Implications of Radial Head Hemiarthroplasty Dish Depth on Radiocapitellar Contact Mechanics

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Purpose To investigate the effect of radial head implant dish depth on radiocapitellar joint contact mechanics.

Methods Computed tomography images of 13 fresh-frozen cadaveric humeri were reconstructed into 3-dimensional finite element models with accurate cartilage geometry. Native humeri were paired with the corresponding native radial heads and axisymmetric radial head prosthesis models of the following dish depths: 1.0 mm, 1.5 mm, 2.0 mm, 2.5 mm, and 3.0 mm. Radiocapitellar contact mechanics were quantified at 4 different flexion angles (0°, 45°, 90°, and 135°) with a 100-N axial load applied to the radial head using a modeling protocol previously validated by cadaveric studies. The radial head was permitted to translate freely to its optimal position while the humerus was fully constrained. Output variables were contact area and peak contact stress.

Results All prostheses had significantly decreased contact area and increased peak contact stress at all flexion angles relative to the native radiocapitellar joint. Contact area increased with prosthesis dish depth until reaching a plateau with a predicted local maximum at a mean depth of 3.2 ± 0.7 mm. Peak contact stress was elevated for both the shallowest and deepest models and reached a predicted local minimum at a mean depth of 1.8 ± 0.3 mm.

Conclusions Contact area and peak contact stress were dependent on radial head prosthesis dish depth. There was an optimal implant dish depth for radiocapitellar contact mechanics at approximately 2 mm.

Clinical relevance Optimizing radiocapitellar contact mechanics using rigorous and systematic prosthesis design techniques may lead to better clinical outcomes due to reduced capitellar cartilage degradation. *(J Hand Surg Am. 2015;40(4):723–729. Copyright © 2015 by the American Society for Surgery of the Hand. All rights reserved.)*

Key words Dish depth, finite element analysis, prosthesis design, radial head, radiocapitellar joint.

RADIAL HEAD FRACTURES ARE COMMON and constitute one-third of elbow fractures.[1] Of those, approximately 18% are comminuted,[2] which often require replacement as internal fixation is not reliable and concomitant ligament injuries often preclude radial head excision.[3] Van Riet et al. reported a mean age of 45 years for patients with radial head fracture, highlighting the importance of long-term viability of a hemiarthroplasty.[4]

Radial head hemiarthroplasty presents a set of challenges because of the high stiffness of most commercially available implants relative to bone and cartilage. Articular cartilage contributes to optimal contact mechanics of the native joint thanks to its low stiffness, which allows it to conform, thus maximizing contact area and reducing stress.[5] In contrast, metallic radial head implants are 100,000 times stiffer than cartilage and decrease contact area by up to two-thirds

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compared with the native joint.[6] As a result, the clinical consequences of radial head hemiarthroplasty can include cartilage degeneration, osteoarthritis, and bone erosion of the capitellum.[7–9] Optimizing contact mechanics by maximizing contact area and minimizing peak contact stress could potentially prevent the degradation of the native cartilaginous surface, leading to better clinical outcomes of radial head hemiarthroplasty.

One important consideration to investigate with respect to radial head hemiarthroplasty design is the depth of the concavity of the articular surface (dish depth) mating with the capitellum of the distal humerus. King et al. reported the mean depth of this dish in the native radial head as 2.4 mm, ranging from 1.1 mm to 3.5 mm,[10] although this may or may not represent the ideal dish depth for a hemiarthroplasty that has different material properties from native bone and cartilage. One previously reported study has (indirectly) addressed the effect of dish depth on radiocapitellar contact mechanics. Sahu et al. compared contact mechanics between axisymmetric and non-axisymmetric prosthesis designs with, among other differences, respective dish depths of 1 mm and 2.3 mm. The shallower dish exhibited a nonconforming articular surface, resulting in reduced contact area and increased contact pressure.[11]

Although these previous studies have reported preliminary observations on the effect of dish depth on radiocapitellar joint mechanics, it is important to systematically examine dish depth as an independent variable and to investigate a wider range of depths. Hence, the purpose of this study was to investigate the effect of radial head implant dish depth on radiocapitellar contact mechanics. This study used a validated finite element analysis to permit the quantification of both contact area and stress. We hypothesized that metallic prostheses would worsen contact mechanics relative to the native joint and a deeper dish would exhibit increased contact area due to increased conformity with the capitellum and a lower peak contact stress due to the articular load being distributed over a greater contact area. The ultimate objective was to determine the best radial head implant dish depth to optimize elbow contact mechanics.

MATERIALS AND METHODS

Image acquisition

Computed tomography (CT) images of 13 fresh-frozen cadaveric elbows (mean age, 72 ± 18 y; range, 21–90 y) were taken using a GE Discovery CT750 HD scanner (GE Healthcare, Pewaukee, WI) with the following specifications: 120 kV, 200 mA, and 0.625-mm slice thickness. Voxel dimensions in the transverse, sagittal, and coronal planes were 0.625 × 0.180–0.229 × 0.180–0.229 mm. Each specimen was disarticulated and stripped of soft tissues, and the humeri and radii were rescanned in air in order to accurately quantify cartilage thickness and distribution.[12]

Model development

CT images of the intact humeri and radii were reconstructed and developed into Finite Element Analysis models using the following protocol previously described and validated by Willing et al., with computational contact area results within 10% of experimentally obtained values.[12] Bone geometry was segmented using Mimics 14.12 (Materialise, Leuven, Belgium) with a minimum threshold of +250 Hounsfield units, while cartilage geometry was segmented with a minimum threshold of −500 Hounsfield units after joint disarticulation and scanning in air. Bone surface models were wrapped and remeshed using FastRBF Toolbox (FarField Technology, Christchurch, New Zealand). Quadrilateral surface meshes were created for the cartilaginous surfaces of each specimen using NETGEN-5.0.0 (RWTH Aachen University, Germany, and Johannes Kepler University of Linz, Austria) with mesh element edge lengths controlled between 0.30 mm and 0.45 mm. Three layers of linear hexahedral (8-node) elements were created by sweeping the quadrilateral cartilage surface mesh towards the subchondral bone surface mesh. The cartilage mesh was tied to the underlying subchondral bone mesh when each model was imported into Abaqus v6.12-2 (Simulia Corp, Providence, RI).

Five axisymmetric radial head hemiarthroplasty prosthesis models were constructed with articulation concavities of the following depths: 1.0 mm, 1.5 mm, 2.0 mm, 2.5 mm, and 3.0 mm. The median 2.0-mm model was designed with a constant radius of curvature, and the remaining depth models were produced by either increasing (for the shallower) or decreasing (for the deeper) the radius of curvature, and then blending this radius into the dish edge of the 2.0-mm model without changing other geometric properties of the dish, such as diameter. The implants were assigned cobalt-chrome material properties ($E = 230$ GPa, $\nu = 0.3$).

Finite element modeling

Each native humerus model was paired with the corresponding native radius model and the radial head prosthesis models of each depth. Appropriate implant size was selected for each specimen based on matching the diameter of the axisymmetric implant to