J Shoulder Elbow Surg (2014) ■, 1-8

ELSEVIER

Journal of Shoulder and Elbow Surgery

www.elsevier.com/locate/ymse

A new concept for tuberosity repair in hemiarthroplasty for fracture: use of a clamp and underlying ledge to form a trapdoor

Keith A. Borowsky, FCS (Orth)*, Vellala Raghu Prasad, FRCS(Tr&Orth), Lara J. Wear, MBBS, Thomas E. Stevenson, MRCS, Adam J. Bennett, MRCS, Nicholas J. Marsden, MRCS

Department of Anatomy, Brighton and Sussex Medical School, Brighton, UK

Background: Sutures are the most common method for tuberosity repair in hemiarthroplasty for fracture. Despite numerous suggested patterns, tuberosity repair remains a weak point leading to poor functional results. This study mechanically tested a new mechanism that avoids difficulties sutures may engender. The hallmark of the prosthesis is a ''trapdoor'' effect. Low-profile metallic clamps with undersurface stoppers are screwed across the tuberosity-tendon junction to an underlying ledge, creating a fixed metallic space. With cuff contraction, the tuberosities are too large to pull through this space.

Materials and methods: Tests were carried out in line with the U.K. Human Tissue Authority regulations. Four-part fractures in 8 cadavers repaired with this method were subjected to simultaneous cyclic tension of 350N and passive glenohumeral motion for 8000 cycles. Both before and after machine stress, repairs were assessed by clasping each tuberosity with a forceps and attempting to displace it in a variety of directions. No movement was present before stressing. Any post-stress movement was considered a failure and recorded in millimeters.

Results: Six specimens after machine stress showed 0-mm movement (95% confidence interval, 34.9%-96.8%). Isolated movements of a single tuberosity occurred in 2 specimens.

Conclusion and discussion: The trapdoor completely withstood challenging elements of cyclic load and passive motion in 75% of cases. The device may represent an alternative to sutures.

Level of evidence: Basic Science, Biomechanics.

Keywords: Shoulder fracture; hemiarthroplasty; clamp; trapdoor; tuberosity fixation

Hemiarthroplasty for 4-part humeral fractures does not always guarantee a good functional result. Pain relief is usually achieved, but functional outcomes are unpredictable.[10] The most commonly cited reason for persistent pain and poor function is loss of the tuberosity position.[2,4,5,7,8,11-14,17,19] The most common method of repair of the tuberosities is with sutures, of which numerous configurations have been suggested.[3] In some studies, biochemical lysis[4] of the tuberosities has been associated with poor results after secondary arthroplasty. Cerclage and vertical suture patterns are the usual methods of repair and have been borrowed from other orthopedic surgical techniques.[6] There are potential problems in applying sutures to

This study was carried out in line with Human Tissue Act regulations as confirmed by the accompanying signed and dated letter from Dr. Claire Smith, Head of Department of Anatomy.

*Reprint requests: Keith A. Borowsky, FCS (Orth), Department of Anatomy, Brighton and Sussex Medical School, 21 Briar Fields, Weavering, Maidstone, Kent, ME14 5UZ, Brighton, UK.

E-mail address: kesujeca@gmail.com (K.A. Borowsky).

1058-2746/$ - see front matter © 2014 Journal of Shoulder and Elbow Surgery Board of Trustees.
http://dx.doi.org/10.1016/j.jse.2014.08.012

the hemiarthroplasty after a humeral fracture. Although the cuff-bone interface where sutures are mainly applied is usually a strong purchase point, the tuberosities themselves and the underlying bone graft may collapse. Therefore, cerclage sutures may become loose. The surface area across which a strand of a suture may be applied (e.g., in a figure-of-8 pattern) may change its orientation. In addition to the effect of bone collapse, the interdigitation of the tuberosities with the shaft and each other can be poor, especially in osteopenic, comminuted bone. Therefore, the spatial orientation of the tuberosity may fractionally change. In addition, as the shoulder is so mobile with a large range of axial rotation, the direction of cuff stress applied to the sutures varies. This means that the frictional points of a strand of suture across a bone surface may be lost. These frictional points sometimes depend on small irregularities of the surface, which may change in orientation. Some prostheses (e.g., Anatomical Shoulder trauma prosthesis; Zimmer, Warsaw, IN, USA) attempt to solve the problem of unpredictable volume by filling the metaphysis with metal so that the tuberosities directly abut against a surface. However, this has the disadvantage of reducing the volume available for bone graft and biologic healing. An alternative approach reduces the metaphyseal metal but still requires a metal surface against which the tuberosities and bone graft are used to maintain the anatomic position (e.g., Aequalis fracture prosthesis; Tornier, Montbonnot, France). Boileau et al[5] emphasized the importance of height, retroversion, and non-metallic space available for bone healing in improving tuberosity repair, but despite this approach, tuberosity healing is unpredictable, particularly in elderly women. One could attribute this to poor biologic response, but tuberosity nonunion in nonsurgical cases in this group is extremely rare. A mechanical reason for failure, ascribed to digging of sutures into tendon and bone and collapse of bone architecture resulting in suture laxity, has been suggested.[6] Besides these factors, sutures have the additional problem of application over a distance usually well above 2 cm. Some manufacturers have attempted to negate this by short suture loops applied to holes close to the humeral head circumference (e.g., Univers fracture prosthesis; Arthrex, Inc, Naples, FL, USA), but there have been no reports of the functional benefit of this method.

We have devised a new prosthesis to overcome the mechanical failures of sutures. The aim of this study was to assess how the new prosthesis would resist simultaneous cyclical cuff tension and glenohumeral motion when applied to repair of a 4-part fracture in cadavers.

Materials and methods

The new prosthesis

The hallmark of this prosthesis is a ''trapdoor'' effect. The prime hold of the tuberosities occurs at the bone-tendon junction where 3 narrow, low-profile metallic clamps partially squeeze the tendon against a smooth, short underlying metallic ledge extending from the humeral head. The clamps are attached to the ledge by transtendinous screws that pass through the tendon at the cuff-bone junction. A metallic stopper on the undersurface of the clamp prevents complete obliteration of the space such that a fixed gap occurs between clamp and ledge. The method of hold is not compression of the tendon. The tendons, being flexible compressible materials, can still move under the clamp, but the attached tuberosity is prevented from movement as it is larger than and abuts against the set narrow metallic gap (Fig. 1). Thus, the prime hold on the tuberosities occurs at the main rim of the clamp along the trapdoor. This makes the problems of suture methods (collapse of bone graft and suture laxity, sliding of sutures over changing bone surfaces, digging in of sutures into tendon, and long application length of sutures) not applicable. Traditional prostheses using sutures need lateral fins for suture attachment points, which require a certain volume of metal in the area where bone must heal. By contrast, the clamp and ledge trapdoor arrangement dispenses with this requirement as the hold occurs at the trapdoor; no lateral shaft metal is required, so that a larger volume is available under the humeral head for bone graft (Fig. 2).

Preparation of specimens

Tests were carried out in line with U.K. Human Tissue Authority regulations. Eight fresh frozen cadaver shoulders were used. The average age of specimens was 56.1 years (range, 43 to 73); 4 were male, and 4 were female. Specimens were defrosted at room temperature for 1.5 days, after which all skin, external musculature, and neurovascular structures were removed, leaving only supraspinatus, infraspinatus, teres minor, and subscapularis muscles, the glenohumeral joint, and the capsule. All of the rotator cuffs were then inspected and found to be intact. The clavicle, acromion, and coracoid processes were removed so that video of the tuberosity fixation areas was possible during machine stress tests.

Method of 4-part fracture production

The cut humeral shaft was slid onto a custom-made vertical rod, and a small oscillating saw was used to make a 5-mm-deep vertical cut. This started 5 mm posterior to the biceps tendon on the greater tuberosity and proceeded inferiorly to the lower level of the subscapularis and infraspinatus tendons. Superiorly, for access, the supraspinatus tendon was split in line with this cut. From the lowest point of the vertical bone cut, 2 horizontal 5-mm-deep cuts were made. The first was directed anteriorly toward the lowest point of the subscapularis tendon insertion; the second was directed posteriorly to the lowest margin of the teres minor insertion. From the vertical cut, the oscillating saw was then angled both anteriorly and posteriorly. This created a posterior fragment of greater tuberosity alone and an anterior fragment housing 5 mm of greater tuberosity, bicipital groove, and lesser tuberosity (Fig. 3). The biceps tendon was excised. By splaying the tuberosity segments and attached cuff farther anteriorly and posteriorly, the humeral head could be exposed and dislocated.

Method of determining height and retroversion

Height, measured from a flat metal bar laid on the summit of the humeral head perpendicular to the shaft and the cut end of the shaft, was recorded. When a prosthesis was cemented in this,

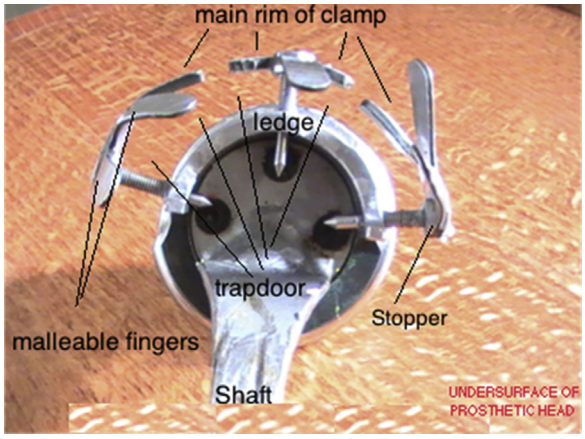

Figure 1 Undersurface of prosthetic head with clamps in situ attaching to ledge from humeral head. The trapdoor is the metallic space between the clamp main rim and the ledge.

Figure 2 The Aequalis trauma stem (*left*). The Anatomical Shoulder trauma stem (*middle*). The current prosthesis with clamps—the shaft attaches substantially medially on the humeral head, and there is a large space for bone graft deep to the clamps (*right*).

distance was re-established. Similarly, retroversion was marked on the shaft by laying a K-wire across the top of the humeral head along a line from the center of the humeral shaft to the center of the cartilaginous humeral head, establishing a retroversion mark for the prosthesis marked on the outer humeral cortex. During cementation of the prosthesis, this mark was used to re-establish version.

Removal of the humeral head and comminution of the calcar were then performed to simulate a fracture.

Method of repair

After creation of the fracture, the shaft of the prosthesis was cemented into place at the premarked height and retroversion with Palacos cement (DePuy Orthopaedics or Heraeus Medical GmbH, Wehrheim, Germany). The clamps and screws were then used to repair the tuberosities (Fig. 4). First, the posterior greater tuberosity complex was slowly brought to a reduced position, and in effecting this reduction, the point at which the posterior hole on the humeral head ledge lined up with the infraspinatus tendon was carefully noted. A screw was inserted into the posterior clamp and its tip made to pierce the tendon at this point. The screw tip, having pierced the tendon, was lined up with the posterior hole, and the screw-clamp complex was gradually screwed down to a complete reduction point. Complete compression of the tendon was prevented by a stopper on the undersurface of the clamp. Similarly, the anterior subscapularis tendon–tuberosity complex was reduced, and the position for the anterior clamp screw was noted. The screw was inserted into the anterior clamp and made to pierce the tendon at this point. Having pierced the tendon, the screw was lined up with the anterior ledge hole, and the anterior clamp-tuberosity complex was screwed down. In general, the middle ledge hole would site in the longitudinal split made in the supraspinatus tendon and the middle clamp and could be easily applied. If not, its screw could be applied through the portion of supraspinatus tendon that on reduction lined up with the middle hole. Clinically, in the authors' experience, the most common tuberosity fracture plane is at a point about 5 mm posterior to the bicipital groove, usually splitting the tuberosities into an anterior complex of the lesser tuberosity, the bicipital groove, and a small portion of the greater tuberosity and a posterior complex of the greater tuberosity alone. Once the screws were tightened down, the malleable finger-like extensions of the clamps could be bent slightly away from the tuberosities such that bone graft from the humeral head could be packed into the space deep to the tuberosities. The malleable parts of the clamp were then hammered down, providing additional hold on the tuberosities (Fig. 5). The chief point of hold, however, appeared to be the trapdoor, that is, the metallic space between a clamp main rim and the underlying humeral head ledge.

Testing the hold on the tuberosities

In this experiment, a single surgeon clasped each tuberosity with a forceps and attempted to move it superiorly and inferiorly, laterally, and coronally and then held the tuberosities still and rotated the shaft on its longitudinal axis to look for any rotational discontinuity between the lower transverse margin of any tuberosity and the upper cut margin of the humerus osteotomy site. Before machine stress, all repairs showed no movement in any direction. After machine stressing, the development of any visible movement in a tuberosity in any direction was defined as failure. Such interfragmentary motion that a surgeon detects can alter the biologic response to fracture healing,[9] and testing for this could be compared with a surgeon's exploring a possible nonunion, failed plate and screws, or suspected loose prosthesis.

Biomechanical stressing of the completed repairs

A custom-made clamp was placed across the lateral scapular margin and tightened across the scapula blade. The arrangement was mounted in a Mecmesin MultiTest twin column machine (Mecmesin, Slinfold, West Sussex, UK). The clamp placed the shoulder in a lateral decubitus position with the medial scapular margin and the cuff musculature facing upward toward the pulling mechanism. Two locking traction sutures of Ethibond No. 5 (Ethicon, Somerville, NJ, USA) were placed just medial to the clamps in the tendons of each of the supraspinatus, infraspinatus, and subscapularis muscles. With cyclic pull affected by

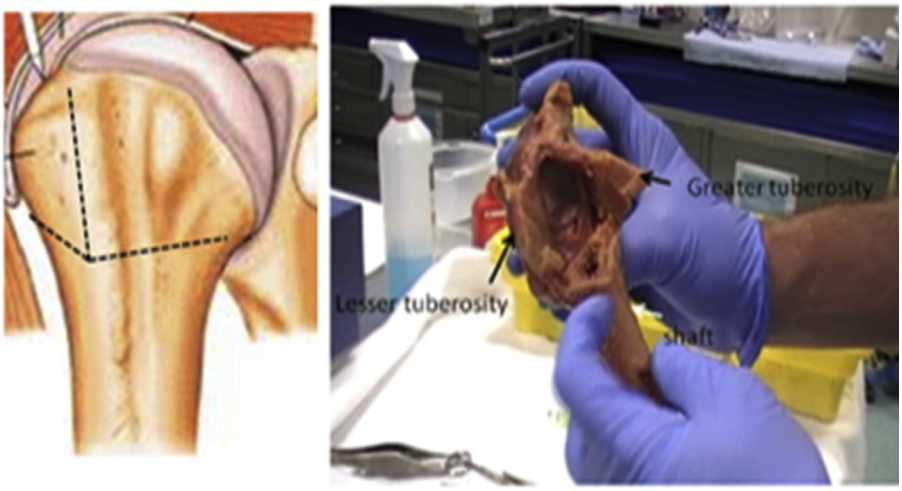

Figure 3 Line diagram of oscillating saw cuts (*left*) and final appearance after creation of fracture and removal of humeral head (*right*).

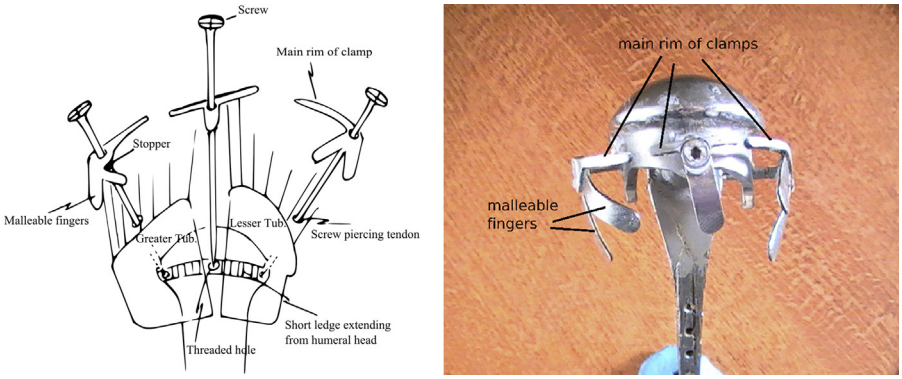

Figure 4 Line diagram showing how the clamps are applied as seen from the lateral aspect of the shoulder (*left*) and prosthesis in the same view (*right*).

the cross-arm, these would represent intermittent cuff contractions. The sutures were placed with 3 passes in the tendon in opposing directions, producing a robust locking suture that never disengaged in any specimen. After the locking stitch was performed, the 2 loose ends were tied together at a distance of about 25 cm from their tendon insertion points to form a closed loop. This loop was applied to a custom-made suture collection device. All in all, a set of 2 traction sutures issued from the subscapularis tendon in the anterior subscapular recess; 2 sets issued from each of the infraspinatus and supraspinatus tendons, along their respective fossae.

The custom-made suture collection device consisted of a series of linked tilting beams to which the traction suture loops were attached. If, for example, 1 of the 2 supraspinatus traction sutures would chance to lengthen, the beam it attached to would incline, so equal tension was maintained; similarly, if the complete supraspinatus beam was out of kilter with the infraspinatus set, a higher beam linking both of these would tilt, producing even tension. This higher beam in turn was balanced against the subscapularis beam by the topmost beam, which was linked to the machine cross-arm. A second effect of the suture collection device was to divide the force applied by the machine, which was programmed to cycle between 350N and 250N of tension over 8000 cycles, each cycle taking about 0.8 second. Each maximum pull of 350N was divided into half (175N) for the subscapularis fossa beam and the combined supraspinatus and infraspinatus beam. The latter 175N was further divided into half (87.5N) for each of the supraspinatus and infraspinatus muscles. To provide concomitant passive glenohumeral motion, the humeral shaft was secured inside a metallic cylinder that formed part of a rack and pinion stepper motor assembly that induced about 30° of repetitive passive forward flexion in the shoulder approximately every 2 seconds. As a rule, the machine transverse arm inducing intermittent cuff tension was begun first. The point of attachment of the suture collection device to the cross-arm could be adjusted so that the overall vector of cuff pull avoided any glenohumeral subluxation. The rack and pinion motor was then set into motion, adding repetitive glenohumeral flexion, the goal being to reproduce the possible stresses that might occur in postoperative rehabilitation (i.e., both stress on the cuff and passive shoulder motion; Fig. 6). The strain on the traction sutures was never such that any snapped in any test, nor did any tendinous application point break loose. From time to time, abrasion of the traction suture against the scapula resulted in fretting and breakage. In such cases, the test

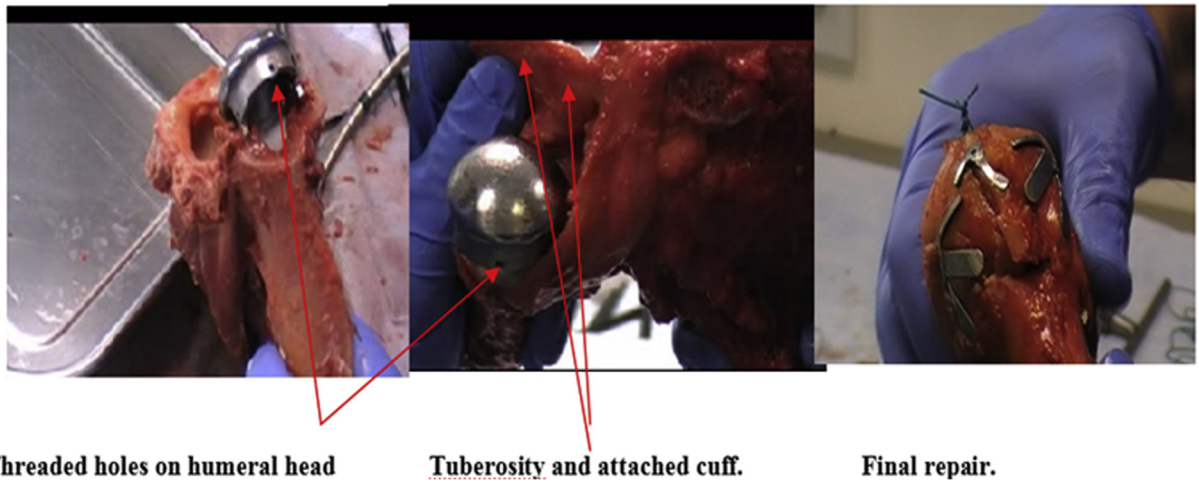

Figure 5 Cadaver illustration of prosthesis cemented in place (*left*). Tuberosities and cuff are partially reduced to determine entry point of clamp screw—the tendon point overlying the ledge screw hole (*middle*). Final appearance after reduction and clamp application; bone graft has been packed under the tuberosities (*right*).

Figure 6 Setup for machine stressing: the shoulder is held in a clamp in the lateral decubitus position (*center*) with traction sutures passing up to the suture-receiving device (*left*). The humerus is encased in a cylinder that is linked to a rack and pinion stepper motor assembly that induces repetitive forward flexion (*right*).

was temporarily stopped and the suture replaced. Total time per specimen, including preparation and mounting and testing to 8000 cycles, usually took 2 days. Overnight storage in a refrigerator at 3°C was necessary, during which time no significant signs of degradation were noted; in particular, the tendon and bone portions retained much the same appearances as at the start. A Sony 16 GB camcorder (Sony, Weybridge, Surrey, UK) was used to record the repair sites throughout machine stressing. After 8000 cycles, each specimen was taken down. Each tuberosity was clasped with a forceps and examined to see if movement could be induced superior-inferiorly, side to side, and by rotation in the coronal plane; then the tuberosities were held still and the shaft rotated to look for any rotational discontinuity between the lower transverse margin of any tuberosity and the upper cut margin of the humerus. Any movement detected in any of these parameters was deemed a failure for that specimen, and the degree of movement was measured against a ruler (online supplementary video is available at www.jshoulderelbow.org).

Statistical analysis

The data in this experiment conform to a binomial distribution as the tests were repeated a fixed number of times, each trial of the experiment had two clearly defined possible outcomes (any movement detected represented failure, no movement represented success), the probability of success was the same for each trial, and the trials were statistically independent. A binomial proportion confidence interval should allow for sampling error. Statistical uncertainty associated with the estimated successful rate of 75% was carried out by constructing a confidence interval. Because the sample size was relatively small, the exact method for confidence interval based on the binomial distribution was employed in this study. A desirable feature of the exact method based on the binomial distribution is that it can ensure the confidence interval is bounded by 0 and 1.

Table I Ability to manually displace tuberosities after 8000 cycles of 350N cuff tension and simultaneous passive glenohumeral motion

	SP1	SP2	SP3	SP4	SP5	SP6	SP7	SP8
Cycles	8000	8000	8000	8000	8000	8000	8000	8000
Greater tuberosity								
Superior-inferior	0 mm	0 mm	0 mm	0 mm	0 mm	0 mm	0 mm	0 mm
Side-side	0 mm	0 mm	0 mm	0 mm	0 mm	0 mm	0 mm	0 mm
Rotation	0 mm	0 mm	0 mm	0 mm	0 mm	6 mm	0 mm	0 mm
Lesser tuberosity								
Superior-inferior	0 mm	0 mm	0 mm	0 mm	0 mm	0 mm	0 mm	0 mm
Side-side	0 mm	0 mm	5 mm	0 mm	0 mm	0 mm	0 mm	0 mm
Rotation	0 mm	0 mm	0 mm	0 mm	0 mm	0 mm	0 mm	0 mm
Shaft discontinuity	0 mm	0 mm	0 mm	0 mm	0 mm	0 mm	0 mm	0 mm

SP, specimen. *Superior-inferior* is the motion recorded in the superoinferior direction. *Side-side* is the motion recorded in the side-to-side direction. *Rotation* is the motion of the bone edge recorded on attempted rotation of the tuberosity in the coronal plane. *Shaft discontinuity* is the motion recorded of the tuberosities in relation to the shaft when tuberosities are held still with forceps and the shaft is rotated. *Cycles* are the total number of 350N maximum tension episodes on the rotator cuff.

Results

Taking failure per specimen as any tuberosity movement at all, 75% were intact with 0-mm movement all round (95% confidence interval, 34.9%-96.8%). The confidence intervals were calculated by the exact method for a binomial proportion.[1] Of the failures, specimen 3 showed a side-to-side movement of 5 mm in the lesser tuberosity and specimen 6 showed movement of the greater tuberosity of 6 mm on attempted rotation in the coronal plane. None of these failure specimens showed any movement in any of the other tests of tuberosity stability. In particular, no rotational dissociation between shaft and tuberosities occurred (Table I).

Discussion

Application of a clamp-like structure to a tendon-bone complex is not a new idea. Sosna et al[18] reported use of a metallic plate with superior teeth that screwed onto the shaft of the prosthesis when using a hemiarthroplasty for fractures of the proximal humerus. They compared their results with a suture technique in both acute and delayed fractures, producing a Constant score of 11 to 12 points higher for their prosthesis. Their technique was suitable for patients who had tuberosities of at least 2 cm in size. Our prosthesis is based on a trapdoor gap of about 4 mm and should improve this size limitation. However, it is possible that with tuberosity fragments smaller than this, the clamps would be insufficient. Our clamps differ in that they are attached to a small ledge extending from the humeral head rather than the shaft. There is the potential for the clamps to produce impingement of metal against the acromion, Use of metal in the subacromial space is not unknown. The Hook Plate (Synthes AO/ASIF) has a subacromial metal bar that, although static, overlies mobile cuff tendons. The Rush pin (Zimmer) bears a metallic hook that sits atop the rotator cuff, moves under the acromion in the same way as the clamps, and is used for the same purposes of fixing tuberosities in fracture. The top part of the Sosna clamp[18] with toothed edge also lies in the subacromial bursa. Our prosthesis seeks to avoid impingement as follows. First, at the most common region for impingement (supraspinatus tendon), the ledge is sunk below the prosthetic head surface by 2 mm. This compensates for the extra 2 mm the clamp thickness imparts. Therefore, the technical height of the clamp-cuff complex is no greater than the native rotator cuff. The skirt starts at −2 mm; the cuff sitting on this therefore ends up 2 mm lower than normal, and the clamp occupies another 2 mm. Second, the farther lateral objects are from the humeral head center, and the more superior they are located on the tuberosity, the more likely they are to impinge. By siting the clamp at the cuff insertion point (i.e., as medial as possible) and sloping it inferolaterally (at a slightly sharper angle than a native greater tuberosity), the possibility for mechanical impingement is diminished. Finally, cadaver studies cannot completely reproduce a live situation. So if for some reason the clamps are not tolerated when they are inserted into patients, they should be made in a way that they can be removed once healing of the tuberosities has occurred. In the present system, they are removable by undoing the attaching screw. We acknowledge that inserting 3 screws intraoperatively could be technically difficult. Also, the way in which the tuberosity bones react to abutment against the clamps is not clear. However, metallic plates against bone are generally well tolerated and promote healing, provided the complex being held is stable. We have no reason to believe the reaction may be any different in this situation. It is possible that the testing regimen of 8000 cycles and 350N of total cuff pull is excessive in terms of the normal postoperative stress in

patients. The true values the rotator cuff pulls with and the number of movements in rehabilitation are not known, and there is variation in the literature. Our test represents the higher limit of values found and as such would be a more rigorous testing of the fixation. In a study using the same test protocol[6] in which suture repairs were evaluated, complete failure of every specimen was reported. A limitation of this current study is that whereas the tests centered on likely aspects of cuff tension and glenohumeral movement that we believe may be present in rehabilitation, load to failure tests could also have been considered. This might be valuable in reflecting the ability of the mechanism to cope with sudden high stresses (e.g., an unexpected fall or movement in the patient). Although fatigue is often estimated from load to failure properties, we do not believe such inferences are easy to apply to clinical practice, in which a complex range of both direction of pull and degree of pull on the construct may be possible. Thus, our test protocol would most likely mimic more constant aspects of rehabilitation; fatigue rather than load to failure may be the more likely challenging factor.[9]

We emphasize that the testing regimen evaluating tuberosity hold, both immediately after applying the clamps and after machine stressing of the specimens, looked for the ability to manually displace the tuberosities rather than inferring loss of hold by static change of position of reduction. Our test is possibly more accurate than routine clinical radiographic methods that rely on change in tuberosity position. Few studies repeat radiographic examination of the fracture in the first few weeks, during which time there may be significant loosening, and some studies repeat radiographic examination at the 6-week mark and then accept a ‘‘maintained ‘‘ position of the tuberosities of up to 1 cm.[15] Ideally, the force used to determine movement should be quantified. Even a firm structure can be made to move with enough force, or a potentially loose structure could be deemed stable if not enough force is used. In clinical situations, however, suspected loose parts are manually probed and manipulated to visually detect any movement. The exact force used to determine this is not generally quantified but is based on the operating surgeon's assessment. In the laboratory, application of a fixed grasping agent to the tuberosity with application of a fixed force to this in the various test directions is possible but also subject to loosening of the grasping device. There is, to our knowledge, no accepted degree of force recommended. Standardizing this setup to all the tuberosities tested and different directions of testing might be complicated and expensive. Nonetheless, this is a weakness of this study. Likewise, determination of the degree of movement could have been implemented with electronic markers, even though these may have intrinsic error and be difficult to implement. This could be another weakness of the study. However, visual 2-point resolution is reported to be 0.075 mm,[16] so accuracy of assessment of movement would be well within the order of 0.1 to 0.3 mm. Initially, after reduction, small gaps of less than 1 mm exist between fracture fragments, and these fill with granulation tissue. It is believed that a 100% increase in this small gap results in cellular rupture,[9] with a negative impact on fracture union. So detection of even small movements is clinically significant. Our test detecting the development of movement should therefore be sensitive and clinically significant. Although we quantified the degree of movement by measuring displacement of the tuberosity edge with a ruler, defining failure as a change from no movement to any movement present is unambiguous.

Finally, although it is still possible that the features we believe occur in suture repair may persist (collapse of tuberosity and graft bone volume, slight change in orientation of fragments with movement, loss of interdigitation between tuberosities with each other and the shaft), they should be less relevant. The mechanism of hold lies at the trapdoor, which is sited along the cuff-bone interface, an inverted U-shaped area that is largely unaffected by the aforementioned problems of tuberosity orientation, collapse, and interdigitation.

Conclusion

The new prosthesis using a trapdoor effect provided impressive hold on the tuberosities in 75% of specimens under demanding conditions of cuff tension and passive glenohumeral motion, set at the higher limits of reported testing parameters. The trapdoor may offer an attractive alternative to sutures.

Acknowledgment

We wish to acknowledge the help and encouragement of Professor Darrell Evans and Tracy Young (Prosector), Professor Sean Hughes, statistician Dr. D. Zhou, and Mr. Alan Mayers for his technical support and expertise.

Disclaimer

The authors, their immediate families, and any research foundation with which they are affiliated have not received any financial payments or other benefits from any commercial entity related to the subject of this article.

Supplementary data

Supplementary data related to this article can be found online at http://dx.doi.org/10.1016/j.jse.2014.08.012.

References

1. Altman DG, Machin D, Bryant TN, Gardner MJ, editors. Statistics with confidence. 2nd ed. London: BMJ Books; 2000. p. 46-7.
2. Antuña SA, Sperling JW, Cofield RH. Shoulder hemiarthroplasty for acute fractures of the proximal humerus: a minimum five year follow up. J Shoulder Elbow Surg 2008;17:202-9. http://dx.doi.org/10.1016/j.jse.2007.06.025
3. Baumgartner D, Nolan BM, Mathys R, Lorenzetti SR, Stüssi E. Review of fixation techniques for the four-part fractured proximal humerus in hemiarthroplasty. J Orthop Surg Res 2011;6:36. http://dx.doi.org/10.1186/1749-799X-6-36
4. Besch L, Daniels-Wredenhagen M, Mueller M, Varoga D, Hilgert RE, Seekamp A. Hemiarthroplasty of the shoulder after four-part fracture of the humeral head: a long-term analysis of 34 cases. J Trauma 2009;66:211-4. http://dx.doi.org/10.1097/TA.0b013e31815d9649
5. Boileau P, Krishnan SG, Tinsi L, Walch G, Coste JS, Molé D. 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. http://dx.doi.org/10.1067/mse.2002.124527
6. Borowsky KA, Raghu Prasad V, Wear LJ, Stevenson TE, Trent ND, Bennett AJ, et al. Is failure of tuberosity suture repair in hemiarthroplasty for fracture mechanical? J Shoulder Elbow Surg 2013;22:971-8. http://dx.doi.org/10.1016/j.jse.2012.09.002
7. Brems JJ. Shoulder arthroplasty in the face of acute fracture: puzzle pieces. J Arthroplasty 2002;17(Suppl 1):32-5. http://dx.doi.org/10.1054/arth.2002.32444
8. Dines DM, Warren RF. Modular shoulder hemiarthroplasty for acute fractures. Surgical considerations. Clin Orthop Relat Res 1994:18-26.
9. Frankle MA, Ondrovic LE, Markee BA, Harris ML, Lee WE. Stability of tuberosity reattachment in proximal humeral hemiarthroplasty. J Shoulder Elbow Surg 2002;11:413-20. http://dx.doi.org/10.1067/mse.2002.126098
10. Goldman RT, Koval KJ, Cuomo F, Gallagher MA, Zuckerman JD. Functional outcome after humeral head replacement for acute three- and four-part proximal humeral fractures. J Shoulder Elbow Surg 1995;4:81-6.
11. Mighell MA, Kolm GP, Collinge CA, Frankle MA. Outcomes of hemiarthroplasty for fractures of the proximal humerus. J Shoulder Elbow Surg 2003;12:569-77. http://dx.doi.org/10.1016/S1058-2746(03)00213-1
12. Moeckel BH, Dines DM, Warren RF, Altchek DW. Modular hemiarthroplasty for fractures of the proximal part of the humerus. J Bone Joint Surg Am 1992;74:884-9.
13. Plausinis D, Kwon YW, Zuckerman JD. Complications of humeral head replacement for proximal humeral fractures. Instr Course Lect 2005;54:371-80.
14. Prakash U, McGurty DW, Dent JA. Hemiarthroplasty for severe fractures of the proximal humerus. J Shoulder Elbow Surg 2002;11:428-30. http://dx.doi.org/10.1067/mse.2002.126615
15. Robinson CM, Page RS, Hill RM, Sanders DL, Court-Brown CM, Wakefield AE. Primary hemiarthroplasty for treatment of proximal humeral fractures. J Bone Joint Surg Am 2003;85:1215-23.
16. Singer M, Totzeck H, Gross H. Handbook of optical systems. In: . Survey of optical instruments, vol. 4. Weinheim: WILEY-VCH, ISBN 978-3-527-40380-6; 2008. p. 57-8.
17. Smith AM, Mardones RM, Sperling JW, Cofield RH. Early complications of operatively treated proximal humeral fractures. J Shoulder Elbow Surg 2007;16:14-24. http://dx.doi.org/10.1016/j.jse.2006.05.008
18. Sosna AD, Pokorny R, Hromádka D, Jahoda V, Barták V, Pinskerová V. A new technique for reconstruction of the proximal humerus after three- and four-part fractures. J Bone Joint Surg Br 2008;90:194-9. http://dx.doi.org/10.1302/0301-620X.90B2.18928
19. Tanner MW, Cofield RH. Prosthetic arthroplasty for fractures and fracture-dislocations of the proximal humerus. Clin Orthop Relat Res 1983:116-28.