Background: Distal humeral hemiarthroplasty is a treatment option for distal humeral fractures, nonunions, and avascular necrosis. The biomechanical effects, however, have not been reported. The purpose of this in vitro study was to quantify the effects of hemiarthroplasty and implant size on elbow joint kinematics.

Methods: Eight fresh-frozen cadaveric arms were mounted in an in vitro motion simulator. An electromagnetic tracking system quantified elbow kinematics. A custom distal humeral stem was implanted by use of navigation, and 3 humeral articular spools were evaluated: optimally sized, undersized, and oversized. Statistical analysis was performed with repeated-measures analysis of variance.

Results: Distal humeral hemiarthroplasty altered elbow kinematics, regardless of implant size. In the valgus position, the optimally sized implant resulted in a mean increase in valgus angulation of 3° ± 1° (P = .003) as compared with the osteotomy control. In the varus position, the optimal and undersized implants both resulted in significant increases in varus angulation: 3° ± 1° (P = .01) and 3° ± 1° (P = .001), respectively. The undersized implant had the greatest alteration in kinematics, whereas the oversized implant best reproduced native elbow kinematics.

Conclusion: This study showed a small but significant alteration in elbow joint kinematics with placement of a distal humeral hemiarthroplasty implant, regardless of implant size. This could be due to errors in implant positioning and/or differences in the shape of the humeral implant relative to the native elbow. These changes in joint tracking may cause abnormal articular contact and loading, which may result in pain and cartilage degeneration over time.

Level of evidence: Basic Science, Kinematics, Cadaveric Model.

Keywords: Elbow hemiarthroplasty; implant design; elbow kinematics

Though described and reported many years ago, there has been recent interest in elbow hemiarthroplasty as a less invasive alternative to total elbow arthroplasty. Hemiarthroplasty may be ideal in situations in which only one...
portion of the elbow joint is affected, such as distal humeral fractures not amenable to open reduction–internal fixation, nonunions, or avascular necrosis. Hemiarthroplasty has the advantage of less invasive surgical approaches, less patient morbidity, avoidance of polyethylene wear concerns, and preservation of bone stock for future reconstructive procedures.2

There is a paucity of literature regarding hemiarthroplasty of the elbow. Clinical studies to date are few, with limited sample sizes, short-term follow-up, inconsistent indications for surgery, and variable implant materials and designs.1,2,3,14,17,19,21-23 In addition to the lack of clinical information, there is a complete void of information regarding the biomechanics of these devices. Altered elbow kinematics may result in symptomatic instability from maltracking, implant loosening, and accelerated wear of the native articulation. Given that surgeons estimate the optimal implant size at surgery, the effect of incorrect implant sizing on joint kinematics and mechanics is unknown. Therefore, the purpose of this study was to determine the influence of distal humeral hemiarthroplasty and implant size on joint kinematics and stability in vitro.

Methods

This in vitro study quantifying the effects of hemiarthroplasty on elbow joint mechanics used 8 fresh, previously frozen male cadaveric arms (aged 76 ± 6.4 years) amputated at the mid humerus. Each arm underwent 64-slice, computed tomography (CT) (GE LightSpeed Ultra; General Electric, New Berlin, WI, USA).

A three-dimensional (3D) surface model was generated (Visualization Toolkit [VTK]; Kitware, Clifton Park, New York, NY, USA) from CT scan DICOM (Digital Imaging and Communications in Medicine) data.

The optimally sized distal humeral implant was determined by measurements taken from the 3D CT reconstruction. Points were defined on the surface of the trochlea and capitellum with a semiautomated algorithm by use of initial boundary points selected by a single user (Fig. 1). The geometric center of the capitellum and trochlea was found by sphere fitting of the capitellum and circle fitting of the trochlear groove. The distance from the geometric center of the trochlear groove to the geometric center of the capitellum was measured for each 3D model. To match the implant to the specimen, comparative measurements were taken from 3D models of the 6 distal humeral implants (Latitude Anatomic, Tornier, Stafford, TX, USA).

Specimens were thawed at room temperature (mean, 22°C ± 2°C) for 18 hours before testing. They were kept hydrated throughout the preparation and testing protocol with normal saline solution. The tendons of the biceps, triceps, and brachialis were sutured by a locking Krackow repair.2 All skin incisions were closed with No. 2 Vicryl (Ethicon, Bridgewater, NJ, USA). A Steinmann pin was placed through the third metacarpal, through the carpus, and into the distal radius to fix the wrist in neutral rotation. Two fully threaded 3.5-mm cortical screws were placed across the distal radioulnar joint to fix the forearm in neutral rotation.

The distal humerus was mounted in an in vitro, unconstrained elbow simulator previously developed in our laboratory.7 The sutures were connected to servomotors via braided Dacron cords. The servomotors applied forces to the tendons that moved the elbow from full extension to full flexion or vice versa at a controlled rate (10/s). The motion simulation was based on electromyographic data and muscle cross-sectional area.8,10 Established muscle load protocols were used during active motion, as reported by Ferreira et al.7 The simulator allowed for testing in the dependent (vertical), horizontal, varus, and valgus positions (Fig. 2). The motion of the ulna with respect to the humerus was quantified with the use of an electromagnetic tracking system (trakSTAR; Ascension Technology, Burlington, VT, USA). Accuracy as reported by the manufacturer is 1.8 mm with 0.5° root-mean-square deviation. A tracker receiver was rigidly fixed to the ulna, and the tracking transmitter was mounted on the simulator rigidly with respect to the humerus.

Testing began with the intact arm. The various elbow orientations, including varus, valgus, dependent, and horizontal positions, were tested in random order both actively and passively in flexion and extension. Passive flexion was performed by 1 investigator (S.J.D.) slowly moving the arm through a full arc of motion. The elbow was then surgically exposed through a midline posterior incision. Medial and lateral fasciocutaneous flaps were created, and the subcutaneous border of the ulna was identified. A chevron-type olecranon osteotomy was performed to gain access to the distal humerus. The osteotomy was fixed with a precontoured olecranon plate and locking screws (Accumed, Hillsboro, OR, USA). The collateral ligaments were left intact. The testing protocol with the native articulation was
repeated after the osteotomy and fixation to act as a control to determine whether there were any kinematic changes due to the osteotomy alone.

A medium humeral stem (Latitude; Tornier) was shortened for ease of placement into the humeral canal. The stem was shortened to optimize articular alignment by avoiding stem impingement with the humeral canal. The shortened stem was placed under computer navigation, which has been shown to improve accuracy and reproducibility of humeral component placement. This step was performed by first digitizing the native elbow’s distal humeral articular surface using a 3D optical tracking system (Optotrak Certus; NDI, Waterloo, ON, Canada). This was accomplished by using a stylus and tracing the native distal humeral articular surface. On the basis of the point cloud created, a 3D surface model was generated. The humeral stem was calibrated to the tracking system, and its location was tracked in real time during navigation relative to the humeral anatomy. The stem location was visualized by viewing the computer-aided design model of the implant spool. During navigation, the spool was not actually attached to the stem; however, its virtual representation aided navigation by aligning it to the virtual humeral articular surface (Fig. 3). Navigation was performed as the stem was cemented in the humeral canal. The optimally sized implant, which was predetermined based on the 3D CT measurements; the implant that was one size too large; and the implant that was one size too small were tested in random order (Fig. 4). The stem was custom designed to fit all 3 implants using a locking mechanism; therefore, only a single stem was cemented throughout the duration of the testing protocol. Loosening of the stems was not observed in any of the tested elbows; all were well fixed at the conclusion of the testing protocol. Just before testing, a fellowship-trained elbow surgeon estimated the size of the implant based on direct visualization of the native distal humerus. This allowed us to determine any trends in accuracy of implant size selection.

We used a 2-way repeated-measures analysis of variance comparing flexion angle and implant size for varus-valgus angulation and internal-external rotation. Significance was defined as $P < .05$.

**Results**

The distal humeral implant was navigated to its optimal position by matching the surface of the implant with the virtual digitized articular surface of the native distal humerus. This resulted in a close match of articular surfaces but not the flexion-extension (FE) axis. The difference between the FE axis of the implant and the FE axis of the native distal humerus was $7° ± 3°$ (range, $4°$-$11°$) ($P < .001$).

**Varus/valgus angulation**

**Olecranon osteotomy**

Small but significant increases in valgus angulation occurred after the olecranon osteotomy with the arm oriented in the valgus position for active and passive motion: $1° ± 1°$ ($P = .047$) and $1° ± 1°$ ($P = .049$), respectively (Fig. 5). In the varus position, there were no differences in varus angulation for either active ($P = .8$) or passive ($P = .2$) motion.

As a result of the small differences in kinematics after the olecranon osteotomy, the post-osteotomy state was used as the control for all further analyses.

**Dependent and horizontal positions**

There was no difference in varus-valgus angulation among the intact, post-osteotomy, optimally sized, oversized, and undersized hemiarthroplasty groups with either active ($P > .05$) or passive ($P > .05$) motion in both the dependent ($P > .05$) and horizontal ($P > .05$) positions.

**Valgus position**

When compared with the post-osteotomy state, there was a significant increase in valgus angulation for all implant sizes with both active and passive motion (Fig. 6). The
optimal implant had an increase in valgus angulation of 3° ± 1° \((P = .003)\), the oversized implant had an increase of 3° ± 2° \((P = .01)\), and the undersized implant had an increase of 4° ± 2° \((P = .01)\). With passive motion, the optimal implant had an increase in valgus angulation of 3° ± 1° \((P < .001)\), the oversized implant had an increase of 3° ± 2° \((P = .02)\), and the undersized implant had an increase of 4° ± 2° \((P = .01)\).

When we compared individual implant sizes, there were no differences between the optimally sized implant and either the oversized or undersized implant \((P > .05)\) (Fig. 6). However, the undersized implant had a significant increase in valgus angulation of 1° ± 1° \((P = .001)\) and 2° ± 1° \((P = .006)\) with active and passive motion, respectively, when compared with the oversized implant.

### Varus position

When compared with the post-osteotomy state, there was a significant increase in varus angulation for the optimally sized and undersized implants with both active and passive motion (Fig. 7). The optimal implant had an increase in varus angulation of 3° ± 1° \((P = .01)\) and the undersized implant had an increase of 3° ± 1° \((P = .001)\). There was no difference in varus angulation between the oversized implant and the post-osteotomy control \((P = .2)\). During passive motion, the optimal implant had an increase in varus angulation of 2° ± 1° \((P = .04)\) and the undersized implant had an increase of 3° ± 1° \((P = .004)\). There was no difference in varus angulation between the oversized implant and the control \((P = .8)\).

When we compared individual implant sizes with each other, there were no differences between the optimally sized implant and either the oversized or undersized implant with active motion \((P > .05)\). With passive motion, the undersized implant had an increase in varus angulation of 1° ± 1° \((P = .01)\) when compared with the optimally sized implant.

With both active and passive motion, there were kinematic differences between the oversized and undersized implants. The undersized implant had an increase in varus angulation of 1° ± 1° \((P = .004)\) with active motion when compared with the oversized implant. With passive motion, the undersized implant had an increase in varus angulation of 2° ± 1° \((P = .003)\) when compared with the oversized implant.

### Ulnohumeral rotation

#### Olecranon osteotomy

Significant changes in ulnohumeral rotation occurred after the olecranon osteotomy with the arm in the valgus position. During active motion, there was a significant increase in external rotation of 2° ± 1° \((P = .005)\) after the olecranon osteotomy. During passive motion, there was also a significant increase in external rotation of 2° ± 1° \((P < .0001)\). No changes in ulnohumeral rotation were present in the varus position with either active or passive motion.

During passive motion in the dependent position, there was an increase in external rotation of 2° ± 1° \((P = .01)\) after the olecranon osteotomy. No changes were found with active motion. Given the alterations in kinematics after the olecranon osteotomy, this was used as the control for analysis.

#### Dependent and horizontal positions

There was no difference in ulnohumeral rotation among the intact, post-osteotomy, optimally sized, oversized, and undersized hemiarthroplasty groups with either active
Valgus position
There was no difference in ulnohumeral rotation among the intact, post-osteotomy, optimally sized, oversized, and undersized hemiarthroplasty groups with either active \((P > .05)\) or passive \((P > .05)\) motion in the valgus position.

Varus position
Significant changes in ulnohumeral rotation occurred with the arm in the varus position. When compared with the post-osteotomy state, there was an increase in internal rotation for the optimally sized and undersized implants with passive motion. The optimal implant had an increase in internal rotation of \(3^\circ \pm 2^\circ (P = .04)\), and the undersized implant had an increase of \(4^\circ \pm 2^\circ (P = .01)\). There was no difference in varus angulation between the oversized implant and the post-osteotomy state \((P = .1)\). No differences were present during active motion.

Implant sizing
Before the humeral cuts were performed, the size of the optimal implant was estimated by a fellowship-trained elbow surgeon. This size was compared with the optimal implant size chosen based on 3D CT measurements. In 3 of the 8 specimens, an incorrect size was chosen. In all cases, an undersized implant was selected.

Discussion
The olecranon osteotomy did not precisely re-create the native kinematics after repair and, as such, was not a perfect control. The surgical technique for the osteotomy involved leaving all major stabilizing ligaments intact, including the anterior band of the medial collateral...
ligament and the lateral ulnar collateral ligament. However, the surgical exposure sacrificed the accessory stabilizers of the elbow, including the posterolateral capsule and the posterior portion of the posterior band of the medial collateral ligament. This likely resulted in a subtle increase in elbow instability, as has previously been reported.20 Interestingly, there was no difference in varus angulation or ulnohumeral internal rotation in the varus position after the olecranon osteotomy with either active ($P > .05$) or passive ($P > .05$) motion. A possible explanation is the relatively greater contribution to elbow stability of the posterior band of the medial collateral ligament when compared with the posterolateral capsule. Another possible explanation is that the olecranon osteotomy, which was fixed with a precontoured locking plate, may not have been repaired in an anatomic position despite our best efforts.

This study shows that distal humeral hemiarthroplasty alters elbow joint kinematics, regardless of the implant size, in both the varus and valgus positions. This difference in kinematics between the post-osteotomy elbow and the elbows with the hemiarthroplasty implant may, in part, be related to the navigation technique. The distal humeral implant was navigated into position by visually matching the digitized surface of the native distal humerus with the surface of the humeral implant. Navigation of distal humeral implants has been shown to increase accuracy; however, inaccurate placement still occurred because of errors in registration and optical implant tracking and because of the subjective nature of the navigation attempting to match the surface contours. This error in navigation may result in a mismatch in the FE axis between the implant and the native distal humerus. The anatomic FE axis of the distal humerus is defined by the geometric center of the capitellum, approximated as a sphere, and by the geometric center of the trochlear groove, approximated as a circle.4-6,13,18 As mentioned earlier, the navigation was performed by matching the surface of the implant with the native distal humeral surface, not the native FE axis. This

![Figure 6](image.png)

**Figure 6** Mean valgus angulation for active motion (A) and passive motion (B) with arm oriented in valgus position for post-osteotomy state and optimally sized, undersized, and oversized implants. There was an increase in valgus angulation for all implant sizes throughout the range of motion ($P < .05$).
resulted in a difference between the FE axis of the native distal humerus and the navigated implant of 7° ± 3° (P < .001). In addition, even the optimally sized distal humeral implant shape did not precisely match the shape of the native distal humerus, indicating that the implant may not precisely re-create normal anatomy. This may further explain the alteration in joint kinematics.

When we compared individual implant sizes, not surprisingly, the undersized implant was consistently more lax than the oversized implant in both the valgus and varus positions. The optimally sized implants would be expected to best re-create physiological tension in the soft tissues and restore normal stability. In our study, a fellowship-trained elbow surgeon chose an implant size based on the size of the native distal humerus. In 3 of the 8 distal humeri, the size was underestimated by the surgeon when compared with the CT-derived optimal dimensions. The results of this study suggest that intraoperatively, when uncertainty exists in choosing between sizes, the surgeon should choose the larger implant because this may reduce postoperative instability and provide more favorable contact mechanics. However, the effect that this may have on articular cartilage contact area, loading, and wear is not known.

This study has limitations. First, we performed an olecranon osteotomy to insert the implant while leaving the stabilizing ligaments intact. This is a common technique to insert a hemiarthroplasty implant clinically, and it closely models other surgical approaches in which the collateral ligaments are taken down and repaired or epicondylar fractures are internally fixed around the implant. Second, we used the width between the center of the capitellum and the center of the trochlea to determine the size of the distal humeral implant. Sizing the implant by a different technique, such as using the diameter of the capitellum and

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Figure 7  Mean varus angulation with active motion (A) and passive motion (B) with arm oriented in varus position. When compared with the post-osteotomy state, there was an increase in varus angulation for the optimally sized and undersized implants. There was no difference in varus angulation between the oversized implant and the control (P = .2). Similar results were found with passive motion. When we compared the oversized and undersized implants, the undersized implant had an increase in varus angulation with both active and passive motion (P < .05).
trochlea, may have led to a different size for the optimal implant, explaining the finding that the oversized implant best re-created normal kinematics. Further studies are needed to evaluate the optimal shape of distal humeral implant designs. Third, the implant size determined from CT scan did not account for articular cartilage. Our approach to determine optimal size, using the width between the center of the capitellum and the center of the trochlea, would not be affected by the thickness of the articular cartilage. Therefore, lack of incorporation of articular cartilage would not have an effect on implant sizing. Fourth, we used an in vitro elbow motion simulator, which may not precisely replicate the clinical scenario. Fifth, our protocol involved prolonged testing with 4 positions and multiple conditions, which may have resulted in changes in the mechanical behavior of the soft tissues. However, previous studies have suggested that these changes may be minor in relation to the experimental effects of interest. Finally, we have quantified the differences in varus-valgus angulation and ulnohumeral rotation; however, we are unsure of the extent to which alterations in angulation or rotation are clinically significant in elbow hemiarthroplasty. In addition, these results can only be applied to the hemiarthroplasty implants tested and should not be generalized to other designs.

Conclusion

This study showed an alteration in elbow joint kinematics with placement of a distal humeral hemiarthroplasty implant, regardless of implant size, when compared with the control group. The kinematic alterations were small; therefore, it is difficult to deduce whether patients would have symptomatic instability. Clinical studies are required to further assess this hypothesis. The modest changes in joint kinematics will cause significant changes in articular contact and loading, which may result in pain, accelerated cartilage degeneration, and arthritis. In addition, within the hemiarthroplasty group, the implant that was too small showed the greatest alteration in joint kinematics and stability. This suggests that intraoperative sizing has an important role in joint stability. Intraoperatively, if a surgeon is faced with uncertainty, the larger implant may be a better option, at least from the perspective of joint kinematics and stability.

Disclaimer

The study received funding from a Resident Research Grant from Physicians’ Services Incorporated Foundation.

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