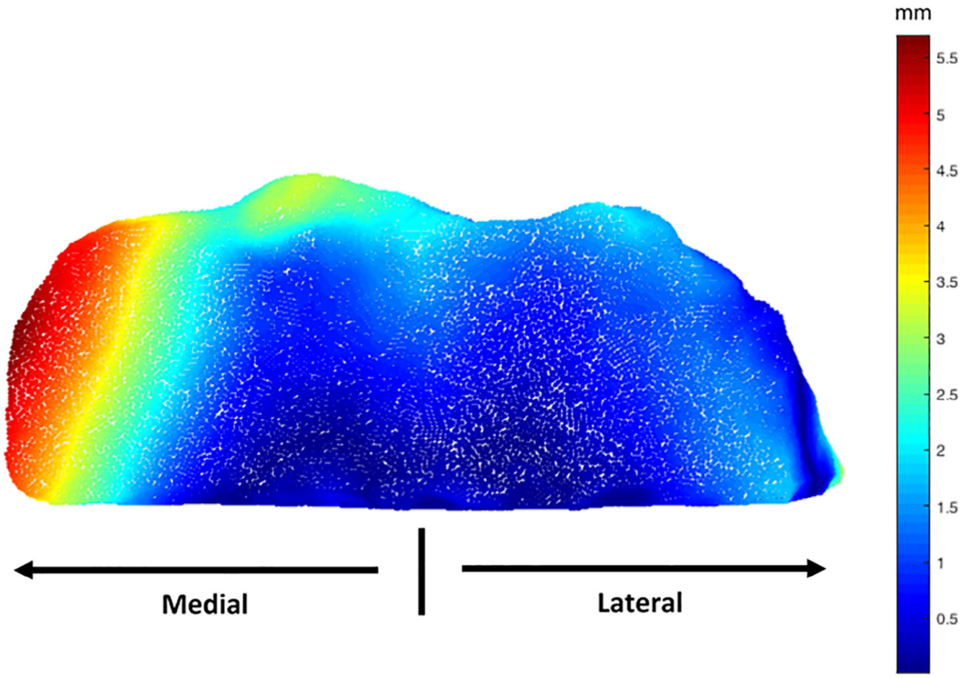

Figure 7 Ipsilateral left-sided 30° osteotomy olecranon graft (left side is medial) mapped to native coronoid. The colors represent the closest distance (in millimeters) between the ipsilateral olecranon graft and the native coronoid articular surface.

ipsilateral and contralateral grafts showed significantly lower deviation values for the lateral side compared with medial in the ipsilateral group ($P < .001$). In the contralateral group (regions 1-4 [mean, 1.3 mm; SD, 1.0 mm; maximum, 5.4 mm; minimum, 0.2 mm] vs regions 7-10 [mean, 1.4 mm; SD, 0.9 mm; minimum, 0.2 mm; maximum, 4.2 mm]), no significant differences were found ($P = .188$) (Fig. 9).

When the angle of the osteotomy was assessed, the 50° osteotomy plane showed the least amount of deviation in comparison with the native coronoid—in both the ipsilateral and contralateral grafts. In both groups, the 50° osteotomy plane showed significantly less deviation than the 30°, 20°, and 10° planes ($P < .02$). Regarding the 60° and 40° cuts, the differences were not statistically significant ($P > .05$). The mean intraclass correlation coefficient was calculated as 0.944, showing high reliability of the measurements.

Discussion

The purpose of this study was to assess the shape match of the olecranon tip, in both ipsilateral and contralateral grafts, for reconstruction of the deficient coronoid process. Our results highlight 2 distinct findings: First, the contralateral olecranon tip graft has a significantly better shape match to the coronoid than the ipsilateral olecranon graft; and second, the angulation of the osteotomy to harvest the graft has a significant impact on its fitment with higher osteotomy angles allowing for better matching. Both of these findings add

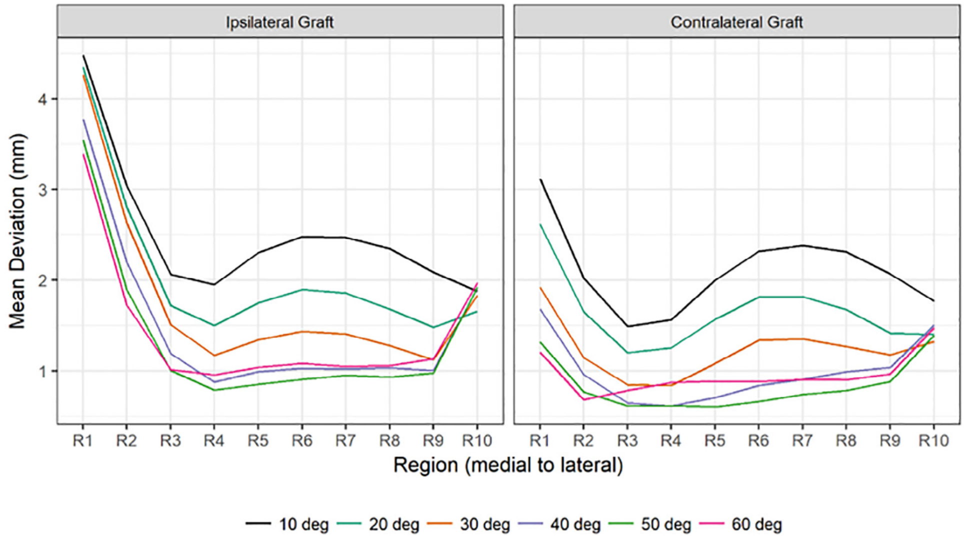

Figure 8 The graph shows the mean deviation (in millimeters) of the ipsilateral (*left*) and contralateral (*right*) grafts with respect to the medial (region 1 [*R1*]) to lateral (region 10 [*R10*]) regions of the grafts. The different colors represent the 6 different olecranon osteotomy planes, with the 10° plane (*black*) showing the highest and the 50° osteotomy plane (*light green*) showing the least deviation compared with the native coronoid. *deg*, degrees.

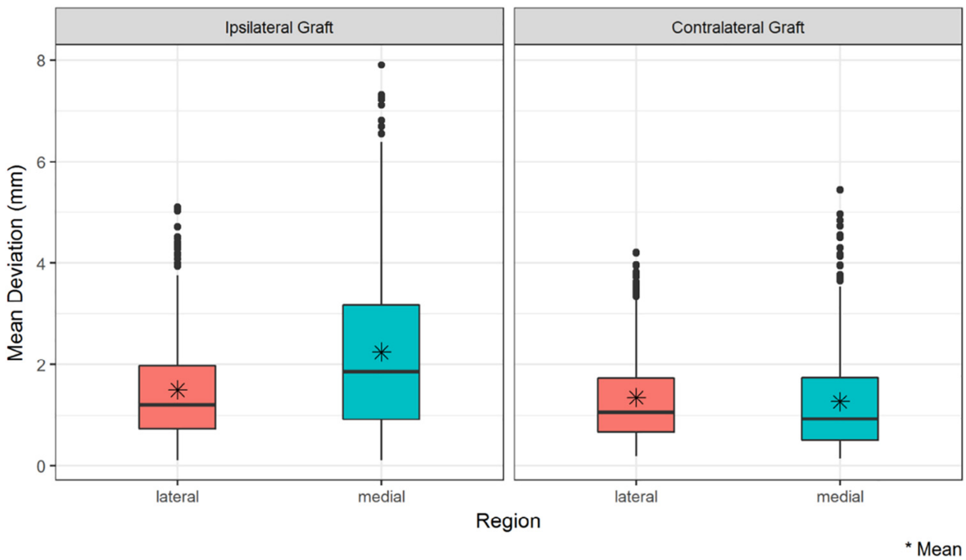

Figure 9 Box plot showing higher deviation for ipsilateral olecranon (*left*) grafts compared with contralateral olecranon grafts (*right*). *Mean.

valuable knowledge for surgeons conducting reconstructive elbow surgery.

The elbow joint depends on an intricate relationship of several stabilizing structures. Besides ligaments and muscles, a complex bony geometry, especially at the ulnohumeral joint, facilitates stable interaction between the upper arm and forearm. The coronoid process is a key component to overall elbow stability and is prone to fracture, often with a concomitant fracture of the radial head.[14] Since the study of Closkey et al[8] in 2000, it has been known that the coronoid process stabilizes the forearm against posterior dislocation under axial loading. Further biomechanical studies have also identified the coronoid process as an important contributor to varus stability.[12,20] Hartzler et al[12] showed a significant increase in varus and internal rotational stability when reconstructing coronoid fractures in cadaveric elbows. In a study by Pollock et al,[20] it was shown that the anteromedial facet of the coronoid process is especially important for varus stability, together with the lateral collateral ligament. As a consequence, acute or chronic deficiency of the coronoid often leads to clinical instability of the elbow, pain, stiffness, and rapid degeneration.[1]

Reconstruction of the coronoid process can be performed by prosthetic replacement, as reported by Bellato and O'Driscoll[7] in 2017. Gray et al[11] showed that by using a metallic coronoid prosthesis in cadavers, elbow stability could be restored. Unfortunately, no coronoid implants are currently commercially available. In terms of longevity and material properties, reconstruction of the coronoid with an osteoarticular graft may be preferred. However, coronoid allografts are not widely available and have all the issues associated with allografts, such as resorption, infection, and nonunion.[19,23] In contrast to allografts, autografts are expected to offer better viability but have donor-site morbidity.[17,18] Despite good shape matching,[15] radial head autografts cause donor-site morbidity and are not typically available except in cases of associated unreconstructible radial head fractures. Osteochondral rib grafts have also been reported; however, these have harvesting issues and associated complications that involve the thorax.[17] The iliac crest is safe for harvesting with reasonably low donor-site morbidity; however, the grafts do not have articular cartilage and, as such, might contribute to rapid degeneration of the articular surface of the trochlea. Alolabi et al[2] investigated the suitability of the ipsilateral olecranon tip as a replacement for coronoid deficiency. In a cadaveric study, they were able to restore normal elbow stability after using the ipsilateral olecranon as a graft for a 40% coronoid defect. Because it is an intra-articular structure, the olecranon tip is covered with articular cartilage. It is common knowledge that the olecranon adds to varus as well as valgus stability.[3,5] The effect of ipsilateral olecranon tip resection on coronoid-deficient elbows has not been reported in biomechanical or clinical settings, so one can only assume that further destabilization by resection of the ipsilateral olecranon may occur. It should also be emphasized that the available biomechanical data concerning the contribution of the olecranon to elbow stability are based on models with otherwise intact ulnohumeral articulations. As the contralateral joint would be otherwise intact, taking the olecranon tip might have fewer destabilizing effects on the joint. Theoretically, this renders the contralateral side as an intriguing alternative donor site for osteochondral grafts for coronoid reconstruction. The relevant advantage of the contralateral olecranon tip as a graft, in our opinion, is the significantly better shape match with the native coronoid, as shown by our data. We found that the overall shape match was better in the contralateral grafts than in the ipsilateral grafts. This is because the olecranon tip, like the coronoid, is not axis symmetrical but has a wave-like shape, with 2 slightly different wing-like structures that meet at the central ridge (Fig. 6). Because it is not axis symmetrical, 1 articular facet better replicates the important anteromedial facet area of the native coronoid.

Most of our daily activities are performed with the elbow under varus loading.[6] Hence, optimal fitting of the medial-sided structures that are responsible for resisting varus could be advantageous in preserving joint function. Biomechanical studies will have to evaluate whether contralateral olecranon grafts allow better restoration of varus stability, as our study investigated only shape matching. In addition, clinical studies are required to assess healing and patient outcomes concerning restoration of elbow stability in cases of chronic coronoid deficiency. Our study has shown only that the side of the graft and the angle of the base of the graft have strong influences on the shape match of the olecranon tip with the native coronoid. The higher-angle 50° osteotomy olecranon graft results in a more upright positioning of the graft at the coronoid recipient site, which renders the graft more like the native coronoid. This was shown for the ipsilateral as well as the contralateral olecranon grafts.

This study does have limitations. Although not directly investigated during this study, a relevant disadvantage of the proposed technique is donor-site morbidity, as the contralateral healthy elbow is subjected to a surgical procedure that does carry inherent risks, such as infection, nerve injury, heterotopic ossification, and stiffness. Another limitation is that the CT scans used for analysis were taken from cadaveric specimens. Because of the commonly limited availability of young specimens, it was not possible to match the specimens' ages to the age group of patients who typically have coronoid fractures. The average age of our specimens was 69 years, which may limit the strength of the conclusions of this report. Increased age comes along with degeneration and changes to the articular structures that might not be present in younger patients; however, we excluded all specimens with CT scans indicating arthritis, trauma, deformity, or prior surgery. The use of CT data from living patients was not possible. Obtaining bilateral CT scans of normal elbows in younger patients was not ethically approved because of the unnecessary radiation exposure. Concerning the surgical technique, it has to be stated that when harvesting the graft, it is necessary to respect the size of the graft and to match it to the ipsilateral native coronoid. An oversized graft may lead to flexion limitation, when the graft impinges on the coronoid fossa.

Conclusion

Our results indicated that the contralateral olecranon tip showed significantly better shape matching to the native coronoid than the ipsilateral olecranon tip graft. In addition, the contralateral graft better reconstructed the important anteromedial facet of the coronoid. Finally, both the contralateral and ipsilateral olecranon grafts had better shape matching with the native coronoid when osteotomy was performed at higher angles, specifically 50°.

Disclaimer

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