Investigation of the geometries of the coronoid process and the fibular allograft as a potential surgical replacement

Hongru Zhao a, Benjamin Herman b, Samer Aedeab, David Sheps b, Marwan El-Rich a,⁎

a Department of Civil and Environmental Engineering, University of Alberta, Canada
b Division of Orthopaedic Surgery, University of Alberta, Canada

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A B S T R A C T

Background: The proximal tibiofibular joint can be used as a source of osteochondral autograft with little to no morbidity at the harvest site.

Methods: CT scans of fourteen left and seven right fibular heads, seven right and six left ulnas obtained from healthy subjects were volume-scaled and analyzed. Ipsilateral ulnar articular surfaces were compared between subjects and contralateral ulnas were compared within the same subject. The average deviations between the surfaces were measured. Manual registration and best-fit alignment were used to locate the area on the fibular heads that would best-fit the 50% coronoid process surface.

Findings: The average deviations in the articular surface between subjects were (mean (SD) 0.79 mm (0.17) and 0.76 mm (0.14) for the left and right ulnas respectively and 0.35 mm (0.07) in the same subject. The average coronoid process height of the scaled ulnas was 15.92 mm (1.15). When comparing the 50% coronoid process with the ipsilateral fibular head geometries, the maximum deviations for all subjects were smaller than 2.0 mm. Two locations were identified as the best-fit locations.

Interpretation: When volume-scaled, the articular congruency of the proximal ulna articular surfaces between subjects is within the allowable limit for a typical intra-articular fracture step. Results suggest it is possible to use the CT scan of a patient’s contralateral elbow as a template to estimate the morphology of the affected side. The fibular head could be an alternative replacement for damaged coronoid process since it is covered by articular cartilage and has locations with a similar curvature as the coronoid process.

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1. Introduction

The coronoid process is a triangular-shaped projection located in the proximal ulna. It combines with the olecranon to form the proximal articular surface that articulates with the trochlea of the distal humerus. The coronoid provides a bony buttress to prevent posterior displacement (Chung et al., 2007). Its anteromedial surface is also the site of attachment for the anterior bundle of the medial collateral ligament of the elbow, which provides valgus stability.

Two-10% of elbow dislocations are associated with a fracture of the coronoid process (Morrey, 1993). Such injuries usually result from a strong varus force with an axial load on the hand when the elbow is between 0° and 35° of flexion (Steinmann, 2008; van Riet et al., 2005). It rarely occurs in isolation as injuries to the radial head and lateral collateral ligament are often present in conjunction with an elbow dislocation (Steinmann, 2008). Lack of proper treatment can lead to varus instability of the elbow and, eventually, ulnohumeral arthritis.

The treatment of coronoid fractures is based on the classification of Regan and Morrey. It bases fractures on the size of the fragment as seen on a lateral X-ray. Type I are avulsions of the tip; type II are fractures less than 50% of the height of the coronoid; and type 3 are greater than 50% (Regan and Morrey, 1989). Type 1 and 2 fractures rarely affect the stability of elbow unless there are associated soft tissue injuries and are usually treated non-operatively. Operative fixation is required for type 3 fractures to restore stability to the joint (Samii and Zellweger, 2008; Steinmann, 2008).

Open reduction and internal fixation with various screw and plate constructs are used to most simple coronoid process fractures (Steinmann, 2008). However, when a coronoid is severely comminuted, autogenous bone graft may be necessary to restore the structural integrity of the coronoid (Chung et al., 2007; Urbaniak and Black, 1985; van Riet et al., 2005). There are also many reports of using osteochondral allograft in cases of bone loss in intra-articular elbow fractures (Breen et al., 1988; Dean et al., 1997; Jerosch et al., 2002; Urbaniak and Black, 1985).
The fibula can be used as a source of bone graft in cases of bone loss (Jerosch et al., 2002; Keating et al., 2005). Specifically, the proximal tibiofibular joint can be used as a source of osteochondral graft with minimal to no morbidity at the harvest site (Jerosch et al., 2002). This would be the case in a severely comminuted coronoid process. It should be noted however, that while the fibular heads offer many advantages as replacements for damaged coronoid process, the associated procedure might be lengthy and technically demanding. Possible complications at the harvest site include peroneal nerve injury, joint instability and arthritis. However, these are rare and can be addressed with a fibular head resection or fusion (Jerosch et al., 2002). In addition, prolonged protected weight-bearing is required. (Keating et al., 2005).

The first objective of this paper is to investigate the articular surface morphology and size of the coronoid process. This is performed by comparing the articular morphology of the coronoid process from different sides of individual subjects as well as making a comparison between subjects. The second objective is to present a rigorous methodological technique based on modern computer tools by which a fibular allograft can be used to replace the coronoid process.

2. Methods

2.1. Data acquisition

The CT scans of the left and right ulnas and the left and right fibulas of seven healthy subjects (3 females and 4 males) with an average age of 24 were acquired. The subjects signed a consent form to be included in the study. The size of the CT scans was set at 512 × 512 pixels, with 0.645 mm resolution. The CT scans were imported into Mimics®, which is a 3D image modeling software. Using Mimics, the original 3D figures of these subjects were regenerated, and eventually, the 3D files were transferred to Geomagic® for investigation. One of the seven subjects moved during acquiring the CT scans of their left ulnas and right fibulas, so the results of this subject’s left ulna and right fibula were not used. Besides that, another subject also moved during the acquisition of the subject’s right fibula, so this subject’s right fibula was not used as well.

2.2. Scale ulnas to the same volume

The first task in comparing the relative geometries of different specimens in a group is to scale the individual parts to the same volume. This was done by picking the average volume of the group and then scaling the individual group members to that average value. The scaling factor $r$ was obtained as follows:

$$r = \sqrt[3]{\frac{V_{av}}{V}}$$

where $V$ is the volume of the member to be scaled and $V_{av}$ is the average volume. The respective volumes were measured and the scaling factor applied using the built in functions in Geomagic. The procedure was applied to two different groups: the left ulnas and the right ulnas.

2.3. Determination of the height of the coronoid process

The height of the coronoid process is an important parameter for studying the coronoid process’ anatomy. To measure this value, the best-fit cylinder of the ulna was created and its central axis was used as the central (longitudinal) axis of the ulna. Then, two cylinders were created along that central axis of the ulna. The bigger cylinder (cylinder 1) exactly passed through the furthest point and the smaller cylinder (cylinder 2) passed through the closest point of the ulna (Fig. 1). The height of the coronoid process was defined as half the difference between the two cylinders’ diameters. The furthest point can be obtained by adjusting the diameter of the bigger cylinder until it just covers the whole ulna, and the bigger diameter was denoted $d_1$. To locate the lowest point, a plane was created by the central axis and the furthest point. The lowest point of the coronoid process was defined as the point on the intersection between the bone surface and the defined plane which is closest to the central axis of the ulna (Fig. 1). The lowest point defined an inner cylinder whose diameter was denoted $d_2$. The height of the coronoid process was calculated using the formula:

$$h = \frac{d_1}{2} - \frac{d_2}{2}.$$

2.4. Isolating the proximal ulna distal to the coronoid process

The proximal ulnas along with the relevant bony articulating surfaces were the only portions of the ulna that were investigated in this work. In order to minimize the effects from the distal parts, only the proximal ulna which comprises about 20% of the ulna’s length was kept while, the remaining part was deleted (Fig. 1A).

2.5. Dimensional variations of the ipsilateral ulnas among different individuals

For each pair of subjects and for each side the scaled proximal ulnas were roughly aligned by using the function “Manual Registration” (Fig. 2), and accurately aligned by the “Best-Fit Alignment” function. After that, “3D analyses” were performed to measure the deviation between the pairs.

For each pair, the “3D analysis” toolbox in Geomagic provided two values to describe the variation between the two surfaces: a positive mean value and a negative mean value describing the average positive and negative deviations of a reference surface with respect to the test surface respectively (a positive or negative deviation refers to a position of a test surface that is above or below a reference surface). The larger absolute value of those two numbers was selected as a measure of the deviation for comparison. Each subject was taken as a reference object and the remaining subjects were compared to this reference subject as test objects. The deviation was reported for two sets of surfaces, the first was for the whole proximal ulna and the second was for the articulating surfaces of the elbow joint. Finally, 144 (60 (5 × 6 × 2) for left proximal ulna and 84 (6 × 7 × 2) for right proximal ulna) deviations were used for the statistical analysis.

2.6. Dimensional variations of left and right ulnas among the same subjects

In order to investigate the dimensional variation between the left and right ulnas, the right side proximal ulna was reflected using the “Mirror” function. Then, the manual registration, the best-fit alignment, and the 3D analysis described in the previous section were applied to compare the reflected right ulna with the left one (Fig. 3).

2.7. Isolating 50% of the coronoid process

The longitudinal plane (plane 1 in Fig. 2A) defined by the central axis and the furthest point was first drawn. Then, a second plane (plane 2 in Fig. 2A) which is perpendicular to the longitudinal plane and located at half of the height of the coronoid process was used to trim the upper 50% coronoid process (Fig. 2A).
2.8. 50% coronoid process width measurement

The width of the 50% coronoid process was obtained on the cross section of the ulna described by the longitudinal axis of the best-fit cylinder (longitudinal axis of the ulna) and the furthest point described above. The width of the 50% coronoid process was calculated as the distance between two intersection points (points 1 and 2 in Fig. 3A) of a line (line 1) which was created by two perpendicular planes (planes 1 and 2 in Fig. 2A) and the surface of the coronoid process (Fig. 3A).

2.9. Comparisons of fibular heads

Only seven subjects were compared, and the result showed that there is a large variation in the shape and curvature of the fibular heads among the subjects (Fig. 4).

2.10. Selection of best-fit locations

We used “Manual registration” and “Best-fit alignment” to locate the area on the fibular heads that would best-fit the 50% coronoid process surface. Usually, in the first trial, at least one location can be found on the fibular head. However, some locations are not qualified as appropriate locations for a replacement to the coronoid process. The locations were tested for four criteria, which include replacement’s height (a similar height with the corresponding 50% coronoid process), width (a similar width with the corresponding 50% coronoid process), articular cartilage (a surface needed to touch elbow joint should be covered by articular cartilage) and rear space (enough rear space was required to fix a replacement). So, whenever the automatic “best-fit alignment” tool in Geomagic resulted in a location that does not satisfy the aforementioned criteria that unqualified location was removed in the next trials.

![Fig. 1. Cross section of an ulna demonstrating the measured values for d1, d2, and h.](image1)

![Fig. 2. “Manual Registration” of two proximal ulnas.](image2)
3. Results

3.1. Coronoid process height

For the scaled left side coronoid, the coronoid process height ranged from 14.47 to 18.32 mm, while the average height was calculated as 15.80 mm (SD = 1.36). For the right side coronoid processes, the height ranged from 14.48 to 17.75 mm, and the average height was calculated to be 16.02 mm (SD = 1.05). The average coronoid process height of the scaled ulnas of the two sides was calculated as 15.92 mm (SD = 1.15).

3.2. 50% coronoid process width

When measuring the 50% coronoid process width, the original (unscaled) geometry of the subjects (6 left coronoid processes and 7 right coronoid processes) were measured. It ranged from 8.16 to 13.24 mm. The average width of 13 subjects was 10.35 mm (SD = 1.59).

3.3. Dimensional variations of the ipsilateral ulnas among different individuals

For the proximal ulnas, the range of the deviation in the entire proximal ulnas was from 0.614 to 1.295 mm, with an average value of 0.893 mm (SD = 0.157). The range of the proximal ulna bony articulating surface was from 0.505 to 1.288 mm, and the average value was 0.794 mm (SD = 0.171).

3.4. Dimensional variations of left and right proximal ulnas among the same subjects

In this test, 6 subjects were analyzed without any scaling. For the entire proximal ulna, the range of deviation was from 0.255 to 0.491 mm.

Fig. 3. “Mirror” and “Manual Registration” of two proximal ulnas.

Fig. 4. Comparison of seven fibular heads in the same view direction.
and the average deviation was 0.37 mm ($SD = 0.089$). For the proximal ulna bony articulating surface, the range was from 0.274 to 0.475 mm, and the average deviation was 0.353 mm ($SD = 0.075$).

### Table 1

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<th>Percentage of subjects within the range</th>
<th>Cumulative percentage of deviations</th>
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3.5. Analysis on best-fit location of 50% coronoid process articulating surface on fibular head

In this analysis, 6 left coronoid processes, 7 right coronoid processes, 7 left fibular heads and 5 right fibular heads were investigated. We attempted to fit the coronoid processes on the ipsilateral fibular heads of all the subjects. So, 77 ($6 \times 7 + 5 \times 7$) values for the deviation analyses would be obtained. However, 3 cases failed; no best location was found on the right fibular heads of subjects C and E when attempting to fit the coronoid process of subject A. Also, no best location was found on the right fibular head of subject C when attempting to fit the right coronoid process of subject G.

In the 74 max distances reported, the range was from 0.846 to 1.997 mm, and the average value was 1.66 mm ($SD = 0.23$). Table 1 shows the number of subjects that would fit within a certain max deviation. For the 74 values obtained, only 2 trials had a maximum deviation less than 1.0 mm. The number of subjects that had a maximum deviation between 1.75 and 2.00 mm was 26 (35.1%). The whole data was separated into 5 ranges. The first one was from 0.0 to 1.0 mm, and the rest of the values were divided into 4 groups with a step of 0.25 mm (1.00–1.25, 1.25–1.50, 1.50–1.75, 1.75–2.00).

#### 3.6. Selection of best-fit locations

The acceptance or rejection of the best-fit locations on the fibular head was based on five criteria:

1. The deviation between the 50% coronoid process and a fibular head is less than 2 mm.
2. The fibular replacement part has to be covered by articular cartilage.
3. After trimming with the base plane of a 50% coronoid process, the replacement’s width is close to the 50% coronoid process width.
4. After trimming with the base plane of a 50% coronoid process, the replacement’s height is close to the 50% coronoid process height.
5. The replacement has enough rear space to be fixed (by screws or strings).

Every coronoid process surface was compared with all the ipsilateral fibular heads, and every combination provided different numbers of best-fit locations. Comparing 50% left coronoid process of subject A with left fibular head of subject D gave the most locations (6 locations) regardless of acceptance or rejection based on the above criteria (Fig. 5). Fig. 5 shows two acceptable best-fit locations on the fibular head of a 50% coronoid process. The colors on the samples show the deviation between a 50% coronoid process and the fibular head. The lighter color (light blue, light yellow and light green)
means less deviation between the two surfaces, and vice versa. The six locations shown in Fig. 5 are those that were automatically identified by Geomagic as the “best-fit” locations for the coronoid process. These have to be checked against the criteria for selection of the acceptable location. In the first check, the locations (location 2 and location 3 in Fig. 5) on the back of the fibular head (subject D) were rejected, because these locations of the fibular head were not covered with articulating cartilage. In the second check, location 5 was rejected; the reason is if the replacement is cut off, the width of the replacement will be much larger than the 50% coronoid process (Figs. 5, 4A). In the third check, location 4 was rejected, because the height of the replacement is much larger than the 50% coronoid process (Figs. 5, 5A). After that, two locations were identified as the best-fit locations (location 1 in Figs. 5 and 6A, and location 6 in Figs. 5 and 7A), because these locations are covered by articular cartilage; they also have similar width and height with the 50% coronoid process; and after trimming that, the rear space is large enough to fix the replacement.

4. Discussion

There have been previous works aimed at characterizing the anatomy of the coronoid process (Guittion et al., 2011; Matzon et al., 2006; Shin et al., 2010). The height, width, olecranon–coronoid angle, articular surface area, and coronoid volume have all been evaluated. Surface area measurements have been focused more at the amount of articular surface area and less at the morphology of the articular surface and how it compares between subjects. Our study has evaluated the congruency of the coronoid between subjects. Moreover, it is the first study to utilize a volume scaling factor. This allows the geometry and morphology to be better evaluated on a size-matched basis, since when a bone graft is considered for use, it is size-matched based on radiographic comparisons (Paul et al., 2008).

This study found that the average deviation in articular surfaces between the coronoid process and fibular head graft was 1.66 mm. This is certainly an allowable amount of incongruency when compared to literature looking at the reduction of intra-articular fractures. Studies looking at clinical outcomes have shown that the amount of displacement that results in acceptable results for patients depends on the joint involved. It is suggested that fractures of the distal radius or the tibial plafond that are malreduced beyond 2 mm can result in altered articular contact pressures that may result in an acceleration in the development of osteoarthritis (Dirschl et al., 2004; Marsh et al., 2002). Fractures of the acetabulum and tibial plateau may allow even greater amounts of articular step-off. There are no reported studies looking at the reduction of intra-articular elbow fractures. The coronoid process articular cartilage thickness has been measured at an average of 3 mm (Rafehi et al., 2012) while the proximal fibula cartilage thickness has been measured at 1.9 mm (Espregueira-Mendes and Vieira da Silva, 2006). This average of a 1.1 mm is also within the 1.66 deviation that we found in our study.

Our study is the first to compare the left and the right coronoid processes of the same individual. The average dimensional variation between the left and right proximal ulnas among the same subjects was 0.37 mm. This implies that if one of the patient’s coronoid processes is fractured, the shape and volume of the contralateral side can be measured to obtain a reliable, albeit mirrored, size and shape of the fractured coronoid process for surgical replacement.

In this work, fibular heads were investigated as alternative replacements for damaged coronoid processes due to their critical advantages. Firstly, the fibular heads are covered by articular cartilage. Since the coronoid processes is part of the elbow joints providing stability, articular cartilage is required on the replacement part. Secondly, fibular heads have relatively large size which is comparable to the coronoid process. Thirdly, 50% of the coronoid process’s surface is composite of a shallow concave and a relatively big “bump” (Fig. 8A), and more than one similar curvature can be found around the edge of fibular heads.

The same considerations were used to test the distal fibular heads. However, comparing with 50% coronoid processes, their surfaces are small and unsmooth, so it is hard to find a best-fit location on distal fibular head. Besides that, after trimming the replacement, the rear space is not big enough due to its narrow width (Fig. 9A). According to these disadvantages, the distal fibular heads were rejected as replacements.

According to these considerations, we summarized the criteria to select a proper fibular head. When selecting the fibular head, the same side fibular head is recommended as the broken coronoid process. The reason is that, there is a “bump” (Fig. 8A) on the fibular head, and this “bump” can fit the same side coronoid process’s bump. Besides that, the fibular heads with a surface that is smooth and congruent with the coronoid process are chosen accordingly.

Conflict of interest

The authors declare that they have no conflicts of interest in the research.

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Appendix A

Fig. 1A. Isolation of proximal ulna.
Fig. 2A. Width of 50% coronoid process.

Fig. 3A. Two perpendicular planes decide a cross section and half the height of coronoid process.

Fig. 4A. Rejection of location 5. Criterion 3 (the replacement’s width is close to the 50% coronoid process’s width) is not satisfied.
Fig. 5A. Rejection of location 4. Criterion 4 (the replacement’s height is close to the 50% coronoid process’s height) is not satisfied.

Fig. 6A. Acceptance of location 1, all selection criteria are satisfied.

Fig. 7A. Acceptance of location 6. All selection criteria are satisfied.

Fig. 8A. A “bump” on the fibular head.

Fig. 9A. A distal fibular head in three views.
References


