Humeral head translation during glenohumeral abduction following computer-assisted shoulder hemiarthroplasty

A. E. Kedgley,
J. A. DeLude,
D. S. Drosdowech,
J. A. Johnson,
R. T. Bicknell

*From the University
of Western Ontario,
Ontario, Canada*

This study compared the effect of a computer-assisted and a traditional surgical technique on the kinematics of the glenohumeral joint during passive abduction after hemiarthroplasty of the shoulder for the treatment of fractures. We used seven pairs of fresh-frozen cadaver shoulders to create simulated four-part fractures of the proximal humerus, which were then reconstructed with hemiarthroplasty and reattachment of the tuberosities. The specimens were randomised, so that one from each pair was repaired using the computer-assisted technique, whereas a traditional hemiarthroplasty without navigation was performed in the contralateral shoulder. Kinematic data were obtained using an electromagnetic tracking device.

The traditional technique resulted in posterior and inferior translation of the humeral head. No statistical differences were observed before or after computer-assisted surgery.

Although it requires further improvement, the computer-assisted approach appears to allow glenohumeral kinematics to more closely replicate those of the native joint, potentially improving the function of the shoulder and extending the longevity of the prosthesis.

The functional outcome following hemiarthroplasty of the shoulder is related to the extent to which the normal anatomy and kinematics of the glenohumeral joint are restored.¹⁻⁶ Traditionally, surgeons have relied on pre-operative templating of radiographs, intra-operative instrumentation, and clinical experience to achieve these goals. However, in cases where anatomical landmarks have been disrupted, such as in displaced three- and four-part fractures of the proximal humerus, orientation of the implant and re-attachment of the tuberosities can both be difficult. Given the marked variability in proximal humeral anatomy,⁷ there is no single position or orientation of the prosthesis that will replicate the normal anatomy in all patients.⁸ In view of these challenges using traditional surgical techniques, a more accurate reduction may be obtained using computer-assisted hemiarthroplasty techniques.

We have developed such a technique and have shown that it can restore the anatomical landmarks better than traditional techniques.⁹ Although a virtual surgery system for the shoulder has recently been reported,¹⁰ to the best of our knowledge, ours is the only computer-assisted technique for shoulder hemiarthroplasty to have been validated *in vitro*.

The purpose of this study was to compare the passive kinematics of the glenohumeral joint during abduction in the scapular plane, following a computer-assisted method of shoulder hemiarthroplasty, with those resulting from a traditional technique. It was hypothesised that computer-assisted hemiarthroplasty would provide better restoration of glenohumeral kinematics than would a traditional surgical approach.

Materials and Methods

Seven pairs of fresh-frozen cadaver shoulder girdles with upper arms (mean age 69 years, 46 to 80) were used. Exclusion criteria were any evidence of previous surgery, trauma or dysplasia of the proximal humerus. One specimen from each pair was randomised to undergo hemiarthroplasty using the computer-assisted technique, whereas the contralateral shoulder was reconstructed using the traditional technique.

Testing procedure. A standard deltopectoral surgical approach was used in all specimens and a simulated four-part fracture of the proximal humerus was created using anatomical landmarks on the surgical neck and tuberosities. This produced four main fracture fragments: the greater tuberosity, lesser tuberosity,

■ A. E. Kedgley, MEdSc, PhD
Candidate
■ J. A. DeLude, MEdSc,
Research Assistant
■ D. S. Drosdowech, MD,
FRCS, Orthopaedic Surgeon
■ J. A. Johnson, PEng, PhD,
Professor of Engineering
Bioengineering Research
Laboratory
Hand and Upper Limb Centre,
St Joseph's Health Care
London, 268 Grosvenor Street,
London, Ontario, Canada N6A
4L6.

■ R. T. Bicknell, MD, MSc,
FRCS, Orthopaedic Surgeon
Division of Orthopaedic
Surgery, Department of
Surgery
Kingston General Hospital,
Nickle 3, 76 Stuart Street,
Queen's University, Kingston,
Ontario, Canada K7L 2V7.

Correspondence should be sent
to Dr R. T. Bicknell; e-mail:
rtbickne@yahoo.ca

©2008 British Editorial Society
of Bone and Joint Surgery
doi:10.1302/0301-620X.90B9.
20612 \$2.00

J Bone Joint Surg [Br]
2008;90-B:1256-9.

Received 12 December 2007;
Accepted after revision 29 April
2008

humeral head and humeral shaft. In both traditional and computer-assisted approaches, the goal was to restore the following seven anatomical characteristics of the proximal humerus: version, inclination and offset of the humeral head, humeral length, position of the medial articulation point and positions of the greater and lesser tuberosities. A modular shoulder hemiarthroplasty implant (Anatomical Shoulder Primary System, Zimmer Inc., Warsaw, Indiana) was used in all cases. At the time, this system did not include any dedicated external or internal guides for the intra-operative estimation of the orientation of the implant.

In the traditional technique, the diameter of the stem was determined based on a 'best-fit' approach, allowing for a 2 mm to 3 mm thick cement mantle. The size of the prosthetic humeral head was selected by measuring the resected humeral head. The prosthesis was assembled with a standardised humeral head offset of 7 mm, neck inclination of 130° and retroversion of 18°, in accordance with the manufacturer's recommendations for fracture reconstruction. In order to estimate the height of the humeral head and the soft-tissue tension on the tuberosities, a trial reduction preceded cementation of the stem. The rotator interval was repaired so that the tuberosities were accurately orientated to each other and to the prosthesis.

In the computer-assisted approach, the seven anatomical characteristics of the proximal humerus were determined and reconstructed according to a pre-operative CT scan and real-time intra-operative feedback. Detailed descriptions of both the computer-assisted and the traditional techniques have been reported previously.⁹ The Materialise's Interactive Medical Image Control System software with a MedCAD module (Materialise, Leuven, Belgium), the Rhinoceros NURBS Modeling for Windows (Robert McNeel & Associates, Seattle, Washington), and a custom-written LabVIEW (National Instruments, Austin, Texas) program were used to calculate the anatomical characteristics. Intra-operatively, the surgeon's goal was to match the planned positions of the implant head and shaft with the actual features of the implant. An electromagnetic tracking device (Flock of Birds, Ascension Technology Corporation, Burlington, Vermont), in conjunction with custom-written LabVIEW software, was used to provide real-time intra-operative feedback. The diameter of the stem was again determined based on a 'best-fit' approach, allowing for a 2 mm to 3 mm thick cement mantle, and the size of the humeral head was selected by comparison with the resected humeral head. Following cementation of the implant, the tuberosities were reattached, again using computer guidance, to best replicate their normal positions.

Passive glenohumeral abduction was performed in the scapular plane with the shoulder in neutral rotation, by moving the arm held at the level of the elbow. One investigator (RTB) tested all specimens. Joint kinematics were recorded using the electromagnetic tracking system. Movements of each specimen were conducted five times to quantify reproducibility.

Data and statistical analysis. Co-ordinate systems, created on both the humerus and scapula from digitised anatomical landmarks,¹¹ were used to compute the translation of the humeral head. The outcome variables were the position of the centre of the humeral head with respect to the scapula in the superoinferior and anteroposterior directions. Data were analysed in 10° increments of abduction. Results from the five trials of each movement were averaged for each specimen. The reproducibility of the measurements was quantified as the SD of the five trials.^{12,13}

Statistical analysis was performed using one- and two-way repeated-measures analysis of variance (ANOVA). The angle of abduction and the state of the humeral head intact and replaced (traditionally or computer-assisted) were examined. When interactions were observed in a two-way repeated-measures ANOVA, a one-way repeated measures ANOVA was performed at each abduction angle (i.e. beginning at 10° and continuing in increments of 10°). These were followed by the Student-Newman-Keuls multiple comparison technique,¹⁴ with significance defined as $p < 0.05$. Stability of the humeral head at each angle of elevation was investigated by calculating the difference in the location of the humeral head at that angle and its position at 30° of elevation.¹⁴

Results

Intra-specimen reproducibility testing showed that passive movements were consistent between trials, with the variability in the path of movement measuring 1.16 mm (SD 1.29) in the superoinferior and 0.97 mm (SD 0.97) in the anteroposterior direction. A significant difference was found between the operative techniques for the anteroposterior position of the humeral head ($p < 0.001$), with the traditional technique resulting in the humeral head being located more posteriorly at all angles of elevation (Fig. 1). Similar differences were also found before and after reconstruction in these specimens where a traditional hemiarthroplasty was performed ($p < 0.001$). There was no such difference in the specimens in which a computer-assisted technique was used ($p = 0.35$).

A significant difference was also found between the operative techniques for the position of the humeral head in the superoinferior direction ($p < 0.001$), with the traditional technique resulting in a more inferiorly positioned humeral head at all angles of elevation (Fig. 2). Significant differences were again found before and after arthroplasty with the traditional technique ($p < 0.001$), but not with the computer-assisted technique ($p = 0.6$).

No differences in stability, as defined above, were found for either direction ($p = 0.93$ for anteroposterior and $p = 0.80$ for superoinferior). No specimen dislocated during trials.

Discussion

A computer-assisted technique of shoulder hemiarthroplasty for the treatment of a simulated four-part fracture of

Fig. 1

Box plot presenting the translations of the humeral head in the anteroposterior direction, compared with its position before replacement, for angles of abduction between 30° and 70° in 10° increments (dotted lines represent mean values and solid lines represent median values).

Fig. 2

Box plot presenting the translations of the humeral head in the superoinferior direction, compared with its position before replacement, for angles of abduction between 30° and 70° in 10° increments (dotted lines represent mean values and solid lines represent median values).

the proximal humerus has been successfully developed.⁹ This technique allowed for patient-specific reconstruction of anatomical characteristics based on pre-operative CT scans, with real-time intra-operative feedback. Improvements in the accuracy of the placement of the glenoid component using computer assistance have also been reported recently.¹⁵

The similarities that were measured in the pre- and post-operative kinematics during passive abduction after computer-assisted hemiarthroplasty can perhaps be explained by the similarities in the anatomical characteristics of the reconstructed and intact states found by Bicknell et al.⁹ They found trends towards improved accuracy and consistency of anatomical reconstruction using the computer-assisted approach described here. The restoration of movement and function of the shoulder is linked to restoration of the anatomy of the joint.¹⁻⁶

We found that, after traditional hemiarthroplasty, the position of the humeral head may change up to 13 mm and 9 mm (Figs 1 and 2) in the superoinferior and anteroposterior directions, respectively. There are several potential biomechanical implications of this inferior and posterior translation, including alterations in joint tracking which may compromise the integrity of the articular cartilage of the glenoid and the stability of the joint. These changes could also alter the moment arms of the peri-articular muscle, resulting in increased joint reaction forces. Abnormal joint tracking or joint reaction forces may lead to chondrolysis of the glenoid, arthritis or peri-articular soft-tissue dysfunction. Wear of the posterior glenoid, caused by posterior subluxation of the prosthetic humeral head, can cause posterior instability and accelerated osteoarthritis. Furthermore, future prosthetic replacement of the glenoid may be more difficult than with a well-centred

glenohumeral joint. Therefore, it is essential that the kinematics of the joint are restored to as close to normal as possible post-operatively.

The major limitation of this study is the fact that only passive shoulder movement was evaluated. Given that active movement would have different effects on kinematic issues such as joint loading and tracking,¹⁴ it is possible that our results may have been different during simulated active movement. However, as early post-operative rehabilitation usually consists of a period of passive range of movement, these results are thought to be applicable to the shoulder hemiarthroplasty patient, particularly in the early post-operative period, but may not be applicable to the kinematics during active movement. Had a less experienced surgeon performed the operations, the restoration of the anatomy using the traditional technique might have been less accurate. Also, the fracture model used was simplistic. The increased variability of the configuration of fractures seen in the clinical setting may make surgical reconstruction more difficult with the traditional technique and easier with the computer-assisted technique. However, as the fracture pattern was standardised throughout the study, comparative results between the traditional and computer-assisted approaches could be obtained.

The strengths of this investigation include its paired, randomised, controlled design and the fact that a single surgeon performed all procedures using third-generation implants.

This is the first study known to examine the kinematic effects of a computer-assisted technique for performing shoulder hemiarthroplasty. Given that a previous study showed that only 3% of shoulder replacement surgeons performed ten or more procedures per year,¹⁶ the use of a computer-assisted approach may improve the accuracy of

reconstruction and also serve as an educational tool. This may lead to improved functional results in patients and increased longevity of implants. The use of a computer-assisted technique for shoulder hemiarthroplasty may also encourage surgeons to develop minimally-invasive techniques for that procedure. Although this technique still requires improvement, computer-assisted hemiarthroplasty of the shoulder should allow glenohumeral kinematics to more closely replicate those of the intact joint.

Supplementary Material

A summary of the surgical techniques used is available with the electronic version of this article on our website at www.jbjs.org.uk

No benefits in any form have been received or will be received from a commercial party related directly or indirectly to the subject of this article.

References

1. Boileau P, Krishnan SG, Tinsi L, et al. Tuberosity malposition and migration: reasons for poor outcomes after hemiarthroplasty for displaced fractures of the proximal humerus. *J Shoulder Elbow Surg* 2002;11:401-12.
2. Boileau P, Walch G. The three-dimensional geometry of the proximal humerus: implications for surgical technique and prosthetic design. *J Bone Joint Surg [Br]* 1997;79-B:857-65.
3. Frankle MA, Greenwald DP, Markee BA, Ondrovic LE, Lee WE 3rd. Biomechanical effects of malposition of tuberosity fragments on the humeral prosthetic reconstruction for four-part proximal humerus fracture. *J Shoulder Elbow Surg* 2001;10:321-6.
4. Hawkins RJ, Switlyk P. Acute prosthetic replacement for severe fractures of the proximal humerus. *Clin Orthop* 1993;289:156-60.
5. Hasan SS, Leith JM, Campbell B, et al. Characteristics of unsatisfactory shoulder arthroplasties. *J Shoulder Elbow Surg* 2002;11:431-41.
6. Iannotti JP, Spencer EE, Winter U, Deffenbaugh D, Williams G. Prosthetic positioning in total shoulder arthroplasty. *J Shoulder Elbow Surg* 2005;14:111-21.
7. Robertson DD, Yuan J, Bigliani LU, Flatow EL, Yamaguchi K. Three-dimensional analysis of the proximal part of the humerus: relevance to arthroplasty. *J Bone Joint Surg [Am]* 2000;82-A:1594-602.
8. Pearl ML, Kurutz S. Geometric analysis of commonly used prosthetic systems for proximal humeral replacement. *J Bone Joint Surg [Am]* 1999;81-A:660-71.
9. Bicknell RT, DeLude JA, Kedgley AE, et al. Early experience with computer-assisted shoulder hemiarthroplasty for fractures of the proximal humerus: development of a novel technique and an in vitro comparison with traditional methods. *J Shoulder Elbow Surg* 2007;16:117-25.
10. Atmani H, Merienne F, Fofi D, Trouilloud P. Computer aided surgery system for shoulder prosthesis placement. *Comput Aided Surg* 2007;12:60-70.
11. Wu G, van der Helm FC, Veeger HE, et al. ISB recommendation on definitions of joint coordinate systems of various joints for the reporting of human joint motion. Part II: shoulder, elbow, wrist and hand. *J Biomech* 2005;38:981-92.
12. Kedgley AE, Mackenzie GA, Ferreira LM, et al. The effect of muscle loading on the kinematics in vitro glenohumeral abduction. *J Biomech* 2007;40:2953-60.
13. Wuelker N, Wirth CJ, Plitz W, Roetman B. A dynamic shoulder model: reliability testing and muscle force study. *J Biomech* 1995;28:489-99.
14. Kedgley AE, Mackenzie GA, Ferreira LM, et al. Humeral head translation decreases with muscle loading. *J Shoulder Elbow Surg* 2008;17:132-8.
15. Nguyen D, Ferreira LM, Brownhill JR, Faber KJ, Johnson JA. Design and development of a computer assisted glenoid implantation technique for shoulder replacement surgery. *Comput Aided Surg* 2007;12:152-9.
16. Hasan SS, Leith JM, Smith KL, Matsen FA 3rd. The distribution of shoulder replacement among surgeons and hospitals is significantly different than that of hip or knee replacement. *J Shoulder Elbow Surg* 2003;12:164-9.