Reconstruction of the Coronoid Process Using the Tip of the Ipsilateral Olecranon

Bashar Alolabi, MD, FRCSC, Alia Gray, MSc, BEng, Louis M. Ferreira, BSc, BEng, PhD, PEng,
James A. Johnson, BSc, BEng, PhD, PEng, George S. Athwal, MD, FRCSC,
and Graham J.W. King, MD, MSc, FRCSC

Investigation performed at the Hand and Upper Limb Centre, St. Joseph's Health Centre, London, Ontario, Canada

Background: Autograft reconstruction of the coronoid using the tip of the olecranon has been described as a treatment option for comminuted coronoid fractures or coronoid nonunions that are not repairable. The purpose of this in vitro biomechanical study of the coronoid-deficient elbow was to determine whether coronoid reconstruction using the tip of the ipsilateral olecranon would restore elbow kinematics.

Methods: An elbow motion simulator was used to perform active and passive extension of six cadaveric arms in the horizontal, valgus, varus, and vertical orientations. Elbow kinematics were quantified with use of the screw displacement axis of the ulna with respect to the humerus. Testing was performed with an intact coronoid, a 40% coronoid deficiency, and a coronoid reconstruction using the tip of the ipsilateral olecranon.

Results: Creation of a 40% coronoid deficiency resulted in significant changes (range, 3.6° to 10.9°) in the angular deviations of the screw displacement axis relative to the intact state during simulated active and passive extension in the varus orientation with the forearm in pronation and in supination ($p < 0.05$). Reconstruction of the coronoid using the ipsilateral olecranon tip restored the angular deviations to those in the intact state ($p > 0.05$) with the arm in all orientations except valgus, in which there was a small but significant difference (0.4° ± 0.2°, $p = 0.04$) during passive motion with forearm supination.

Conclusions: Reconstruction of the coronoid using the tip of the ipsilateral olecranon was an effective method for restoring normal kinematics over a range of elbow motion from 20° to 120° in a cadaveric model of an elbow with a 40% coronoid deficiency. This reconstruction technique may prove beneficial for patients with elbow instability due to coronoid deficiency.

Clinical Relevance: This study supports the biomechanical concept of coronoid reconstruction using the ipsilateral olecranon tip for coronoid fractures or nonunions involving 40% of the coronoid process.

Peer Review: This article was reviewed by the Editor-in-Chief and one Deputy Editor, and it underwent blinded review by two or more outside experts. It was also reviewed by an expert in methodology and statistics. The Deputy Editor reviewed each revision of the article, and it underwent a final review by the Editor-in-Chief prior to publication. Final corrections and clarifications occurred during one or more exchanges between the author(s) and copyeditors.

The coronoid process is one of the primary stabilizers of the ulnohumeral joint[1-12]. It plays an important role in preventing posterior displacement and subluxation of the elbow as well as in preventing varus instability[13]. Large coronoid fractures have been associated with elbow instability and maltracking[2,6,9,12,14]. Untreated, these fractures often lead to poor outcomes because of elbow stiffness, recurrent instability, and degenerative changes[15-17]. Open reduction and internal fixation of large coronoid fractures combined with lateral collateral ligament and possibly medial collateral ligament repair has been recommended, as this can restore elbow stability and kinematics[12,16,18,19]. However, open reduction and internal fixation of the coronoid may not be possible because of comminution or nonunion, necessitating coronoid reconstruction or replacement[16,20].

Moritomo et al. described two patients treated with reconstruction of the coronoid using the ipsilateral olecranon tip[21], but to our knowledge the long-term outcomes of this procedure have not been reported. Also, there is concern that resection of

Disclosure: One or more of the authors received payments or services, either directly or indirectly (i.e., via his or her institution), from a third party in support of an aspect of this work. In addition, one or more of the authors, or his or her institution, has had a financial relationship, in the thirty-six months prior to submission of this work, with an entity in the biomedical arena that could be perceived to influence or have the potential to influence what is written in this work. No author has had any other relationships, or has engaged in any other activities, that could be perceived to influence or have the potential to influence what is written in this work. The complete **Disclosures of Potential Conflicts of Interest** submitted by authors are always provided with the online version of the article.

J Bone Joint Surg Am. 2014;96:590-6 • http://dx.doi.org/10.2106/JBJS.L.00698

the olecranon tip during this procedure may cause instability and changes in elbow kinematics, as suggested by Bell et al.[22]. Other methods of reconstruction of the coronoid have been published, including the use of iliac crest bone graft, a fragment of the radial head, rib osteochondral graft, and structural allograft[23-26]. Many of these methods are not reliable for restoring congruent ulnohumeral alignment[16], involve some degree of donor site morbidity, have unpredictable results, and/or have insufficient follow-up to determine long-term outcomes[23]. To our knowledge, none of these methods have been tested biomechanically to demonstrate restoration of elbow kinematics.

The purpose of this in vitro biomechanical study was to determine whether reconstructing the coronoid using the tip of the ipsilateral olecranon would restore baseline kinematics to the coronoid-deficient elbow. Our hypothesis was that such coronoid reconstruction would improve but not fully restore kinematics in the elbow with a 40% coronoid deficiency.

Materials and Methods

Six fresh-frozen cadaveric upper-extremity specimens (amputated at the transhumeral level) from male donors with a mean age (and standard deviation) of 77.8 ± 8.0 years were thawed for eighteen hours at room temperature (22° ± 2°C). Computed tomography (CT) images (LightSpeed VCT; GE Healthcare, Waukesha, Wisconsin) of the specimens were made prior to testing to confirm that the elbows demonstrated no evidence of degenerative or posttraumatic changes. Sutures (number-2 ETHIBOND; Ethicon, Somerville, New Jersey) were secured to the tendons of the wrist flexors (flexor carpi ulnaris and flexor carpi radialis), of the wrist extensors (extensor carpi ulnaris and carpi radialis longus), and of the brachioradialis, pronator teres, supinator, biceps, brachialis, and triceps, using a running locking suture technique as described previously[11]. The humerus was secured in an elbow motion simulator[2,3,11,12,27] that allowed unconstrained elbow and forearm motion. The sutures connected to the triceps, biceps, and brachialis were directed through alignment guides mounted to the base of the simulator to reproduce their physiologic line of action. Additional alignment guides were placed at the medial epicondyle for the pronator and wrist flexors, at the lateral epicondyle for the wrist extensors, and at the supracondylar ridge for the brachioradialis. The sutures were attached to stainless steel cables, which were connected to computer-controlled pneumatic actuators and servomotors to simulate active elbow and forearm motion. A universal hinge allowed the simulator to be positioned in the horizontal, valgus, varus, and vertical orientations (see Appendix).

An anatomic coordinate reference system for each bone was established by digitizing osseous landmarks during the testing and following its completion[28,29]. The motion of the ulna relative to the humerus was tracked with use of a Flock of Birds electromagnetic tracking system (Ascension Technology, Burlington, Vermont) that had root-mean-square accuracy of 1.8 mm and 0.5°. Three-dimensional kinematics of the ulna relative to the humerus were expressed with use of the screw displacement axis[28,30-36]. The angular deviations (a measure of data dispersion) were calculated for the screw displacement axis in both the coronal (frontal) and transverse (axial) planes. The screw displacement axis was calculated from the recordings made at 10° intervals during elbow extension from 120° to 20°. An electromagnetic tracking receiver mounted to the ulna recorded motion relative to the transmitter, which was mounted rigidly with respect to the humerus. In this configuration, the screw displacement axis algorithm had an orientation accuracy of 1.04° ± 0.03°[31].

Active and passive elbow extension were simulated with the arm in all four orientations of the simulator. Testing was performed with the forearm in pronation and in supination. For active extension, forces were applied to the tendons by the actuators and servomotors after the forearm was manually positioned in full pronation or full supination. The forearm rotation was maintained during active extension by means of the forces applied by the actuators to the relevant tendons. The muscle loading protocol was based on electromyographic data and the muscle cross-sectional area[11,12,37-40]. During passive motion, a single investigator manually extended the arm while maintaining the forearm in full pronation or supination.

The testing was first performed on the intact arm. A straight posterior midline incision was then made, and medial and lateral skin flaps were elevated. The anterior and posterior capsule as well as the posterior band of the medial collateral ligament were sectioned. The extensor muscle mass was separated from the lateral collateral ligament and was reflected off the lateral epicondyle. Medially, the flexor muscle mass was separated from the medial collateral ligament and was reflected off the medial epicondyle. Both the lateral and medial collateral ligaments were sectioned from their humeral insertions and repaired with a running locking suture (number-2 Hi-Fi; ConMed Linvatec, Largo, Florida) with use of a transosseous bone tunnel method[11,12,41,42]. To simulate ligament repair, actuators applied 20 N of tension to both collateral ligaments. This magnitude of force was chosen as it has been shown to restore normal elbow kinematics in previous studies[41,42]. The ligament sutures were tensioned simultaneously while the elbow was reduced manually at 60° of flexion with the forearm in neutral rotation. Once tensioned, two clamps secured the cables attaching the ligaments to the actuators. The intact-coronoid state with repaired ligaments was then tested. In order to focus on the effects of coronoid deficiency and reconstruction rather than on the effectiveness of collateral ligament repair, the intact-coronoid state with repaired ligaments was considered the control, and all measurements and statistical analyses were compared with this state (the coronoid control).

A medial approach through the floor of the cubital tunnel (splitting the two heads of the flexor carpi ulnaris) was utilized to access the coronoid. A plane, parallel to the posterior proximal ulnar flat spot, for creating a 40% transverse coronoid deficiency (Fig. 1) was identified with use of digital calipers (Digimatic CD-6; Mitutoyo, Kawasaki, Japan) and was cut with a 0.4-mm oscillating saw. The total height of the coronoid was measured from the tip to the base. The base was defined by a plane parallel to the flat spot and intersecting the deepest portion of the greater sigmoid notch. The ligaments were retensioned, and the coronoid-deficient elbow was tested. An osteotomy, perpendicular to the articular surface, was performed from a location on the guiding ridge of the ipsilateral olecranon at

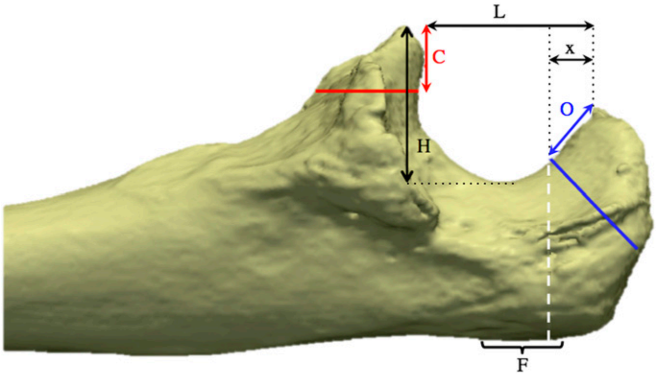

Fig. 1

Schematic representation of the proximal aspect of the ulna demonstrating the flat spot (F), the total height of the coronoid (H), 40% of the height of the coronoid (C), the height of the olecranon tip equivalent to 40% of the coronoid height (O), the total length of the olecranon articular surface (L), and the amount of olecranon articular surface resected by the olecranon osteotomy (x). The solid red and blue lines represent the coronoid and olecranon osteotomies, respectively, that were performed in this study. The dashed white line represents the orientation of the osteotomy used by Bell et al.[22]. For the same amount of articular surface resection (x), that osteotomy requires resection of an additional portion of the proximal aspect of the ulna compared with our osteotomy (as indicated by the area between the dashed white line and the blue line).

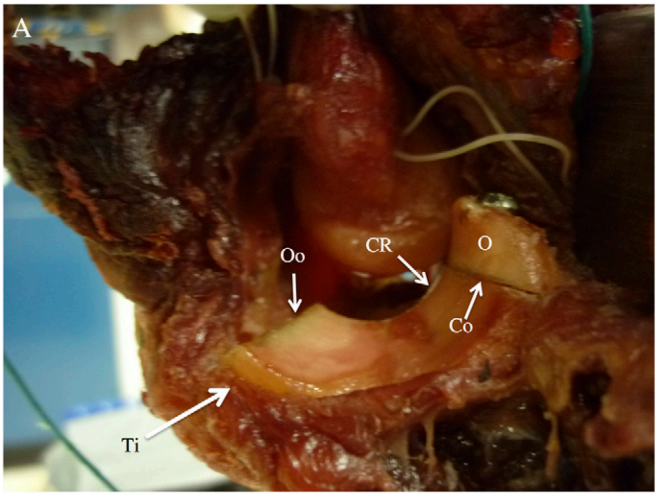

Fig. 2-A

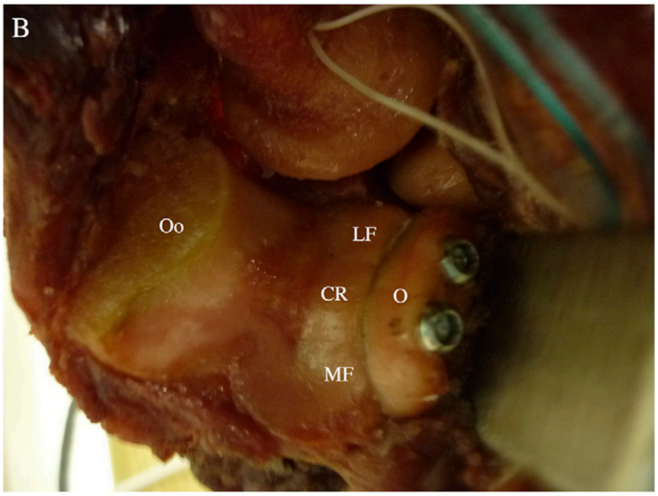

Fig. 2-B

Medial (**Fig. 2-A**) and anterior (**Fig. 2-B**) views demonstrating reconstruction of the coronoid with the ipsilateral olecranon tip (O). Note the coronoid osteotomy site (Co), olecranon osteotomy site (Oo), intact triceps tendon insertion (Ti), and two fully threaded 2.7-mm screws used to fix the olecranon tip from an anterior-to-posterior direction. The photographs show how the olecranon tip restores the coronoid guiding ridge (CR); however, the medial (MF) and lateral (LF) facets of the coronoid are not congruent with the olecranon tip, with the most medial and lateral aspects of the coronoid facets being somewhat proud and the olecranon tip recessed.

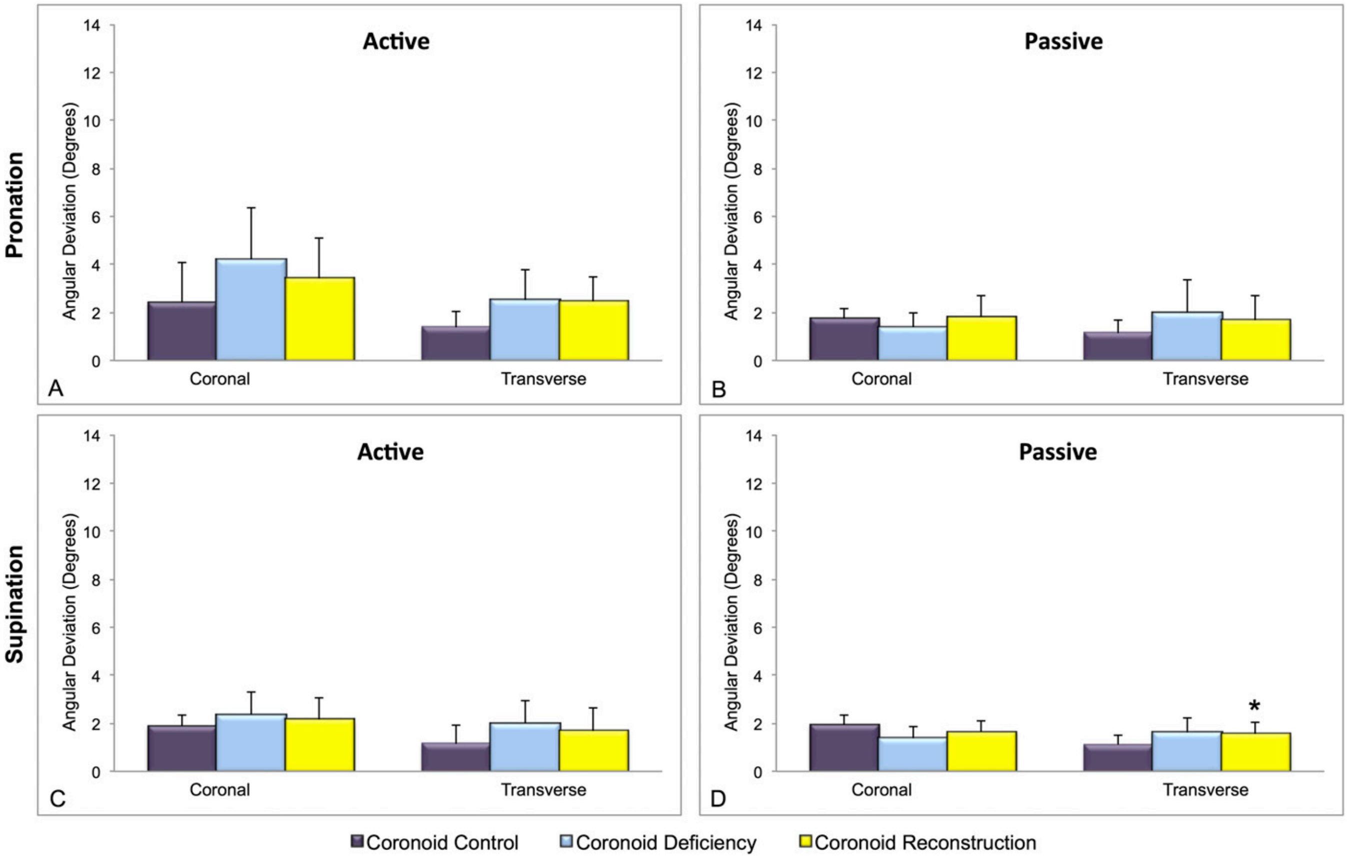

Fig. 3

Mean angular deviation of the screw displacement axis in the coronal and transverse planes during active and passive elbow extension with forearm pronation and supination in the valgus orientation. The whiskers indicate the standard deviation, and the asterisk indicates a significant difference.

a distance equal to 40% of the coronoid height from the tip of the olecranon. The olecranon tip was positioned over the coronoid deficiency so that the guiding ridges of the coronoid and the olecranon tip were collinear and the articular surfaces of the coronoid and olecranon were best optimized. The olecranon tip was compressed with use of a reduction clamp and was secured with two fully threaded 2.7-mm screws (Synthes Canada, Mississauga, Ontario, Canada) placed anterior-to-posterior, just distal to the subchondral region of the articular surface of the coronoid and olecranon tip (Fig. 2). The elbow with the olecranon autograft was tested after retensioning of the collateral ligaments.

Statistical analyses of the angular deviations of the screw displacement axis were performed with use of one-way repeated-measures analysis of variance with a Bonferroni correction to adjust for multiple comparisons. The factor for the one-way analysis was the coronoid state (coronoid control, coronoid deficiency, or coronoid reconstruction with the olecranon tip). A p value of <0.05 was considered significant, and the 95% confidence interval (CI) was calculated for each value that reached significance. Clinical relevance was set at a 2° change in deviation, and a priori and post hoc power analyses of the data demonstrated sufficient power (>0.8) to detect a 2° difference between study conditions.

Source of Funding

Funding for this project was provided through research grants by the Canadian Institutes of Health Research and the Physicians' Services Incorporated Foundation.

Results

All values in this section represent the mean (and standard deviation) for the angular deviation of the screw displacement axis across the six specimens.

Horizontal Orientation

During active extension with forearm pronation, the coronoid-deficient elbow displayed a 7.9° ± 6.7° increase (p = 0.22) in the coronal angular deviation and a 3.9° ± 4.9° increase (p = 0.65) in the transverse angular deviation relative to the coronoid control. However, these changes were not significant. There were also no significant differences in angular deviation among the three states (coronoid control, coronoid-deficient, and coronoid reconstruction) during active or passive extension, regardless of forearm rotation (p > 0.05).

Valgus Orientation (Fig. 3)

During active extension with forearm pronation or supination, there were no differences in angular deviations among the three states (p > 0.05) (Figs. 3-A and 3-C). Passive extension with forearm pronation also did not result in any difference in screw displacement kinematics among the three states (p > 0.05) (Fig. 3-B).

During passive extension with forearm supination, a very small (0.4° ± 0.2°) difference in angular deviation in the transverse plane between the coronoid control and coronoid reconstruction states reached statistical significance (95% CI = 0.04 to 0.84, p = 0.03) (Fig. 3-D). However, this difference was likely clinically insignificant. No other differences in angular deviation were detected among the three states (p > 0.05) (Fig. 3-D).

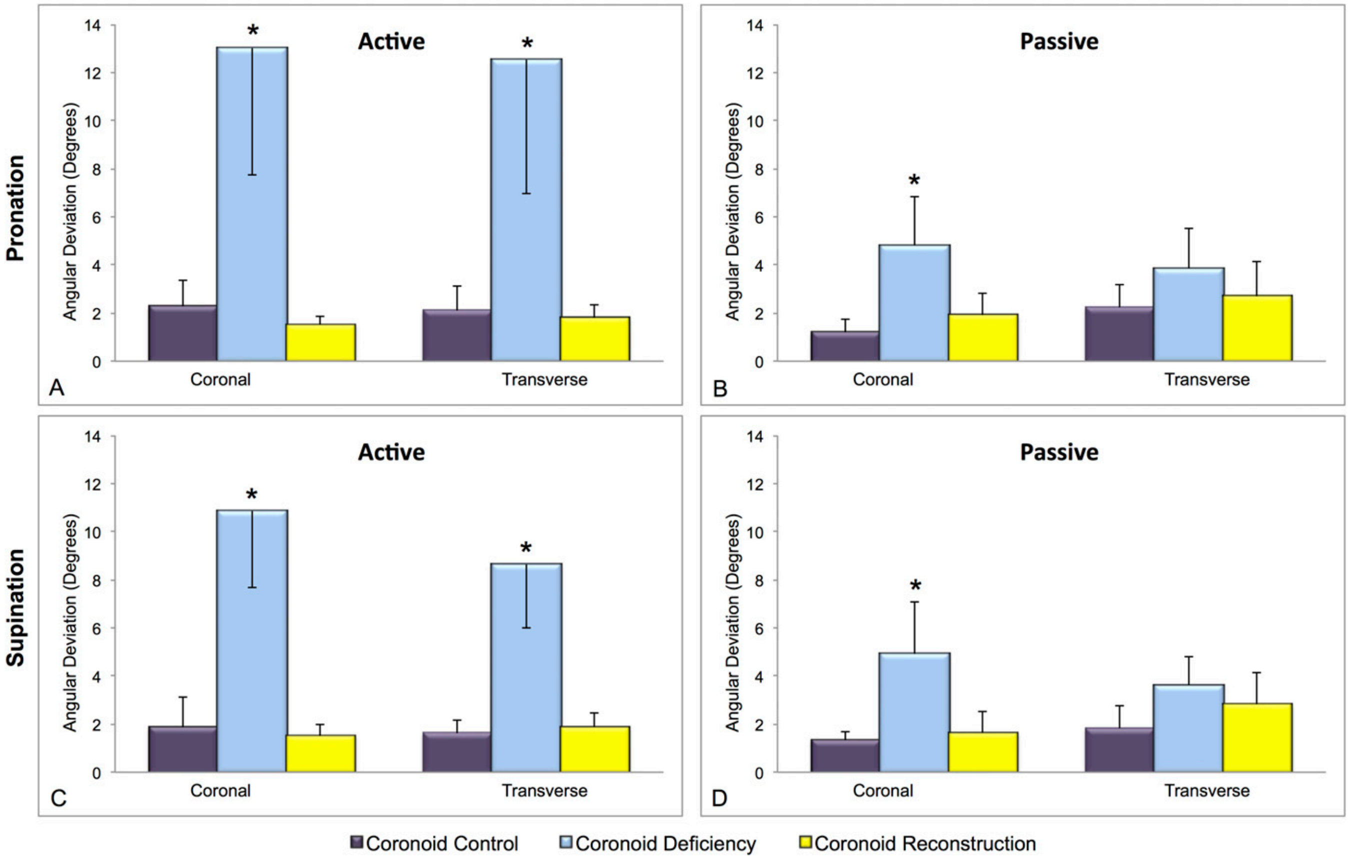

Fig. 4

Mean angular deviation of the screw displacement axis in the coronal and transverse planes during active and passive elbow extension with forearm pronation and supination in the varus orientation. The whiskers indicate the standard deviation, and the asterisk indicates a significant difference.

Varus Orientation (Fig. 4)

During active extension with forearm pronation, the coronoid-deficient elbow demonstrated significant changes in coronal angular deviation (10.9° ± 5.0°, 95% CI = 2.2° to 19.3°, $p = 0.02$) and transverse angular deviation (10.6° ± 5.5°, 95% CI = 1.1° to 18.8°, $p = 0.03$) relative to the coronoid control (Fig. 4-A). Likewise, during active extension with forearm supination, the coronoid-deficient elbow demonstrated significant changes in coronal angular deviation (9.0° ± 2.7°, 95% CI = 4.4° to 13.6°, $p < 0.01$) and transverse angular deviation (7.0° ± 2.7°, 95% CI = 2.4° to 11.7°, $p = 0.01$) relative to the coronoid control (Fig. 4-C). No other significant changes in angular deviation were detected among the three states during active extension with forearm pronation or supination ($p > 0.05$) (Fig. 4).

During passive extension with forearm pronation, the coronoid-deficient elbow displayed changes in angular deviation in the coronal plane (3.6° ± 1.8°, 95% CI = 0.5° to 6.8°, $p = 0.03$), but not the transverse plane ($p > 0.05$) relative to the coronoid control (Fig. 4-B). During passive extension with forearm supination, the coronoid-deficient elbow displayed changes in angular deviation in the coronal plane (3.6° ± 2.0°, 95% CI = 0.1° to 7.0°, $p = 0.04$) but not the transverse plane ($p > 0.05$) relative to the coronoid control (Fig. 4-D). No other significant differences in angular deviation were seen among the three states during passive extension with forearm pronation or supination ($p > 0.05$) (Fig. 4).

Vertical Orientation

There were no changes in elbow kinematics among the three states during either active or passive extension with forearm pronation or supination ($p > 0.05$).

Discussion

This study demonstrated that a 40% transverse coronoid deficiency caused substantial alterations in the kinematics of the elbow in the varus orientation, as demonstrated by the increased angular deviations of the screw displacement axes relative to the coronoid with sectioned and repaired collateral ligaments. These findings confirm those of other studies, demonstrating that a 40% coronoid deficiency resulted in substantial alterations in elbow kinematics even with an intact radial head and repaired collateral ligaments[2,12,15]. Therefore, it is important to repair larger coronoid fractures with open reduction and internal fixation, when possible, or with other strategies such as using the ipsilateral olecranon tip, when the coronoid is irreparably fractured.

Moreover, this study indicated that reconstructing the 40% coronoid-deficient elbow with the ipsilateral olecranon tip restored kinematics similar to those of the coronoid-intact elbow if the collateral ligaments are repaired. The small difference observed between the coronoid control and olecranon tip reconstruction states in the valgus orientation during passive motion with forearm supination may be due to differences in shape between the olecranon and coronoid as well as the loss of stability provided by the olecranon tip, specifically the posteromedial aspect of the olecranon. However, the magnitude of this difference was quite small, less than 1° (95% CI, 0.04° to 0.84°), and may not be clinically important.

Preoperative imaging is important to determine the size of the coronoid fracture as it is difficult to judge intraoperatively, especially if there is substantial comminution. The percentage of coronoid deficiency can be estimated by analyzing the CT scan of the fractured elbow or by comparing lateral radiographs of the injured and the contralateral, normal elbow.

The angular deviation of the screw displacement axis of the coronoid-deficient elbow during active motion showed a larger variation with the forearm in pronation compared with supination. These differences are possibly a result of the stabilizing effect of supination on the coronoid-deficient elbow and are consistent with previous studies[2,12]. These effects in the coronoid-deficient elbow presumably become more apparent during active motion because of the stabilizing effects of the musculature pulling the greater sigmoid notch into the trochlear groove.

The olecranon osteotomy required to reconstruct 40% of the coronoid as described by Bell et al.[22] resulted in excision of a mean of 23% (range, 18% to 24%) of the olecranon articular surface (Fig. 2). The fact that we found only small differences between the coronoid control and coronoid reconstruction states suggests that the structural deficiency due to resection of this portion of the olecranon process was minimal. This finding is in contrast to that of Bell et al., who reported that even small amounts of olecranon resection (e.g., 12.5% or 25.0%) resulted in significant increases in varus-valgus angulation and in ulnohumeral rotation[22]. This discrepancy, however, can be explained by the difference in the olecranon osteotomy technique between the two studies. In the present study, the olecranon osteotomy was performed perpendicular to the articular surface, whereas Bell et al. performed it perpendicular to the flat spot of the proximal aspect of the ulna[22]. As illustrated in Figure 1, an osteotomy perpendicular to the flat spot results in resection of a substantially larger amount of the articular surface of the olecranon compared with an osteotomy perpendicular to the articular surface. Also, the study by Bell et al. involved detachment and repair of the triceps tendon, whereas the insertion of the triceps was preserved in the present study. Therefore, the present study suggests that resection of no more than 20% to 25% of the olecranon tip to reconstruct a coronoid deficiency of up to 40% does not result in substantial alterations in elbow kinematics.

It was our observation that the olecranon osteotomy required to reconstruct 40% of the coronoid height generally exited the posterior aspect of the ulna just proximal and anterior to the insertion of the triceps. Therefore, there is a limit on how much of the coronoid can be reconstructed with the tip of olecranon before damaging the triceps insertion. When using this technique, it is important to clearly identify the insertion of the triceps and to ensure that the insertion is not violated during the osteotomy. Although the ipsilateral olecranon tip demonstrated reasonable congruency with the remainder of the coronoid, especially with regard to the guiding ridge, we did observe a mismatch between the shape of the medial and lateral facets of the ipsilateral olecranon tip and that of the excised coronoid tip. We speculate that the effectiveness of the olecranon tip in restoring elbow kinematics demonstrates that matching the exact shape of the deficient coronoid is perhaps not critical, as long as the anterior buttress effect of the coronoid is restored and the guiding ridge is reconstructed. However, this mismatch may result in subtle alterations in kinematics and abnormal articular contact pressures with the potential to result in the development of degenerative changes over time.

To our knowledge, this is the first biomechanical study to examine the effect of autograft reconstruction of the coronoid process, specifically using the ipsilateral olecranon tip. Moritomo et al. reported using this technique in two patients with good short-term results[21]. Other reports of reconstruction of the coronoid with parts of the ipsilateral fractured radial head, iliac crest bone graft, an osteochondral graft from a rib, and allograft have been published[23-26]. However, these techniques have not been tested biomechanically and the short-term clinical results have been mixed.

We previously showed that use of a prosthetic replacement coronoid to treat an irreparable coronoid tip fracture or nonunion restored stability to the coronoid-deficient elbow if the collateral ligaments were repaired[20]. The present study demonstrated similar results for coronoid reconstruction with the ipsilateral olecranon tip. Because of concerns regarding failure and loosening associated with use of a prosthetic replacement in young patients, we believe that reconstruction with the ipsilateral olecranon tip may represent a better surgical solution in younger patients, whereas prosthetic replacement may be more favorable in older patients and those requiring larger coronoid reconstructions.

The chief limitation of this study is the fact that it was conducted in vitro, a setting that differs from the in vivo one in which ligaments and soft tissues have the ability to heal. Also, we did not have a control state involving olecranon tip resection in the setting of an intact coronoid. However, we did not include that state in our protocol because it represents a scenario that would not occur clinically; the reconstruction procedure would only be performed in the setting of an irreparable coronoid fracture. Given the repeated-measures design of the study, we had to choose one size and orientation for the coronoid deficiency. We chose a horizontal osteotomy equaling 40% of the coronoid size, as this would most closely resemble a terrible-triad coronoid fracture[43]. Therefore, the results of this study may not be applicable to other types of coronoid fractures. Moreover, because of the natural variation in the range of motion of cadaveric elbows from elderly donors, our study examined the screw displacement axis kinematics only from 20° to 120° of elbow flexion. Since the elbow is most stable in deep flexion, it is unlikely that changes in elbow kinematics would have been observed at >120° of elbow flexion. It is theoretically possible that the deficiency of the coronoid process would cause some kinematic alterations at terminal extension or in hyperextension; however, most patients requiring this procedure would have undergone previous surgical procedures involving the elbow, so some degree of stiffness would be expected. Therefore, we believe that a range from 20° to 120° is clinically relevant. The stepwise design of the study also necessitated reuse of the specimen for testing different conditions and necessitated repeated tensioning of the ligaments. The effectiveness of the olecranon tip transfer in restoring kinematics similar to those of the coronoid control state supports the repeated-measures design of the study, as the last condition tested proved similar to the first. Finally, the ability of an avascular osteochondral fragment to heal without displacement and to revascularize without collapse will require further study in the future.

In conclusion, reconstruction of the coronoid using the tip of the ipsilateral olecranon was shown to be an effective method for restoring normal kinematics over a range of motion between 20° and 120° in elbows with a 40% transverse coronoid deficiency. This may prove beneficial for patients with an unstable elbow as a result of an unreconstructible comminuted coronoid fracture or nonunion. Clinical studies are needed to determine whether these osteochondral autografts will unite and whether the mismatch in shape between the olecranon and coronoid will predispose the elbow to progressive degenerative changes over time.

Appendix

*e*A A figure showing the elbow simulator is available with the online version of this article as a data supplement at jbjs.org. ■

Bashar Alolabi, MD, FRCSC
Alia Gray, MSc, BEng
Louis M. Ferreira, BSc, BEng, PhD, PEng
James A. Johnson, BSc, BEng, PhD, PEng
George S. Athwal, MD, FRCSC
Graham J.W. King, MD, MSc, FRCSC
Hand and Upper Limb Centre,
St. Joseph's Health Centre,
268 Grosvenor Street, London,
ON N6A 4L6, Canada.
E-mail address for G.J.W. King: gking@uwo.ca

References

1. Morrey BF. Complex instability of the elbow. Instr Course Lect. 1998;47:157-64.

2. Beingessner DM, Dunning CE, Stacpoole RA, Johnson JA, King GJ. The effect of coronoid fractures on elbow kinematics and stability. Clin Biomech (Bristol, Avon). 2007 Feb;22(2):183-90. Epub 2006 Nov 13.

3. Beingessner DM, Stacpoole RA, Dunning CE, Johnson JA, King GJ. The effect of suture fixation of type I coronoid fractures on the kinematics and stability of the elbow with and without medial collateral ligament repair. J Shoulder Elbow Surg. 2007 Mar-Apr;16(2):213-7.

4. Doornberg JN, Ring D. Coronoid fracture patterns. J Hand Surg Am. 2006 Jan;31(1):45-52.

5. Doornberg JN, Ring DC. Fracture of the anteromedial facet of the coronoid process. J Bone Joint Surg Am. 2006 Oct;88(10):2216-24.

6. Closkey RF, Goode JR, Kirschenbaum D, Cody RP. The role of the coronoid process in elbow stability. A biomechanical analysis of axial loading. J Bone Joint Surg Am. 2000 Dec;82(12):1749-53.

7. Hull JR, Owen JR, Fern SE, Wayne JS, Boardman ND 3rd. Role of the coronoid process in varus osteoarticular stability of the elbow. J Shoulder Elbow Surg. 2005 Jul-Aug;14(4):441-6.

8. McKee MD, Pugh DM, Wild LM, Schemitsch EH, King GJ. Standard surgical protocol to treat elbow dislocations with radial head and coronoid fractures. Surgical technique. J Bone Joint Surg Am. 2005 Mar;87(Pt 1)(Suppl 1):22-32.

9. Schneeberger AG, Sadowski MM, Jacob HA. Coronoid process and radial head as posterolateral rotatory stabilizers of the elbow. J Bone Joint Surg Am. 2004 May;86(5):975-82.

10. Morrey BF, An KN. Stability of the elbow: osseous constraints. J Shoulder Elbow Surg. 2005 Jan-Feb;14(1)(Suppl S):174S-8S.

11. Pollock JW, Brownhill J, Ferreira L, McDonald CP, Johnson J, King G. The effect of anteromedial facet fractures of the coronoid and lateral collateral ligament injury on elbow stability and kinematics. J Bone Joint Surg Am. 2009 Jun;91(6):1448-58.

12. Pollock JW, Pichora J, Brownhill J, Ferreira LM, McDonald CP, Johnson JA, King GJ. The influence of type II coronoid fractures, collateral ligament injuries, and surgical repair on the kinematics and stability of the elbow: an in vitro biomechanical study. J Shoulder Elbow Surg. 2009 May-Jun;18(3):408-17.

13. Steinmann SP. Coronoid process fracture. J Am Acad Orthop Surg. 2008 Sep;16(9):519-29.

14. Regan W, Morrey BF. Classification and treatment of coronoid process fractures. Orthopedics. 1992 Jul;15(7):845-8.

15. Regan W, Morrey B. Fractures of the coronoid process of the ulna. J Bone Joint Surg Am. 1989 Oct;71(9):1348-54.

16. Ring D, Hannouche D, Jupiter JB. Surgical treatment of persistent dislocation or subluxation of the ulnohumeral joint after fracture-dislocation of the elbow. J Hand Surg Am. 2004 May;29(3):470-80.

17. Ring D, Jupiter JB, Sanders RW, Mast J, Simpson NS. Transolecranon fracture-dislocation of the elbow. J Orthop Trauma. 1997 Nov;11(8):545-50.

18. Ring D, Jupiter JB, Zilberfarb J. Posterior dislocation of the elbow with fractures of the radial head and coronoid. J Bone Joint Surg Am. 2002 Apr;84(4):547-51.

19. O'Driscoll SW, Jupiter JB, Cohen MS, Ring D, McKee MD. Difficult elbow fractures: pearls and pitfalls. Instr Course Lect. 2003;52:113-34.

20. Alolabi B, Gray A, Ferriera LM, Johnson JA, Athwal GS, King GJW. Reconstruction of the coronoid using an extended prosthesis: an in vitro biomechanical study. J Shoulder Elbow Surg. 2012 Jul;21(7):969-76. Epub 2011 Jul 22.

21. Moritomo H, Tada K, Yoshida T, Kawatsu N. Reconstruction of the coronoid for chronic dislocation of the elbow. Use of a graft from the olecranon in two cases. J Bone Joint Surg Br. 1998 May;80(3):490-2.

22. Bell TH, Ferreira LM, McDonald CP, Johnson JA, King GJ. Contribution of the olecranon to elbow stability: an in vitro biomechanical study. J Bone Joint Surg Am. 2010 Apr;92(4):949-57.

23. Damiani M, King GJ. Coronoid and radial head reconstruction in chronic posttraumatic elbow subluxation. Instr Course Lect. 2009;58:481-93.

24. Chung CH, Wang SJ, Chang YC, Wu SS. Reconstruction of the coronoid process with iliac crest bone graft in complex fracture-dislocation of elbow. Arch Orthop Trauma Surg. 2007 Jan;127(1):33-7. Epub 2006 Aug 8.

25. Kohls-Gatzoulis J, Tsiridis E, Schizas C. Reconstruction of the coronoid process with iliac crest bone graft. J Shoulder Elbow Surg. 2004 Mar-Apr;13(2):217-20.

26. van Riet RP, Morrey BF, O'Driscoll SW. Use of osteochondral bone graft in coronoid fractures. J Shoulder Elbow Surg. 2005 Sep-Oct;14(5):519-23.

27. Pollock JW, Brownhill J, Ferreira LM, McDonald CP, Johnson JA, King GJ. Effect of the posterior bundle of the medial collateral ligament on elbow stability. J Hand Surg Am. 2009 Jan;34(1):116-23.

28. Duck TR, Dunning CE, Armstrong AD, Johnson JA, King GJ. Application of screw displacement axes to quantify elbow instability. Clin Biomech (Bristol, Avon). 2003 May;18(4):303-10.

29. King GJ, Zarzour ZD, Rath DA, Dunning CE, Patterson SD, Johnson JA. Metallic radial head arthroplasty improves valgus stability of the elbow. Clin Orthop Relat Res. 1999 Nov;368:114-25.

30. Duck TR, Dunning CE, King GJ, Johnson JA. Variability and repeatability of the flexion axis at the ulnohumeral joint. J Orthop Res. 2003 May;21(3):399-404.

31. Duck TR, Ferreira LM, King GJ, Johnson JA. Assessment of screw displacement axis accuracy and repeatability for joint kinematic description using an electromagnetic tracking device. J Biomech. 2004 Jan;37(1):163-7.

32. Woltring HJ. 3-D attitude representation of human joints: a standardization proposal. J Biomech. 1994 Dec;27(12):1399-414.

33. London JT. Kinematics of the elbow. J Bone Joint Surg Am. 1981 Apr;63(4):529-35.

34. Bottlang M, Madey SM, Steyers CM, Marsh JL, Brown TD. Assessment of elbow joint kinematics in passive motion by electromagnetic motion tracking. J Orthop Res. 2000 Mar;18(2):195-202.

35. Stokdijk M, Meskers CG, Veeger HE, de Boer YA, Rozing PM. Determination of the optimal elbow axis for evaluation of placement of prostheses. Clin Biomech (Bristol, Avon). 1999 Mar;14(3):177-84.

36. Deland JT, Garg A, Walker PS. Biomechanical basis for elbow hinge-distractor design. Clin Orthop Relat Res. 1987 Feb;215:303-12.

37. Funk DA, An KN, Morrey BF, Daube JR. Electromyographic analysis of muscles across the elbow joint. J Orthop Res. 1987;5(4):529-38.

38. Johnson JA, Rath DA, Dunning CE, Roth SE, King GJ. Simulation of elbow and forearm motion in vitro using a load controlled testing apparatus. J Biomech. 2000 May;33(5):635-9.

39. Amis AA, Dowson D, Wright V, Miller JH. The derivation of elbow joint forces, and their relation to prosthesis design. J Med Eng Technol. 1979 Sep;3(5):229-34.

40. Ferreira LM, Johnson JA, King GJW. Development of an active elbow flexion simulator to evaluate joint kinematics with the humerus in the horizontal position. J Biomech. 2010 Aug 10;43(11):2114-9.

41. Fraser GS, Pichora JE, Ferreira LM, Brownhill JR, Johnson JA, King GJ. Lateral collateral ligament repair restores the initial varus stability of the elbow: an in vitro biomechanical study. J Orthop Trauma. 2008 Oct;22(9):615-23.

42. Pichora JE, Fraser GS, Ferreira LF, Brownhill JR, Johnson JA, King GJ. The effect of medial collateral ligament repair tension on elbow joint kinematics and stability. J Hand Surg Am. 2007 Oct;32(8):1210-7.

43. Doornberg JN, van Duijn J, Ring D. Coronoid fracture height in terrible-triad injuries. J Hand Surg Am. 2006 May-Jun;31(5):794-7.