e-Appendix

Silicone Rubber Validation

The method of determining the in vivo centroid of articular contact on the glenoid component from the recreated total shoulder arthroplasty joint positions in the virtual environment was validated with use of a silicone rubber casting technique[59,60]. Anatomic total shoulder arthroplasty components were implanted in a bone substitute, and the distal diaphysis of the humerus was potted in polymethylmethacrylate bone cement. The scapula was rigidly fixed with the normal glenoid surface perpendicular to the ground, representing roughly a 90° rotation from the anatomic position to simplify load application. Above the glenoid, the polymethylmethacrylate-potted shaft of the humerus was fixed in a cylindrical jig mounted to a six-degrees-of-freedom load cell (160M50S; JR3, Woodland, California) attached to the manipulator of an industrial robot (UZ150F; Kawasaki Motors, Lincoln, Nebraska) (Fig. E-1, *A*). The humerus was positioned to represent approximately 60° and 90° of abduction of the long axis of the humerus in neutral rotation, taking into account the scapulothoracic rotation with humeral abduction of approximately two to one[25,61-64]. A dual-plane fluoroscopic imaging system was positioned around the glenohumeral joint. The joint was disarticulated, and fast-setting silicone rubber (QuickSet; Alumilite, Kalamazoo, Michigan) was placed on the glenoid articular surface, immediately followed by the application of 350 N from the humeral head in the direction perpendicular to the ground. A force of 350 N was chosen because it was within the range of reported physiologic glenohumeral loads[20,35,65-69] and may approximate the holding of a 10-lb (4.5-kg) weight abducted in the coronal plane. The silicone rubber set in approximately one minute. Fluoroscopic images were acquired under load, and then the joint was disarticulated. The silicone rubber was squeezed out of the location where contact occurred between the humeral and glenoid articular surfaces. This voided area was digitized (MicroScribe G2LX; Immersion, San Jose, California) along with geometric landmarks on the glenoid component to facilitate alignment in a virtual environment (Fig. E-1, *B*). Similar to the method presented earlier, a virtual dual-plane fluoroscopic imaging system[58] was created and the fluoroscopic images corrected for distortion were imported into the virtual environment. The imaged in vitro positions of the humerus and glenoid components were reproduced virtually, and the glenoid centroids of contact were measured with use of the overlap method previously described in this paper (Fig. E-1, *C*). These manual pose-matching and centroid measurement protocols were repeated for a total of twelve independent trials to assess the repeatability of the technique. The contact centroid measured from the overlap method in the virtual environment was compared with the area centroid measured from the digitized silicone rubber casting taken as the gold standard. This procedure was repeated for a total of one trial at approximately 60° of abduction and two trials at approximately 90° of abduction of the long axis of the humerus in the coronal plane.

The difference in the absolute distance of the measured centroid of contact between the overlap method and silicone rubber casting technique is listed as Delta X and Delta Y, respectively, in Table E-1. To calculate delta, the average contact centroid location from the twelve independent matches was subtracted from the silicone rubber gold-standard centroid location, and the absolute value was taken. In general, for both X and Y directions, the average offset of the overlap method to the gold standard was at most 0.30 mm, which is on the order of the accuracy of the MicroScribe digitizing equipment. The repeatability of measuring the contact centroid in the virtual environment was defined as the standard error of the twelve independent pose-match centroid calculations and was listed as SD X Fluoro and SD Y Fluoro, respectively, in Table E-1. On the average, for both X and Y directions, the standard error of repeating the placement of the centroid of contact with use of the overlap method on the glenoid surface was approximately 0.1 mm. This was on the order of the accuracy previously reported[58] for our method of reproducing in vivo joint positions in a virtual environment. Therefore, this noninvasive fluoroscopic imaging technique can be confidently applied to determine the in vivo glenohumeral articular contact locations in patients after total shoulder arthroplasty.

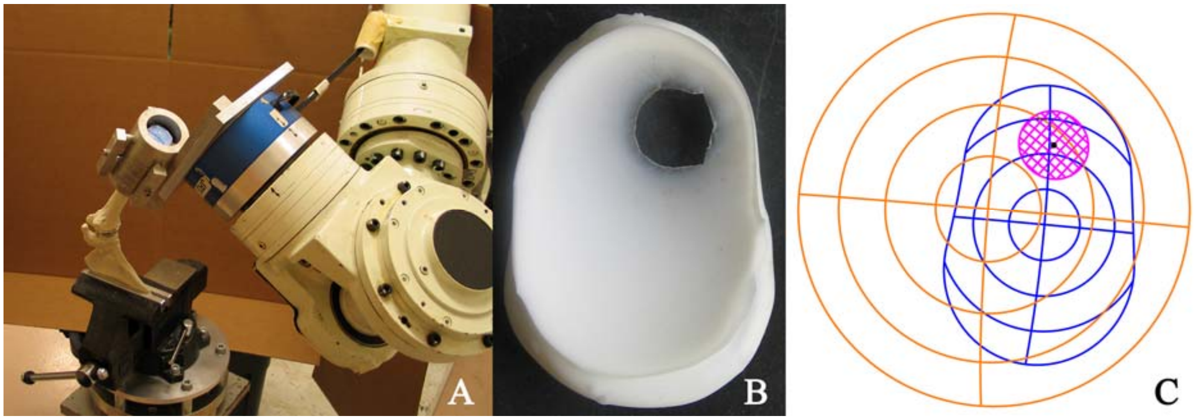

Fig. E-1

Validation of the silicone rubber casting technique. *A:* Robotic loading apparatus with the humeral shaft in approximately 60° of abduction relative to the scapula, simulating a total humeral-thoracic abduction of 90°. *B:* Silicone rubber casting after glenohumeral load application. *C:* Computer modeling environment representation of overlap of the humeral and glenoid articular surfaces depicting the centroid of articular contact. (Reprinted, with permission, from: Massimini DF. Technique and application of a non-invasive three dimensional image matching method for the study of total shoulder arthroplasty [MSc thesis]. Cambridge, MA: Department of Mechanical Engineering, Massachusetts Institute of Technology; 2009.)

TABLE E-1 The Difference in the Absolute Distance of the Measured Centroid of Contact Between the Overlap Method and Silicone Rubber Casting Technique*

Trial	Delta X *(mm)*	Delta Y *(mm)*	SD X Fluoro *(mm)*	SD Y Fluoro *(mm)*
90° of abduction (1)	0.63	0.02	0.04	0.08
90° of abduction (2)	0.12	0.03	0.05	0.10
60° of abduction	0.15	0.22	0.05	0.18
Average	0.30	0.09	0.05	0.12

*Delta X and Delta Y are the translational difference between the calculated centroid of contact with use of the virtual fluoroscopic technique and the measured centroid with use of the silicone rubber technique in the X axis and Y axis, respectively. SD X Fluoro and SD Y Fluoro are the standard deviation (SD) of the repeatability of locating the centroid when independently matching the glenoid and humeral components within the virtual fluoroscopic imaging system in the X axis and Y axis, respectively. (1) refers to trial 1 of 2, and (2) refers to trial 2 of 2. (Reprinted, with permission, from: Massimini DF. Technique and application of a non-invasive three dimensional image matching method for the study of total shoulder arthroplasty [MSc thesis]. Cambridge, MA: Department of Mechanical Engineering, Massachusetts Institute of Technology; 2009.)