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The effect of implant malalignment on joint loading in total elbow arthroplasty: an in vitro study

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Hypothesis: Aseptic loosening is one of the leading causes of failure in total elbow arthroplasty. Incorrect implant positioning and alignment in other joints such as the knee have been found to lead to excessive loading and wear. Although similar alignment difficulties exist in the elbow, the effect of implant malalignment on wear-inducing loads is not yet known. This in vitro study determined the effect of anterior malpositioning and varus-valgus and internal-external malrotations on humeral stem loading in total elbow arthroplasty.

Methods and materials: Computer-navigated linked elbow arthroplasty was conducted in 8 cadaveric elbows. A modular, instrumented humeral component was used to measure loading during simulated elbow motion while the position of the ulna relative to the humerus was recorded.

Results: Loading increased for all malaligned implant positions tested ($P < .05$). During simulation of implant malpositioning, combinations of internal-external and varus-valgus malrotations that tended to preserve the line of action of the elbow flexors had lower loads than combinations that did not.

Discussion: This in vitro study showed that loading does increase after humeral component malalignment; however, further studies are required to determine the long-term effects on polyethylene wear and component loosening.

Level of evidence: Basic Science Study, Biomechanical Study.

Keywords: Elbow; arthroplasty; biomechanics; forces; malalignment

Aseptic loosening remains the most common cause of failure of total elbow arthroplasty, and several mechanisms have been reported.[7,8,12,14,17,25] The additional constraint imposed by the linkage mechanism in semiconstrained arthroplasties can lead to increases in ulnohumeral loading,[1] increases in polyethylene wear debris,[9,19,21] and pullout of the ulnar component.[8] Articular wear may be further increased by off-axis loading of malpositioned components. Errors in placement of up to 8° in internal-external rotation and 6° in varus-valgus orientation can occur during the identification of the humeral flexion-extension axis in an optimal laboratory setting.[6] Malpositioning of the flexion-extension axis is likely even more common in clinical practice, probably because of limited surgical exposure, periarticular bone loss, and deformity.

In light of the foregoing data, this in vitro study was undertaken to measure the effects of humeral component malpositioning on the loading of a linked total elbow arthroplasty. Using an adjustable humeral component, we compared

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the loads at the elbow after optimal implantation using computer-navigated surgery with those after anterior, internal-external, and varus-valgus malpositioning. We hypothesized that humeral component malpositioning would increase implant loading and that the loads would be lowest with the implant in the optimal position.

Methods and materials

Experimental design and testing approaches

We tested 8 fresh-frozen upper extremities (mean age, 75 years; age range, 42-93 years; 5 male), amputated at the mid humerus, using an elbow motion simulator capable of producing load and motion control to achieve active flexion trials for the dependent (humerus vertical) position.[11] The active flexion used in this analysis represents the most anatomically relevant motion because it does not require direct manipulation of the forearm (ie, passive flexion) to create motion. Passive flexion[10] trials were performed for the dependent orientation, as well as for the varus and valgus gravity-loaded orientations-the humerus oriented horizontally with the medial epicondyle pointed downward (varus) or with the lateral epicondyle pointed downward (valgus). Passive motion was created by the investigator at the wrist without supporting the weight of the arm during flexion. An electromagnetic tracking system (Flock of Birds; Ascension Technology Corporation, Burlington, VA, USA) quantified the position of the ulna relative to the humerus and was also used for the computer-assisted navigation procedure. The custom navigation system allowed the surgeon to align the flexion-extension axis of the humeral and ulnar components to their respective anatomic flexion axis. The radial component of the arthroplasty was aligned to the deepest point of the intact radial head.

A linked Latitude (Tornier, Stafford, TX, USA) total elbow arthroplasty with a modified humeral component was used (Fig. 1).[13] This modified construct was able to simulate implant alignment errors of $\pm 6°$ of varus-valgus rotation and $\pm 8°$ of internal-external rotation by use of interchangeable stage components. Yolks were made to accommodate 3 sizes (small, medium, and large) of specimens, where sizing was determined by the humeral articular width as is done clinically. For each size of implant, a yolk was made to replicate the native offset between the canal axis and the flexion-extension axis.

A second yolk simulated a 5-mm anterior shift of the implant articulation axis. In total, 8 angular malalignments and 1 anterior shift were compared with the optimally positioned implant. A list of the positions tested is given in Table I. A short-stemmed ulnar component and an appropriately sized radial head component were used in all specimens.

The humeral component was equipped with a 2 degree of freedom (*df*) load cell for measuring varus-valgus bending and internal-external torsion. Uniaxial strain gauges (model EA-06-125BZ-350; Vishay Intertechnology, Malvern, PA, USA) were affixed on the medial and lateral sides of the load cell and arrayed in a half-bridge configuration to measure the varus-valgus bending. To measure the internal-external torsion, biaxial gauges (model SK-06-062TH-350; Vishay Intertechnology) were arrayed on the anterior and posterior sides of the load cell in a full-bridge configuration. A linear calibration was performed by use of known weights; the R^2 values for the linear fits on the calibration curves were greater than 0.95. Varus-valgus bending and internal-external torsion were measured during both simulated active dependent flexion and passive flexion for all orientations. These were quantified because they would relate primarily to the eccentric loads that occur at the articulation and hence are most concerning with regard to wear. For example, the varus-valgus bending and internal-external torsion would be most significant in this regard at 0° and 90° of flexion, respectively. At other angles, the vector combination of these 2 loads would be relevant. Hence, the resultant loading at the humeral stem was calculated by combining the varus-valgus bending and internal-external torsion by using the sum of squares.

The humeral, ulnar, and radial components were implanted by a computer-assisted surgical technique that used tracking receivers attached to each component.[4,5] Figure 2 shows a representative image of the implant positioned in the elbow. The humeral component was aligned with the flexion-extension axis of the humerus, defined by a line connecting the geometric centers of the capitellum and trochlear sulcus, approximated as a sphere and circle, respectively.[3] The ulnar component was aligned such that the center and plane of the implant's guiding ridge coincided with those of the greater sigmoid notch. The deepest point of the radial head implant was aligned to the deepest point of the native radial head dish. The collateral ligaments were sectioned during implantation and not repaired. Joint kinematics were recorded by the tracking system.

Statistical analysis

For statistical analysis, we used Statistica software (StatSoft, Tulsa, OK, USA). Repeated-measures 3-way analysis of variance with statistical significance set at .05 was used to determine the effects of forearm pronation-supination, implant malpositioning, and flexion angle on loading of the humeral implant. Flexion angles from 0° to 120°, at 15° increments, were tested.

Results

Forearm pronation and supination

There was no isolated effect of pronation or supination on resultant loading ($P = .07$) for dependent active flexion. There were no combined effects of forearm pronation/supination and implant position on resultant loading for active flexion with the arm in the dependent orientation ($P > .2$). However, resultant loads were higher with the arm in pronation than in supination ($P < .05$) for flexion angles lower than 105°.

Implant position

For dependent active flexion, with the forearm in supination, the resultant load of the optimally positioned implant was lower than all the malpositioned cases ($P < .01$), except for when the implant was rotated externally (Fig. 3). For this case, the resultant loading of the optimally positioned implant was only lower at flexion angles greater than 60° ($P < .05$).