Manuscript Details

Manuscript number CLBI_2018_588_R1

Title Effect of Baseplate Positioning on Fixation of Reverse Total Shoulder Arthroplasty

Article type Research Paper

Abstract

Background: The glenoid component in reverse total shoulder arthroplasty is recommended to be positioned inferiorly or with a downward tilt with the intention of reducing scapular notching. However, it is still unclear whether modifying the position of the glenoid prosthesis affects implant stability. The aim of this study was to determine the association between implant positioning and glenoid prosthesis fixation using Grammont reverse total shoulder arthroplasty. Methods: Four positions for the glenoid prosthesis were studied using the finite element method. The glenosphere was positioned as follows: 1) in the middle of the glenoid fossa, 2) flush with the inferior glenoid rim, 3) with an inferior overhang, 4) with a 15° inferior inclination. Bone-prosthesis micromotions and strain-induced bone adaptations were quantified during five daily activities. Findings: When the glenoid component was tilted inferiorly, the activities producing anterior-posterior shear forces (e.g. standing up from an armchair) caused an increase in peak micromotions. In the lateral-middle glenoid, inferior positioning caused a 64.6% reduction in bone apparent density. In the lateral-inferior glenoid, central positioning led to the most severe bone resorption, reaching 43.9%. Interpretation: Reducing activities which generate anterior-posterior shear forces on the shoulder joint will increase bone formation and may improve the primary stability of the implant when fixed in the position with an inferior tilt. Postoperative bone resorption is highly dependent on implant positioning. Understanding the relationship between bone resorption and implant positioning will help surgeons improve the long-term stability of reverse total shoulder arthroplasty.

Keywords inferior position; inferior tilt; reverse total shoulder arthroplasty; bone remodeling; micromotion; fixation.

Taxonomy Clinical Anatomy, Functional Anatomy, Musculoskeletal Anatomy, Bone, Joint (Skeletal System)

Corresponding Author Min Zhang

Corresponding Author's Institution School of Biological Science and Medical Engineering, Beihang University, Beijing, China；Beijing Advanced Innovation Centre for Biomedical Engineering, Beihang University, Beijing, China

Order of Authors Min Zhang, Sarah Junaid, Thomas Gregory, Ulrich Hansen, Cheng-Kung Cheng

Suggested reviewers andrew amis, Roger Emery

Submission Files Included in this PDF

File Name [File Type]

Cover Letters.doc [Cover Letter]

JCLB_authorchecklist_final.doc [Checklist]

Response to reviewers.doc [Response to Reviewers]

Highlights.doc [Highlights]

Manuscript.doc [Manuscript File]

Fig. 1 Four fixation configurations of glenoid prosthesis.ppt [Figure]

Fig. 2 Regions of interest in comparisons of glenoid prostheses.ppt [Figure]

Fig. 3 Micromotion distributions at the resected surface.ppt [Figure]

Fig. 4 Maximum of predicted micromotions at the bone-prosthesis interface.doc [Figure]

Fig. 5 Bone remodelling process on the glenoid frontal plane.doc [Figure]

Fig. 6 Percentage of change of bone apparent denstity.doc [Figure]

Conflict of interest.doc [Conflict of Interest]

Author statement.doc [Author Statement]

Figure Legends.doc [Supporting File]

Supplementary Loading conditions used in this study.doc [Supporting File]

To view all the submission files, including those not included in the PDF, click on the manuscript title on your EVISE Homepage, then click 'Download zip file'.

Author Statements

No work in this study is on prior or duplicate submission or publication elsewhere, and no work is presented as an abstract at a professional meeting. The manuscript has been read and approved by all authors. All the authors believe that the manuscript represents honest work.

I confirm that the submitted paper complies with the journal's requirements and the study by Viceconti et al (2005).

Reference

Viceconti et al. Extracting clinical data from finite element simulations. Clin Biomech 2005;20:451–454

CLINICAL BIOMECHANICS AUTHOR CHECKLIST

Authors of all papers should submit this checklist together with their manuscript. The checklist will be made available to Editors to assist with preliminary assessment. Please refer to the Guide for Authors found at https://www.elsevier.com/journals/clinical-biomechanics/0268-0033/guide-for-authors before submitting your manuscript

To prevent the paper being sent back to you prior to review all boxes need to be marked with a tick or N/A to verify that the manuscript has met the requirements needed.

Basic requirements	***Author response or further detail***	**Tick**
Highlights	Avoid using abbreviations in highlights and ensure each bullet point (between 3 & 5 required) doesn't exceed 85 characters	√
Title page	Avoid using abbreviations in the title	√
Title page	There should be no phone/fax on title page even if supplied (just the corresponding author's email address).	√
Word Count	Give word counts on the title page for both the abstract and the main text (excluding references and legends). The length should not normally exceed 4000 words with around six figures/tables (large data tables and multi-part figures are generally best placed in Supplementary Data).	√
Line numbers/Page numbers	Line numbers and page numbers need to be present in the manuscript	√
Abstract	In the Abstract, the following section headings (in italics) should each start on a new line: Background, Methods, Findings, and Interpretation. Only universally accepted and understood abbreviations are allowed in the Abstract (e.g. CT, MR), but no specialties or author-defined abbreviations (e.g. OA, osteoarthritis; TKR, total knee replacement etc). Please also ensure bullet points DO NOT appear in the abstracts. Finally the abstract must not exceed 250 words.	√
Standard Deviation	Avoid using ± symbol (in-text & tables) - use for example "mean xx (SD yy)" The abbreviation "SD" (standard deviation) should be set without the dots	√
General	Add country to all addresses	√
General	Check for incorrect and inconsistent case/italics for symbols. Ensure statistical abbreviations are in correct case and style (e.g., capital italic for P). Use n for number. SI units must be used. Conventions for abbreviations can be found in Units, Symbols and Abbreviations (available from the Royal Society of Medicine, www.rsmpress.co.uk). Confidence intervals are preferred over just P values.	√
Acronyms	Acronyms need to be defined at first use.	√
Acronyms	Acronyms with 'of' in them such as 'range of motion' should be abbreviated as RoM (not ROM)	√
Equipment info	Sources of equipment etc. should have company, city, and country.	√
Section heading	The main text should be divided into appropriate headings: Introduction, Methods, Results, Discussion, and Conclusions. Section 2 of main text should be Methods (not Material and Methods) Subheadings may also be used and reviews may use other headings.	√
Section heading	The section heading 'Introduction' should be used for all FLAs.	√
Figure Citations	Active and inactive figure citations and figure label (caption) for this journal's articles should be abbreviated.	√
Reference	Sometimes Clin Biomech is provided in the reference lists as Clin Biomech (Bristol, Avon). (Bristol, Avon) should not be used in reference lists, it should just read Clin Biomech. Please ensure that (Bristol, Avon) is deleted when it appears in reference lists.	√

References	References that cite personal communications do not need to be listed in the reference list. Therefore, when you refer to a 'personal communication' it should not be tagged as a reference and no corresponding entry is required in the reference list.	√
References	There are no strict requirements on reference formatting at submission. References can be in any style or format as long as the style is consistent. Where applicable, author(s) name(s), journal title/book title, chapter title/article title, year of publication, volume number/book chapter and the pagination must be present. Use of DOI is highly encouraged. The reference style used by the journal will be applied to the accepted article by Elsevier at the proof stage. Note that missing data will be highlighted at proof stage for the author to correct.	√

Response to Reviewers

Comments from the editors and reviewers:

Editor:

- Add abstract word count to title page (ensuring it doesn't exceed 250 words)

Ans： Thank you for your comment. I have added abstract word count on the title page. The word count is 245.

-Reviewer 1

Line observations:

103. All the glenoid positions were guided by an experienced orthopedic shoulder surgeon…question: are these movements explained in other articles?? To cite a few

Ans: Thank you for your comment. In this manuscript, FP1 (glenoid prosthesis was fixed in the middle of the glenoid fossa) is the recommended position in Grammont design. This position was explained in Boileau's study (2005).

Reference

Boileau, P., 2005. Grammont reverse prosthesis Design, rationale, and biomechanics, J Shoulder Elbow Surg, 14, 147S-161S, doi:10.1016/j.jse.2004.10.006

Other implant positions were explained or shown in the X-ray images in below articles.

1. Boileau, P., 2011. Bony Increased-offset Reversed Shoulder Arthroplasty Minimizing Scapular Impingement While Maximizing Glenoid Fixation. Orthop Elat Res 469, 2558-2567, doi: 10.1007/s11999-011-1775-4.

Fig. 5A–B (**A**) An AP radiograph performed 3 months after surgery demonstrates complete bone graft healing. (**B**) No bone graft resorption or lysis and no scapular notching are observed at 36 months' followup. Note the low and inferiorly tilted positioning of the glenoid implant in addition to its lateralization.

2. Boileau, P., 2016. Complications and revision of reverse total shoulder arthroplasty. Orthop Traumatol Surg Res 102, S33-S43, doi: 10.1016/j.otsr.2015.06.031.

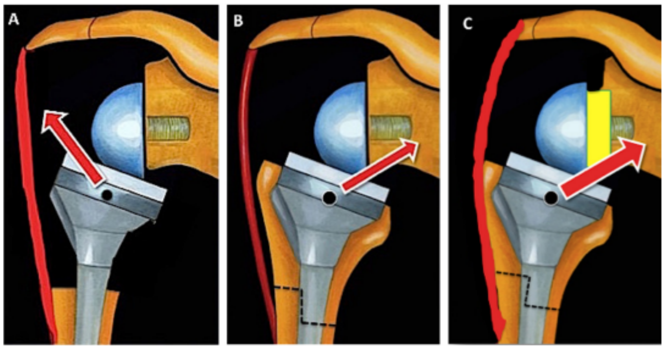


Fig. 3. Deltoid wrapping angle. A. Implant instability with proximal humeral bone defect by loss of deltoid wrapping angle. B. Proximal humeral bone graft, improving deltoid wrapping angle. C. Glenoid bone graft (BIO-RSA) increasing humeral lateralization and deltoid wrapping angle (increased deltoid coaptation force).

3. Feeley, B. T., 2014. Decreased scapular notching with lateralization and inferior baseplate placement in reverse shoulder arthroplasty with high humeral inclination. Int J Shoulder Surg 8, 65–71, doi: 10.4103/0973-6042.140112.

111. The glenoid head and base plate of the implant were manufactured?? question: why the manufactured word??

Ans: Thank you for your comment. I want to explain that the glenoid head and baseplate are made of cobalt-chrome, so they were modeled as linear isotropic materials with a Young's modulus of 220 GPa. A rephrased sentence was added into the manuscript and shown below:

“The glenoid head and baseplate of the implant, which are manufactured from cobalt-chrome, were modeled as linear isotropic materials with a Young’s modulus of 220 GPa.”

165. Why the value of 0.75 was used? (the cite is placed but the reasons of selecting this number and how it can affect the final results??. in a few words describe more the selected value

Ans: Thank you for your comment. s is a constant for determining the extent of the stimulus range. In this study, s=0.75 was used. Because 0.75 has been successfully validated with in-vitro tests by Kerner et al. (1999) and Charalampos Bitsakos (2005). The detailed description of clinical validation with the periprosthetic human bone adaptation were reported in Charalampos Bitsakos’ PhD dissertations in the Biomechanics Section, Mechanical Engineering Department, Imperial College London (2005). The sentence below was added into the manuscript to explain the value further.

“In this study, s=0.75 was used (Kerner et al., 1999), as this value has been successfully validated with in-vitro tests by Kerner et al. (1999) and Bitsakos (2005).”

Reference

1. Bitsakos, C., 2005. Computer Simulation of Periprosthetic Bone Remodelling after Total Hip Arthroplasty. PhD. thesis, Imperial College London, London, UK.

2. Kerner, J., Huiskes, R., van Lenthe, G.H., Weinans, H., van Rietbergen, B., Engh, C.A., Amis, A.A., 1999. Correlation between pre-operative periprosthetic bone density and post-operative bone loss in THA can be explained by strain-adaptive remodelling. J Biomech 32, 695-703, doi: 10.1016/S0021-9290(99)00041-X.

-Reviewer 2

Title: Effect of Baseplate Positioning on Fixation of Reverse Total Shoulder Arthroplasty

General Comments: This manuscript investigates the relationship between the placement of the glenoid component and implant fixation using finite element analysis. Loosening of the glenoid is a common complication for Grammont reverse RTSA—often requiring revision surgery. Many factors such as osseointegration, scapular notching, and strain-induced bone loss can result in asceptic glenoid loosening. Biomechanical evaluation was performed utilizing the finite element method. The glenosphere was positioned in the middle of the glenoid fossa, flush with the inferior glenoid rim, inferior overhang, and with a 15° inferior inclination. Bone-prosthesis micromotions and strain-induced bone adaptations were quantified during five daily activities. There seems to be a need for biomechanical evaluation and supporting data regarding glenoid positioning and subsequent stability. This study can potentially provide meaningful outcomes and be impactful, but as it stands, minor revision is needed.

Ans： Thank you for your comment. RTSA has been changed into RSA in the manuscript.

My main concerns are:

（1） Paper lacks hypothesis. Adding a formal hypothesis would significantly strengthen the impact of the manuscript.

Ans：Thank you for your comment. A hypothesis, which is shown below, was added in the manuscript.

"It hypothesizes that the placement of glenoid component will relate to the implant fixation. This study is aimed to investigate the hypothesis using finite element analysis."

I have listed specific comments for each section below.

Abstract:

Introduction:

Line 57: "Inferior positioning and inferior tilting are recommended to minimise postoperative scapular notching in RTSA"...spelling error: minimize.

Ans：Thank you for your comment. Minimise is British spelling. It is acceptable as long as consistent spelling was used in the manuscript. British spelling was used in the whole manuscript.

Line 69: Consider elaborating on the findings reported by Chae et al. as a summary. "The relationship between micromotion and bone ingrowth has been used to predict the occurrence of postoperative integration and to evaluate the primary fixation of implants using finite element models (Chae et al., 2016)."

Ans： Thank you for your comment. Modified summary from Chae's report was added in the manuscript and shown below:

"Finite element method has been used to calculate bone-prosthesis micromotion after RSA, and then to predict the occurrence of postoperative integration utilizing the relationship between micromotion and bone ingrowth (Chae et al., 2016)"

Line 73: In the sentence, "Apart from scapular notching and osteoporosis, stress-shielding is another factor leading to erosion of the bone bed supporting the RTSA (Ahir and Walker, 2004)." Consider removing "Apart from scapular notching and osteoporosis..."

Ans： Thank you for your comment. Modified sentence was added into the manuscript and shown below:

"Stress-shielding is another factor leading to erosion of the bone bed supporting the RSA (Ahir and Walker, 2004)."

Line 77: "Suárez (2012) evaluated the effects of the assumption of bonding condition and unbonding condition at the bone-prosthesis interface on bone adaptation in a finite element model." Delete the word condition in "bonding condition.."

Ans：Thank you for your comment. Modified sentence was added into the manuscript and shown below:

“Suárez (2012) evaluated the effects of the assumption of bonding and unbonding conditions at the bone-prosthesis interface on bone adaptation in a finite element model.”

Line 82: I think the best article from Boileau to quote here would be this one :

Boileau et al., Angled BIO-RSA (Bony-Increased Offset-Reverse Shoulder Arthroplasty).2017 JSES

Ans： Thank you for your comment. Boileau has made big contributions to the application of reverse shoulder arthroplasty from “Grammont reverse prosthesis Design, rationale, and biomechanics” published in 2005 to “Bony-Increased Offset-Reverse Shoulder Arthroplasty” published in 2017. I agree that the article “Bony-Increased Offset-Reverse Shoulder Arthroplasty” is the most proper one here. The changed reference has been added into the manuscript.

Line 83-35: As I mentioned previously, the existence of testable hypothesis will make paper stronger and message “lauder”.

Ans： Thank you for your comment. A hypothesis, which is shown below, was added in the manuscript.

“It hypothesizes that the placement of glenoid component will relate to the implant fixation. This study is aimed to investigate the hypothesis using finite element analysis.”

Methods:

Line 97: Please note in the methods the reference line you used to measure the inclination in all cases. Please be specific, ideally 2 data points for each: determination of the entry point of the central peg and orientation (i.e. inclination in this study). Also, it would make your study more complete if you list the measured version in the case used.

Ans： Thank you for your comment. The reference line used in Nyffeler's study was used to measure the inclination in this study. The sentences below were added into the manuscript to specify the reference line and determination of the entry point of the central peg and orientation.

"With the intersection of the superoinferior and anteroposterior axes being a reference point (Nyffeler et al., 2005), determination of the entry point of the central peg for the four implant positions (Fig. 1) was 0 mm for FP1, 0.8 mm inferiorly for FP2, 4.7 mm inferiorly for FP3 and 0 mm for FP4. Inclinations for the four prosthesis positions (Fig. 1) were 0°(FP1), 0°(FP2), 0°(FP3) and 15°(FP4) respectively."

Reference

Nyffeler, R.W., Werner, C.M.L., Gerber, C., 2005. Biomechanical relevance of glenoid component positioning in the reverse Delta III total shoulder prosthesis. J Shoulder Elbow Surg 14, 524-528, doi: 10.1016/j.jse.2004.09.010.

Line 108: Were material properties derived at any point from the cadaveric sample? Not clear to me. Please elaborate.

Ans: Yes, material properties were derived from the cadaveric sample. In the FE modelling, the average of CT values (Hounsfield Unit) of four points in each tetrahedral element was set as the CT value of this element. The material property of this element was obtained in terms of CT-apparent density correlation (Equation 1) and modulus-density relationship (Equation 2).

$$\rho_{apparent} = 0.0009H + 0.1072 \quad \text{Equation 1}$$

$$E = 3790\rho^3 \quad \text{Equation 2}$$

Because the mesh size in the lateral scapula and remaining bone were only 1.5 mm and 3.0 mm respectively, the site-dependent and heterogeneous characteristics of human bone can be represented by the method assigning material property on an element-by-element basis. Detailed validation of the FE model of the scapula was reported in our previous work (Zhang, 2012).

Reference:

1. Zhang, M., 2012. Effects of Scapular Notching and Bone Remodelling on Long-Term Fixation of the Glenoid Component in Reverse Shoulder Arthroplasty. PhD. thesis, Imperial College London, London, UK.

Line 167: The five physiologic activities tested in this study were discussed, but the forces used/applied during the FE modeling were omitted from the manuscript and supplement. I would suggest authors to consider mentioning it somewhere.

Ans：Thank you for your comment. The forces used to calculate micromotions in the FE modeling was added on Line 146. Details were shown below. The forces used to calculate bone remodeling was described on Line 170-173.

Line 146: "The micromotion of all the nodes at the bone-implant interface in each physiological activities shown in the supplementary (Kontaxis, 2010) was recorded for each implant position."

Results:

Well written and presented in organized fashion.

Discussion:

Very thorough. Provided many examples of relevant and recent evidence currently in the literature.

Line 220: Consider deleting "in order" in the sentence, "This study simulated implantation of the glenoid components of an RTSA in four different positions in order to analyse micromotion at the bone-prosthesis interface and bone adaptation"

Ans：Comment was accepted. Thank you for it. Modification was added into the manuscript.

Line 224: Consider deleting i.e. position-specific in the sentence, "(2) postoperative bone resorption is highly dependent on implant positioning, i.e. position-specific."

Ans：Thank you for the comment. Modification was shown below:

"(2) postoperative bone resorption is highly dependent on implant positioning."

Line 238: Consider changing "Inclining the glenosphere led to an increase in peak micromotions, with Task 2 (lifting a block to head height) producing a value of 82.5 µm and Task 5 (standing up from an armchair) showing micromotion of 137.4 µm." into 2 sentences and change the beginning of the line to: "Tilting the glenoid component inferiorly led to an increase in peak micromotions. Resulting in Task 2 (lifting a block to head height) producing a value of 82.5 µm and Task 5 (standing up from an armchair) showing micromotion of 137.4 µm."

Ans：Thank you for the comment. Modification was added into the manuscript and shown below:

"Tilting the glenoid component inferiorly led to an increase in peak micromotions. Noticeably, the value was 82.5 µm in Task 2 (lifting a block to head height) and 137.4 µm in Task 5 (standing up from an armchair)."

Line 240: Consider changing "indicated" to "suggests" in sentence: "This indicated that bone ingrowth would not occur in the inferior part of the glenoid because both values exceeded the upper limit of 50 µm for stimulating bone formation (Pilliar et al., 1986)."

Ans： Thank you for the comment. Modification was added into the manuscript and shown below:

"This suggests that bone ingrowth would not occur in the inferior part of the glenoid because both values exceeded the upper limit of 50 μm for stimulating bone formation (Pilliar et al., 1986)."

Line 246: Consider modifying this sentence, "In Task 5, where the greatest micromotion was observed across all five activities, micromotion below 50 µm (the threshold of bone ingrowth) covered 73.5% of the baseplate." To "The greatest micromotion was observed in Task 5. However, micromotion below 50 µm covered 73.5% of the baseplate"

Ans： Thank you for the comment. The modification was added into the manuscript.

Line 253-254: Reducing activities …will improve the primary stability … . Please consider replacing will with may. This statement can't be derived from your study, but suggestion can be made. Same for abstract.

Ans： Thank you for the comment. The modification was added into the manuscript.

References:

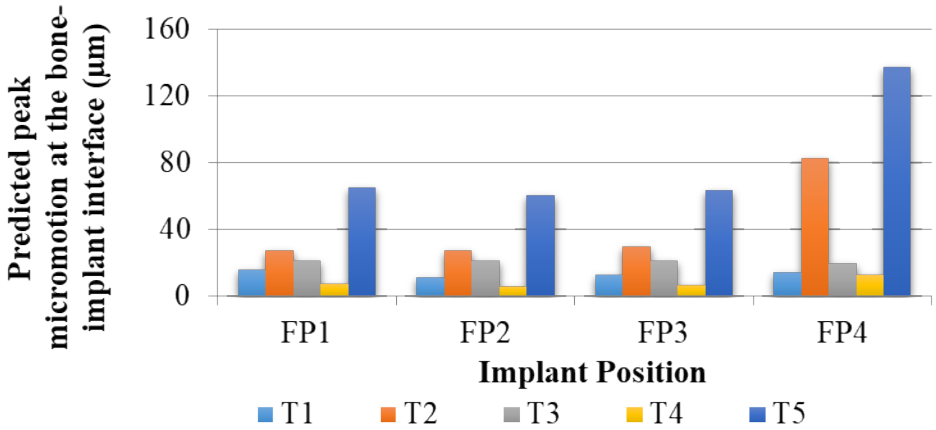
Very good, as suggested previously, add Boileau paper.

Figures:

Fig 4 & 6: I would suggest authors to invert the data as you analyzed the effect of the position of the glenoid.

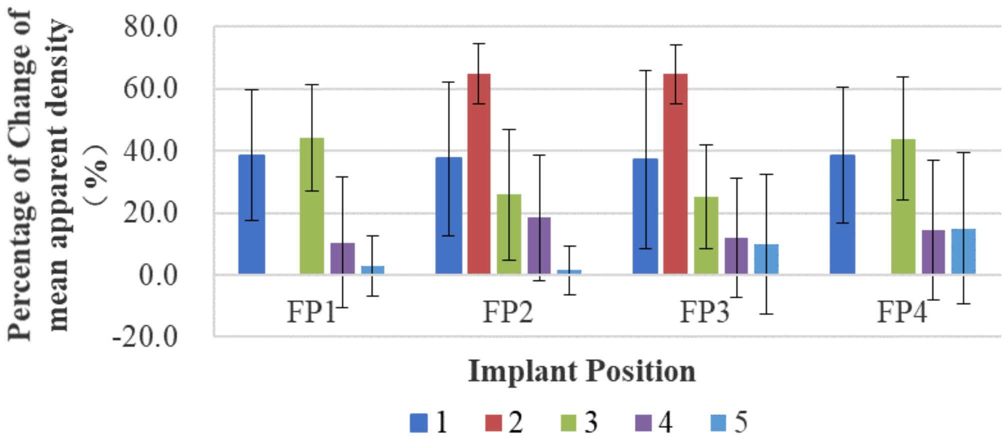
Ans： Thank you for the comment. Modification are shown in Figure 4 and Figure 6 and below.

Fig. 4:



T1 - Combing hair； T2 - Lifting a block to head height；
T3 - Lifting a block to shoulder height； T4 - Hands on the lower back； T5 - Sit-to-stand from an armchair

Fig. 6



1 - Lateral superior; 2 - Lateral middle; 3 - Lateral inferior;
4 - Medial superior; 5 - Medial inferior

Highlights

- Inferior tilting of implant leads to increased micromotion in the inferior glenoid
- The amount of micromotion is activity-specific
- Reducing activities with anteroposterior shear forces improves implant stability
- Inferior positioning increases bone resorption in the lateral-middle glenoid
- Central positioning increases bone resorption in the lateral-inferior region

Effect of Baseplate Positioning on Fixation of Reverse Total Shoulder Arthroplasty

Min Zhang PhD[1, 2], Sarah Junaid PhD[2, 3], Thomas Gregory MD[2, 4], Ulrich Hansen PhD[2], Cheng-Kung Cheng PhD[1]

[1] School of Biological Science and Medical Engineering, Beihang University, Beijing, China， 100083; Beijing Advanced Innovation Centre for Biomedical Engineering, Beihang University, Beijing, China， 102402.

[2] Mechanical Engineering Department, Imperial College London, UK.

[3] Engineering and Applied Sciences, Aston University, Birmingham, UK

[4] Department of Orthopaedic Surgery, Avicenne Teaching Hospital, APHP, University ParisXⅢ, Bobigny, France

Min Zhang: zhangminsky123@msn.com

Sarah Junaid: s.junaid@aston.ac.uk

Thomas Gregory: tms.gregory@gmail.com

Ulrich Hansen: u.hansen@imperial.ac.uk

Cheng-Kung Cheng: ckcheng2009@gmail.com

Corresponding author: Name: Min Zhang

E-mail address: zhangminsky123@msn.com

Mailing address: No. 37, Xueyuan Road, Haidian District, Beijing, China 100083

Word count for abstract: 245; Word count for the main text: 3600

Declarations of interest: none

Abstract

Background: The glenoid component in reverse total shoulder arthroplasty is recommended to be positioned inferiorly or with a downward tilt with the intention of reducing scapular notching. However, it is still unclear whether modifying the position of the glenoid prosthesis affects implant stability. The aim of this study was to determine the association between implant positioning and glenoid prosthesis fixation using Grammont reverse total shoulder arthroplasty.

Methods: Four positions for the glenoid prosthesis were studied using the finite element method. The glenosphere was positioned as follows: 1) in the middle of the glenoid fossa, 2) flush with the inferior glenoid rim, 3) with an inferior overhang, 4) with a 15° inferior inclination. Bone-prosthesis micromotions and strain-induced bone adaptations were quantified during five daily activities.

Findings: When the glenoid component was tilted inferiorly, the activities producing anterior-posterior shear forces (e.g. standing up from an armchair) caused an increase in peak micromotions. In the lateral-middle glenoid, inferior positioning caused a 64.6% reduction in bone apparent density. In the lateral-inferior glenoid, central positioning led to the most severe bone resorption, reaching 43.9%.

Interpretation: Reducing activities which generate anterior-posterior shear forces on the shoulder joint will increase bone formation and may improve the primary stability of the implant when fixed in the position with an inferior tilt. Postoperative bone resorption is highly dependent on implant positioning. Understanding the relationship between bone resorption and implant positioning will help surgeons improve the long-term stability of reverse total shoulder arthroplasty.

Keywords inferior position; inferior tilt; reverse total shoulder arthroplasty; bone remodeling; micromotion; fixation.

1. Introduction

Loosening of the glenoid is a common complication for Grammont reverse total shoulder arthroplasty (RSA), with an incidence rate of 3.5% to 9%, and often requires reintervention (Zumstein et al., 2010; Boileau, 2016). In addition to infection, there are many other factors leading to aseptic glenoid loosening, i.e. scapular notching, osseointegration, and strain-induced bone loss (Pilliar et al., 1986; Huiskes et al., 1987; Chae et al., 2015; Boileau, 2016).

Scapular notching is caused by mechanical impingement between the humeral component and the scapular neck during arm adduction and is hastened by bone osteolysis. It is reported to be present in approximately 50% to 96% of Grammont RSA (Sirveaux et al., 2004; Simovitch et al., 2007; Kempton et al., 2011). Inferior positioning and inferior tilting are recommended to minimise postoperative scapular notching in RSA (Nyffeler et al., 2005; Kelly II et al., 2008). The space between the glenoid bone and the inferior rim of the glenoid component is generally recommended to be maintained within the range of 2 mm to 6 mm (Kelly II et al., 2008; Kontaxis and Johnson, 2009; Kempton et al., 2011). The recommended angle of inclination is between 10° and 15° (Nyffeler et al., 2005; Kempton et al., 2011).

Osseointegration is the direct structural and functional connection between living bone and the surface of a load-bearing implant. Pilliar reported that the occurrence of bone ingrowth is closely correlated with the relative movement between the bone and the implant, which is also known as micromotion (Pilliar et al., 1986). Bone ingrowth occurs in the presence of micromotion within a threshold of 50 μm (Pilliar et al., 1986). However, when bone-implant micromotion exceeds 150 μm, mature fibrous connective tissues form a less stable connection with the implant (Pilliar et al., 1986). Finite element method has been used to calculate bone-prosthesis micromotion after RSA, and then to predict the occurrence of postoperative integration utilizing the relationship between micromotion and bone ingrowth (Chae et al., 2016).

Stress-shielding is another factor leading to erosion of the bone bed supporting the RSA (Ahir and Walker, 2004). Finite element analysis has been used extensively for predicting stress distribution and strain-induced bone remodelling (Büchler et al., 2002; Sharma et al., 2009; Sharma et al., 2010; Suárez et al., 2012). Suárez (2012) evaluated the effects of the assumption of bonding and unbonding conditions at the bone-prosthesis interface on bone adaptation in a finite element model. Sharma (2010) reported on the correlation between strain-induced bone adaptation and the design of total shoulder prostheses.

Even though inferior positioning and inferior tilting have been proposed for minimizing scapular notching (Boileau, 2017), it is still unclear how this may affect bone ingrowth and bone adaptation during normal daily activities. It hypothesizes that the placement of glenoid component will relate to the implant fixation. This study is aimed to investigate the hypothesis using finite element analysis.

2. **Methods**

2.1 Finite element (FE) modelling

CT images (Voxel sizes: 0.48mm× 0.48mm× 0.33mm) of a 71-year-old cadaveric scapula without any previous shoulder surgeries and disease (Science Care, Phoenix, USA) were used to create the geometry of the bone in Avizo 5 (Mercury Systems, Andover, USA). The geometry of a Delta CTA RSA (Depuy Synthes Company, Warsaw, USA) was inserted into the bone model according to the recommended surgical techniques for a Delta CTA implant (2005 version) (Depuy Synthes Company, Warsaw, USA). Four positions of the glenoid component were simulated (Fig. 1): (a) glenoid prosthesis fixed in the middle of the glenoid fossa (FP1), (b) glenoid prosthesis positioned flush to the glenoid rim (FP2), (c) glenoid component moved inferiorly until the inferior locking screw protruded from the bone (FP3), (d) glenoid component inclined inferiorly by approximately 15° (FP4) (Nyffeler et al., 2005). With a fixed angle of 17° from the inferior surgical screw to the middle peg of the implant, the distance between the bottom of the glenosphere and the inferior rim of the glenoid bone for FP3 was 3.9 mm, which is within the reported range of overhang of the glenoid component (2 to 4 mm) for a Delta CTA RSA (Nyffeler et al., 2005). With the intersection of the superoinferior and anteroposterior axes being a reference point (Nyffeler et al., 2005), determination of the entry point of the central peg for the four implant positions (Fig. 1) was 0 mm for FP1, 0.8 mm inferiorly for FP2, 4.7 mm inferiorly for FP3 and 0 mm for FP4. Inclinations for the four prosthesis positions (Fig. 1) were 0°(FP1), 0°(FP2), 0°(FP3) and 15°(FP4) respectively. In the FP4 model, the downward tilt of the glenoid implant required resection of the inferior glenoid pole. All the glenoid positions were guided by an experienced orthopaedic shoulder surgeon. For each placement, geometries of the scapula and the implant were imported into FE software. In this study, MSC. Marc Mentat (MSC Software Corporation, Santa Ana, USA) was utilized for creating resected surface on the glenoid, meshing and FE analysis. All models were constructed from linear tetrahedral elements and assumed to be linearly elastic and isotropic. The material properties of bone in each FE model were calculated using the relationship introduced by Carter and Hays (1977) and were assigned element-by-element. The FE model of the scapula was validated against the cadaveric scapula in our previous work (Zhang, 2012). The glenoid head and baseplate of the implant, which are manufactured from cobalt-chrome, were modeled as linear isotropic materials with a Young's modulus of 220 GPa. The four titanium screws used to secure the implant were modeled as linear isotropic materials with a Young's modulus of 110 GPa.

The baseplate of the Delta CTA RSA was press-fit to the bone. To evaluate micromotion at the bone-baseplate interface, the baseplate in the FE model was assumed to be unbounded and set with a frictional surface-to-surface contact with the bone. 0.4 was recommended for the friction coefficient at the baseplate-bone interface (Harman et al., 2005; Hopkins et al., 2008). In addition, varying the coefficient of friction was found not significantly affect the predicted micromotions in our previous work (Zhang, 2012). In this current study, the four peripheral surgical screws in the RSA were assumed to be securely tightened. Thus, the interface between bone and screws was modelled as a rigidly bonded interface. Five physiological activities from daily life were simulated: 1) Combing hair, 2) Lifting a block higher than the shoulders, 3) Lifting a block to shoulder height, 4) Hands on the lower back, 5) Sit-to-stand from an armchair (Supplementary) (Kontaxis, 2010). Force magnitudes (Supplementary (d) (e)) and loading positions (Supplementary (f) (g)) in each activity were obtained from Kontaxis' study, as well as the scapular reference coordinate (Kontaxis, 2010). In the intact bone model (Supplementary (b)), AI represents the inferior angle, AA is the posterior point of the acromion, and TS is the medial end of the scapular spine.The origin of the coordinate system in the FE model of the intact bone is on the point AA; Xs is on the line determined by AA and TS; Ys is vertical to Xs; Zs is vertical to the plane determined by AA, TS and AI; The coordinate system of the implanted scapula was defined based on the resected surface (Supplementary (c)). The origin of the coordinate system in the FE model of the implanted scapula is on the middle point of the baseplate. X is vertical to the resected surface, Y is from the inferior to the superior, Z is from the posterior to the anterior. The medial ends of the scapula in each FE model were fixed to prevent movement and so as not to influence the motion of the glenoid. Bone-implant micromotions and strain-induced bone resorption were recorded for various fixation positions. The quality of the meshes was checked using a mesh convergence study, finding that a mesh size of 1.5 mm in the lateral scapula and 3.0 mm in the remaining bone offered a reliable prediction of interface micromotion and bone adaptation.

2.2 Micromotion analysis

The relative displacement of each pair of contacting nodes on the fixation interface after loading was calculated. This indicated the extent of micromotion of that pair of nodes. The micromotion of all the nodes at the bone-implant interface in each physiological activities shown in the supplementary (Kontaxis, 2010) was recorded for each implant position. The calculation method was validated by Harman and Hopkins (Harman et al., 2005; Hopkins et al., 2008). Our previous study investigated micromotion and post-operative stress variations in six FE models of cadaveric scapulae implanted with a Delta CTA RSA in the middle of the glenoid (Zhang, 2012). The results showed the same level of micromotion and bone density distribution across all models. Thus, this study used one of the scapulae for analyzing micromotion and bone remodelling with the Delta CTA RSA fixed in various positions.

2.3 Bone adaptation analysis

The strain-induced bone remodelling algorithm proposed by Weinans et al. was used in this study (Weinans et al., 1992). This algorithm was developed in accordance with 'Wolff's

Law' and uses strain energy density as the feedback. It has been clinically validated using the adaptation of periprosthetic human bone by Kerner et al. (Kerner et al., 1999). For the purpose of investigating changes in bone density in this current study, only the internal structure was remodelled and the outer shape of the glenoid was assumed to be unchanged. Changes in bone apparent density were calculated on an element-by-element basis and expressed by Equation 1.

$$\begin{aligned} \Delta\rho^i &= \tau\Delta t A(\rho^i)\{S^i - S_n{}^i(1+s)\}, \qquad S^i \geq S_n{}^i(1+s) \\ &= \tau\Delta t A(\rho^i)\{S^i - S_n{}^i(1-s)\}, \qquad S^i \leq S_n{}^i(1-s) \\ & (0\,\mathrm{g/cm^3} < \rho < 1.8\,\mathrm{g/cm^3}) \end{aligned} \qquad \text{Equation 1}$$

Where i relates to elements, S is the bone remodelling stimulus ($S = U/\rho$), U is the strain energy density, S_n is the reference stimulus, τ is the time scale (the relationship between simulated time and real time), $A(\rho)$ is the free surface density (Martin, 1984), Δt is the time increment expressed in Equation 2, and s is a constant for determining the extent of the stimulus range. In this study, s=0.75 was used (Kerner et al., 1999), as this value has been successfully validated with in-vitro tests by Kerner et al. (1999) and Bitsakos (2005). The reference stimulus ($S_n = U_n/\rho_n$) was calculated according to the strain energy (U_n) and bone apparent density (ρ_n), which were obtained from an intact scapula bone. Five physiological daily activities were applied to the intact scapula (Supplementary) (Kontaxis, 2010). The stimulus was calculated for each loading condition and the average of the stimuli from all loading conditions represented the stimulus (S) in one iteration. In each iteration, the Young's modulus was calculated using the relationship proposed by Carter and Hayes (1977) and was updated when the next iteration started. The Poisson's ratio was assumed to be constant during the entire bone adaption process.

$$\tau\Delta t = \frac{\Delta\rho_{max}}{\{A(\rho)(S-(1+s)S_n)\}_{max}} \qquad \text{Equation 2}$$

Variations in distribution of bone apparent density in the frontal plane, which passes through the middle of the stem, were recorded and used to predict postoperative adaptive bone resorption in the scapula.

Five regions of interest were chosen for statistical comparison of glenoid positioning (Fig. 2). Three regions were in the lateral glenoid and two regions were in the medial glenoid (Fig. 2). The bone apparent density in each region was averaged. A student's t-test was applied to investigate the relationship between the position of the glenoid implant and strain-induced bone adaptation. A *P* value of less than 0.05 was considered significant.

3. **Results**

Micromotion at the bone-prosthesis interface was recorded for the four glenoid implant positions under five loading conditions (Tasks 1 to 5) (Supplementary). The interface micromotion while standing up from an armchair (Task 5) was illustrated in Fig. 3. The results indicate that large interface micromotions were predominantly located at the tip of the central peg, as well as at the superior and inferior rims of the baseplate. In comparison with the other three positions, an inferior tilt of the glenoid prosthesis led to a considerable increase in micromotion at the inferior region of the baseplate.

The maximum micromotion at the bone-prosthesis interface for each implant position (Fig. 1) under the five loading conditions (tasks 1 to 5) (Supplementary) is illustrated in Fig. 4. It was found that the maximum micromotion in FP4 (inferior tilt of the glenoid implant) reached 82.5 µm in Task 2 (Lifting a block to head height) and 137.4 µm in Task 5 (Standing up from an armchair). In Task 5, where the greatest micromotion was observed across all activities, micromotion of less than 50 µm (the threshold value for bone ingrowth) covered 73.5% of the baseplate. For the implant positions without any inferior tilting, the average peak micromotion for the five loading conditions (Supplementary) was 27.4 µm for FP1, 25.2 µm for FP2 and 26.6 µm for FP3. However, for Task 5 alone, the peak micromotion reached 67.2 µm for FP1, 63.5 µm for FP2 and 65.4 µm for FP3.

Variations in the distribution of postoperative bone apparent density with time for the four glenoid implant positions were predicted with a bone remodelling algorithm. Results at four follow up stages are shown in Fig. 5. It was found that severe bone resorption occurred around the central peg and the back of the baseplate in all four models. Low apparent densities predominantly appeared above the central peg when the glenoid component was located inferiorly (FP2 and FP3) and were distributed almost evenly around the central peg in FP1 and FP4.

The percentage change in mean bone apparent density in the postoperative period of F4 in the five regions of interest is shown in Fig. 6. It is noticeable that the bone apparent density at the lateral-middle (2) region showed high strain-induced bone resorption for FP2 (64.1% (SD 9.7%)) and FP3 (64.6% (SD 9.5%)). There were no lateral-middle values in the case of central positioning of the glenoid (FP1 and FP4), as this region just covered the hole for the implant stem. In the lateral-inferior region (3), central positioning of the glenoid component (FP1: 43.9% (SD 17.1%) and FP4: 43.8% (SD 19.8%)) led to greater variation in bone apparent density than moving the glenoid component inferiorly (FP2: 25.9% (SD 21.1%) (p<0.05) and FP3: 25.0% (SD 16.7%) (p<0.05)). In addition, Fig. 6 also illustrates a greater reduction in bone apparent density in the lateral region (1, 2, 3) than in the medial region (4, 5).

4. **Discussion**

This study simulated implantation of the glenoid components of an RSA in four different positions to analyse micromotion at the bone-prosthesis interface and bone adaptation. The most important findings were that (1) inferior tilting of the glenoid component lead to high levels of micromotion in the inferior glenoid, but this is activity-specific, and (2) postoperative bone resorption is highly dependent on implant positioning.

The micromotion detailed in Fig. 4 shows that inferior positioning (FP3) of the implant did not result in different levels of micromotion than could be expected with a traditional implant position (FP1). For the positions with 0° tilt, the average peak micromotion for all the loading conditions (27.4 μm in FP1, 25.2 μm in FP2 and 26.6 μm in FP3) was lower than the upper limit of 50 μm, above which bone formation would not occur (Pilliar et al., 1986). This indicated a suitable initial stability of the glenoid prosthesis. This finding is consistent with radiological reports for successful RSAs (Roche et al., 2013; Boileau, 2016). Variations in peak micromotions for the different activities show that a patient's lifestyle may affect the initial stability of the implant. The high peak micromotions observed for Task 5 (67.2 μm in FP1, 63.5 μm in FP2 and 65.4 μm in FP3) indicates that further studies into the relationship between lifestyle and micromotion could be beneficial for developing improved guidelines for postoperative recovery.

Tilting the glenoid component inferiorly led to an increase in peak micromotions. Noticeably, the value was 82.5 μm in Task 2 (lifting a block to head height) and 137.4 μm in Task 5 (standing up from an armchair). This suggests that bone ingrowth would not occur in the inferior part of the glenoid because both values exceeded the upper limit of 50 μm for stimulating bone formation (Pilliar et al., 1986). Roberts et al. reported similar findings in an anteroposterior radiographic study, where serious inferior radiolucent lines were observed with the use of an inferior-tilt configuration (Roberts et al., 2007). Using in-vitro testing and finite element simulations, Chae et al. also reported high micromotion in the inferior part of the glenoid (Chae et al., 2015; Chae et al., 2016). The greatest micromotion was observed in Task 5. However, micromotion below 50 μm covered 73.5% of the baseplate. This explains the initial stability of the glenoid component when fixed with an inferior tilt (Simovitch et al., 2007). Variations in peak micromotion for position FP4 (inferior titling of baseplate) for the five loading conditions (Task 1: 16.1 μm, Task 2: 82.5 μm, Task 3: 19.8 μm, Task 4: 12.3 μm, Task 5: 137.4 μm) showed that the increase in micromotion induced by glenoid positioning is activity-specific. Reducing activities that produce high anterior-posterior shear forces (for example, Task 2 & 5) may improve the primary stability of the prosthesis when fixed with an inferior tilt.

In comparison to positioning with a 0° inclination, tilting the implant inferiorly induced a superior shift in the glenohumeral resultant force on the glenosphere surface and increased bone loss around the inferior glenoid pole. The magnitude of the resultant glenohumeral (GH) force, which originates from the muscles surrounding the shoulder, is assumed not to be related to implant positioning. Changing the position of the loading point may reduce the shear forces on the implant and thus was not a factor for the increase of micromotions in FP4. Tilting the implant required the inferior scapular pole to be resected, leading to increased contact between trabecular bone and the implant. This weak bone supporting the implant may explain the high micromotions in the inferior region observed in our study (Chae et al., 2015). An inferior inclination of the glenosphere requires the removal of cortical bone, which has been suggested to increase the risk of glenoid loosening (James et al., 2011; Kempton et al., 2011; Roche et al., 2013). In addition, specific recommendations for reducing scapular notching by tilting the glenosphere are still controversial (Edwards et al., 2012; Li et al., 2013).

Bone density distributions in the frontal plane for four glenoid positions under various loading conditions were predicted in this study. The results indicated the same tendency for strain-induced bone resorption in all four implant positions. Bone loss occurred initially in the area next to the bone-prosthesis interface, and then expanded to the peripheral regions. This finding is consistent with radiographic observations of bone loss in Grammont RSA (Roberts et al., 2007; Fávaro et al., 2015).

This study also demonstrated that changing the position of the glenoid prosthesis induced different levels of strain-induced bone resorption. An inferior movement of the glenoid component led to greater bone resorption in the lateral-middle region, while central positioning of the glenoid component induced increased bone loss in the lateral-inferior region. These observations are corroborated by radiographic images (Roberts et al., 2007; Farshad and Gerber, 2010; Fávaro et al., 2015). Farshad et al. reported that radiographic bone resorption at eight years after RSA was more severe than at three years, with the most noticeable region being above the central peg (Farshad and Gerber, 2010). The distribution of bone resorption with inferior positioning of the glenoid prosthesis in RSA is possibly caused by the inferior movement of the glenohumeral force on the glenoid bone. The inferior movement was 1.8 mm for FP2 and 3.9 mm for FP3 . Thus the load above the middle peg (lateral-middle region) after implantation reduced significantly, leading to low postoperative strains and greater bone resorption.

A limitation of this study is that the time constant used in the strain-induced bone remodelling algorithm has only been validated in studies on hip replacements for dogs (Kerner et al., 1999; Bitsakos, 2005). It is necessary to develop a time constant which could connect the predicted bone remodelling with clinical data obtained from patients with RSA. It would be beneficial to assess bone resorption in real time with different glenoid positions. Another limitation is that the bone-baseplate interface was assumed to be unbonded, which is a worst case scenario. In a study evaluating the effect of various connection conditions at the bone-baseplate interface on the amount of bone resorption, Suárez et al. reported that bonding the interface (best case scenario) produced slightly less bone resorption than when the interface was unbonded (worst case scenario) (Suárez et al., 2012). This current study evaluated the amount of bone resorption when the glenoid component was fixed in various positions. Changing the position of the implant will lead to the same effects on results as long as the bone-baseplate interface connection conditions in the various FE models are the same.

5. **Conclusions**

In conclusion, tilting the glenoid component inferiorly would lead to increased micromotion in the inferior glenoid, but the amount of micromotion depends on the activity being performed. Reducing activities with anterior-posterior shear forces will improve the primary stability of the bone-prosthesis interface when the prosthesis is fixed with an inferior tilt. Moving the glenoid component inferiorly led to a reduction in bone apparent density in the lateral-middle region. Central positioning of the glenoid component increased bone resorption in the lateral-inferior glenoid. Understanding the relationship between postoperative bone resorption and implant positioning is beneficial for improving the long-term stability of RSA.

Acknowledgement

We wish to thank Dr. Kontaxis from Newcastle University for the provision of force data for Delta reverse total shoulder arthroplasty in physiological daily activities. We would also like to thank Dr. Denny Lie, Singapore General Hospital, for helpful discussions on the standard surgical technique for Delta CTA reverse total shoulder arthroplasty.

Conflict of interest statement

All the authors, their immediate family, 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.

References

1. Ahir, S.P., Walker, P.S., 2004. Analysis of glenoid fixation for a reversed anatomy fixed-fulcrum shoulder replacement. J Biomech 37, 1699-1708, doi: 10.1016/j.jbiomech.2004.01.031.
2. Bitsakos, C., 2005. Computer Simulation of Periprosthetic Bone Remodelling after Total Hip Arthroplasty. PhD. thesis, Imperial College London, London, UK.
3. Boileau, P., 2016. Complications and revision of reverse total shoulder arthroplasty. Orthop Traumatol Surg Res 102, S33-S43, doi: 10.1016/j.otsr.2015.06.031.
4. Boileau, P., Morin-Salvo, N., Gauci, M., Seeto, B., Chalmers, P., Holzer, N., Walch, G., 2017. Angled BIO-RSA (bony-increased offset-reverse shoulder arthroplasty): a solution for the management of glenoid bone loss and erosion. J Shoulder Elbow Surg 26, 2133-2142, doi: 10.1016/j.jse.2017.05.024.
5. Büchler, P., Ramaniraka, N., Rakotomanana, L., Iannotti, J., Farron, A., 2002. A finite element model of the shoulder: application to the comparison of normal and osteoarthritic joints. Clin Biomech 17, 630-639, doi: https://doi.org/10.1016/S0268-0033(02)00106-7.
6. Carter, D.R., Hayes, W.C., 1977. The compressive behaviour of bone as a two-phase porous structure. J Bone Joint Surg Am 59, 954-962, doi: https://insights.ovid.com/pubmed?pmid=561786.
7. Chae, S., Lee, J., Han, S., Kim, S., 2015. Inferior tilt fixation of the glenoid component in reverse total shoulder arthroplasty: A biomechanical study. Orthop Traumatol Surg Res 101, 421-425, doi: 10.1016/j.otsr.2015.03.009.
8. Chae, S.W., Lee, H., Kim, S.M., Lee, J., Han, S.H., Kim, S.Y., 2016. Primary stability of inferior tilt fixation of the glenoid component in reverse total shoulder arthroplasty: A finite element study. J Orthop Res 34, 1061-1068, doi: 10.1002/jor.23115.

9. Edwards, T.B., Trappey, G.J., Riley, C., O̍ Connor, D.P., Elkousy, H.A., Gartsman, G.M., 2012. Inferior tilt of the glenoid component does not decrease scapular notching in reverse shoulder arthroplasty: results of a prospective randomized study. J Shoulder Elbow Surg 21, 641-646, doi: 10.1016/j.jse.2011.08.057.
10. Farshad, M., Gerber, C., 2010. Reverse total shoulder arthroplasty--from the most to the least common complication. Int Orthop 34, 1075-1082, doi: 10.1007/s00264-010-1125-2.
11. Fávaro, R.C., Abdulahad, M., Filho, S.M., Valério, R., Superti, M.J., 2015. Rotator cuff arthropathy: what functional results can be expected from reverse arthroplasty? Rev Bras Ortop 50, 523-529, doi: 10.1016/j.rbo.2015.04.007.
12. Harman, M., Frankle, M., Vasey, M., Banks, S., 2005. Initial glenoid component fixation in "reverse" total shoulder arthroplasty-A biomechanical evaluation. J Shoulder Elbow Surg 14, 162S-167S, doi: 10.1016/j.jse.2004.09.030.
13. Hopkins, A.R., Hansen, U.N., Bull, A.M.J., Emery, R., Amis, A., 2008. Fixation of the reversed shoulder prosthesis. J Biomech 17, 974-980, doi: 10.1016/j.jse.2008.04.012.
14. Huiskes, R., Weinans, H., Grootenboer, H.J., Dalstra, M., Fudala, B., Slooff, T.J., 1987. Adaptive bone-remodeling theory applied to prosthetic-design analysis. J Biomech 20, 1135-1150, doi: 10.1016/0021-9290(87)90030-3.
15. James, J., Huffman, K.R., Werner, F.W., Sutton, L.G., Nanavati, V.N., 2011. Does glenoid baseplate geometry affect its fixation in reverse shoulder arthroplasty? J Shoulder Elbow Surg 21, 917-924, doi: 10.1016/j.jse.2011.04.017.
16. Kelly II, J.D., Humphrey, C.S., Norris, T.R., 2008. Optimizing glenosphere position and fixation in reverse shoulder arthroplasty, Part One: The twelve-mm rule. J Shoulder Elbow Surg 17, 589-594, doi: 10.1016/j.jse.2007.08.013.

17. Kempton, L.B., Balasubramaniam, M., Ankerson, E., Wiater, J.M., 2011. A radiographic analysis of the effects of glenosphere position on scapular notching following reverse total shoulder arthroplasty. J Shoulder Elbow Surg 20, 968-974, doi: 10.1016/j.jse.2010.11.026.
18. Kerner, J., Huiskes, R., van Lenthe, G.H., Weinans, H., van Rietbergen, B., Engh, C.A., Amis, A.A., 1999. Correlation between pre-operative periprosthetic bone density and post-operative bone loss in THA can be explained by strain-adaptive remodelling. J Biomech 32, 695-703, doi: 10.1016/S0021-9290(99)00041-X.
19. Kontaxis, A., Johnson, G.R., 2009. The biomechanics of reverse anatomy shoulder replacement - A modelling study. Clin Biomech 24, 254-260, doi: 10.1016/j.clinbiomech.2008.12.004.
20. Kontaxis, A., 2010. Biomechanical analysis of reverse anatomy shoulder prosthesis. PhD. thesis, Newcastle University, Newcastle UK.
21. Li, X., Knutson, Z., Choi, D., Lobatto, D., Lipman, J., Craig, E.V., Warren, R.F., Gulotta, L.V., 2013. Effects of glenosphere positioning on impingement-free internal and external rotation after reverse total shoulder arthroplasty. J Shoulder Elbow Surg 22, 807-813, doi: 10.1016/j.jse.2012.07.013.
22. Martin, R.B., 1984. Porosity and specific surface of bone. CRC Crinical Reviews Biomed. Engng. 10, 179-222, doi: https://www.ncbi.nlm.nih.gov/pubmed/6368124.
23. Nyffeler, R.W., Werner, C.M.L., Gerber, C., 2005. Biomechanical relevance of glenoid component positioning in the reverse Delta III total shoulder prosthesis. J Shoulder Elbow Surg 14, 524-528, doi: 10.1016/j.jse.2004.09.010.
24. Pilliar, R.M., Lee, J.M., Maniatopoulos, C., 1986. Observations on the effect of movement on bone ingrowth into porous-surfaced implants. Clin Orthop Relat Res 208, 108-113, doi: https://www.ncbi.nlm.nih.gov/pubmed/3720113.

25. Roberts, C.C., Ekelund, A.L., Renfree, K.J., Liu, P.T., Chew, F.S., 2007. Radiologic assessment of reverse shoulder arthroplasty. Radiographics 27, 223-235, doi: 10.1148/rg.271065076.

26. Roche, C.P., Diep, P., Hamilton, M., Crosby, L.A., Flurin, P.H., Wright, T.W., Zuckerman, J.D., Routman, H.D., 2013. Impact of inferior glenoid tilt, humeral retroversion, bone grafting, and design parameters on muscle length and deltoid wrapping in reverse shoulder arthroplasty. Bull Hosp Joint Dis 71, 284-293, doi: http://presentationgrafix.com/dev/cake/files/archive/pdfs/66.pdf.

27. Roche, C.P., Marczuk, Y., Wright, T.W., Flurin, P.H., Grey, S., Jones, R., Routman, H.D., Gilot, G., Zuckerman, J.D., 2013. Scapular notching and osteophyte formation after reverse shoulder replacement. Bone Joint J 95, 530-535, doi: 10.1302/0301-620X.95B4.30442.

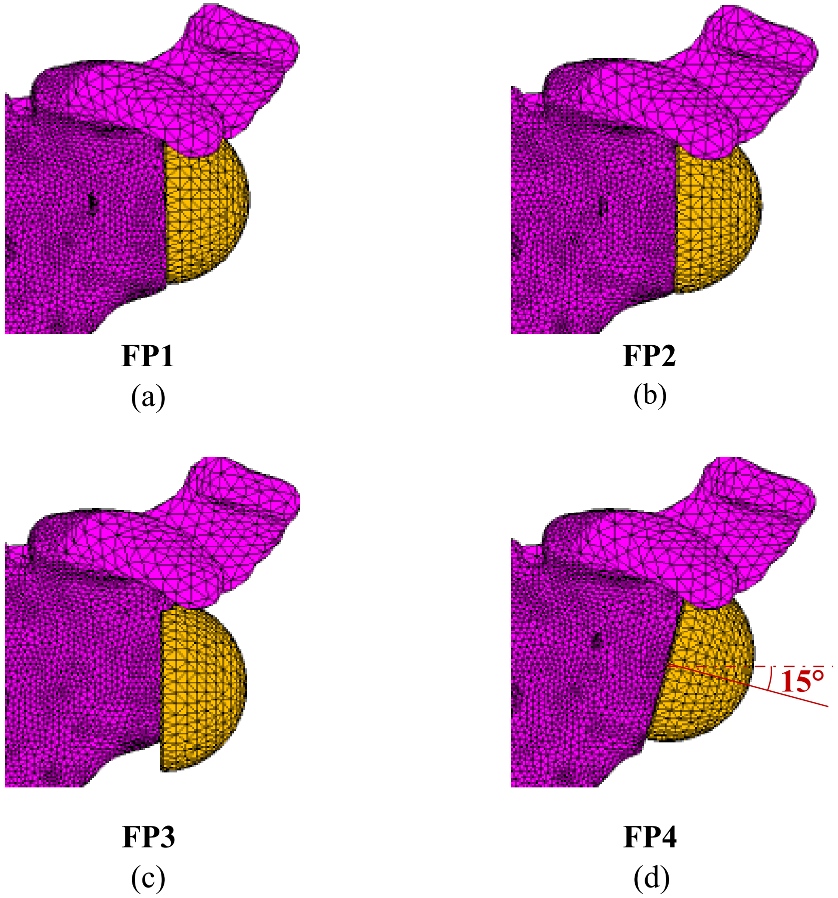
28. Sharma, G.B., Debski, R.E., McMahon, P.J., Robertson, D.D., 2009. Adaptive glenoid bone remodeling simulation. J Biomech 42, 1460-8, doi: 10.1016/j.jbiomech.2009.04.002.

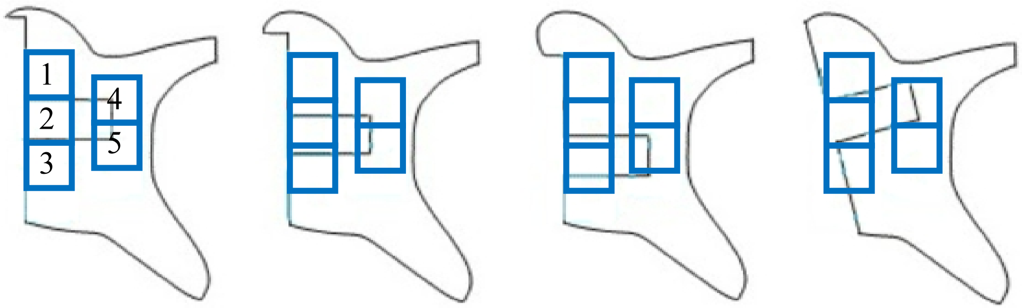
29. Sharma, G.B., Debski, R.E., McMahon, P.J., Robertson, D.D., 2010. Effect of glenoid prosthesis design on glenoid bone remodeling: adaptive finite element based simulation. J Biomech 43, 1653-1659, doi: 10.1016/j.jbiomech.2010.03.004.

30. Simovitch, R.W., Zumstein, M.A., Lohri, E., Helmy, N., Gerber, C., 2007. Predictors of scapular notching in patients managed with the Delta III reverse total shoulder replacement. J Bone Joint Surg Am 89(3), 588-600, doi: 10.2106/JBJS.F.00226.

31. Sirveaux, F., Favard, L., Oudet, D., Huquet, D., Walch, G., Mole, D., 2004. Gammont inverted total shoulder arthroplasty in the treatment of glenohumeral osteoarthritis with massive rupture of the cuff: Results of a multicentre study of 80 shoulders. Bone Joint J 86, 388-395, doi: 10.1302/0301-620X.86B3.14024.

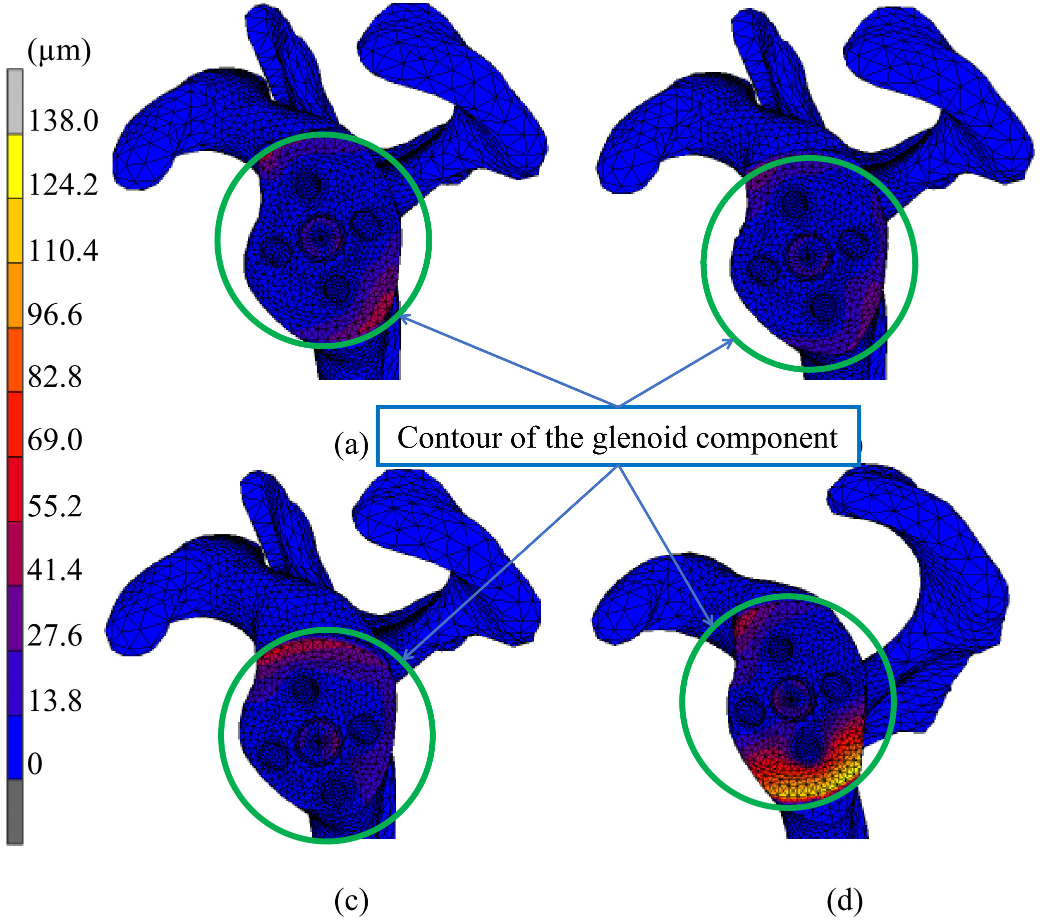
32. Suárez, D.R., Weinans, H., van Keulen, F., 2012. Bone remodelling around a cementless glenoid component. Biomech Model Mechanobiol 11, 903-913, doi: 10.1007/s10237-011-0360-9.
33. Weinans, H., Huiskes, R., Grootenboer, H.J., 1992. The behavior of adaptive bone-remodeling simulation models. J Biomech 25, 1425-41, doi: 10.1016/0021-9290(92)90056-7.
34. Zhang, M., 2012. Effects of Scapular Notching and Bone Remodelling on Long-Term Fixation of the Glenoid Component in Reverse Shoulder Arthroplasty. PhD. thesis, Imperial College London, London, UK.
35. Zumstein, M.A., Pinedo, M., Old, J., Boileau, P., 2010. Problems,complications, reoperations, and revisions in reverse total shoulder arthroplasty: a systematic review. J Shoulder Elbow Surg 20, 146-157, doi: 10.1016/j.jse.2010.08.001.

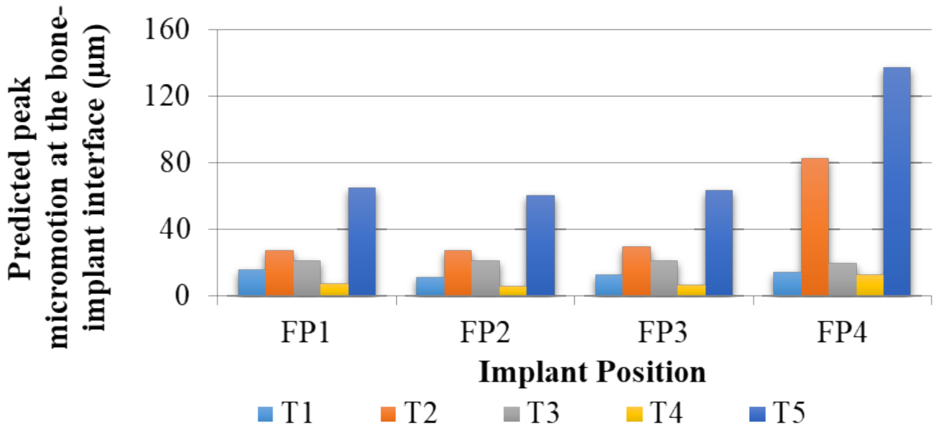

FP1
(a)
FP2
(b)
FP3
(c)
15°
FP4
(d)



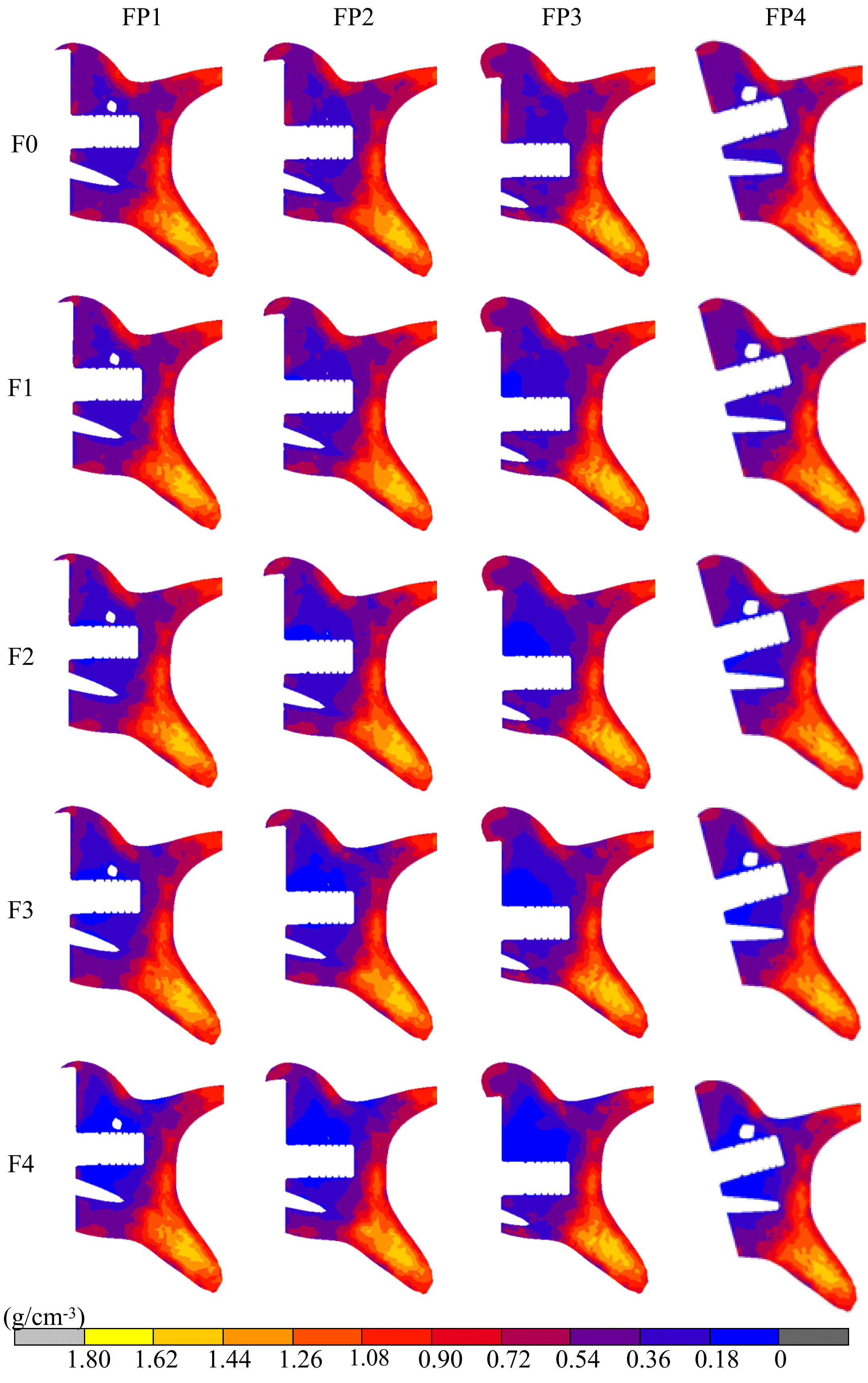
1 - Lateral superior; 2 - Lateral middle; 3 - Lateral inferior;

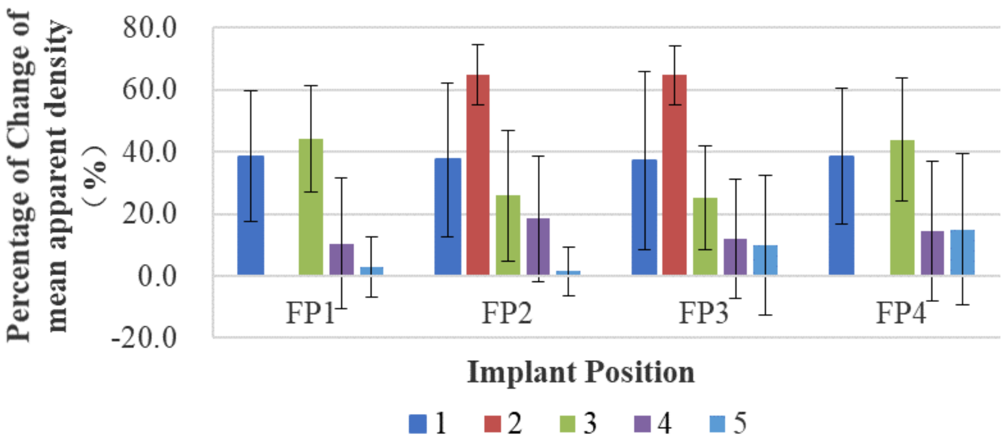
4 - Medial superior; 5 - Medial inferior


(μm)
138.0
124.2
110.4
96.6
82.8
69.0
55.2
41.4
27.6
13.8
0
(a)
Contour of the glenoid component
(c)
(d)



T1 - Combing hair； T2 - Lifting a block to head height； T3 - Lifting a block to shoulder height； T4 - Hands on the lower back； T5 - Sit-to-stand from an armchair


FP1
FP2
FP3
FP4
F0
F1
F2
F3
F4
(g/cm-3)
1.80
1.62
1.44
1.26
1.08
0.90
0.72
0.54
0.36
0.18
0



1 - Lateral superior; 2 - Lateral middle; 3 - Lateral inferior;

4 - Medial superior; 5 - Medial inferior

Conflict of interest statement

All the authors, their immediate family, 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.

Author contributions

Name of Author	**Contribution** （CRediT roles）
Min Zhang	Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Project administration; Validation
Sarah Junaid	Validation
Thomas Gregory	Clinical support
Ulrich Hansen	Supervision
Cheng-Kung Cheng	Supervision

Figure Legends

Fig. 1 Four fixation configurations of the glenoid prosthesis.

Fig. 2 Five regions of interest for statistical comparison of glenoid positions.

Fig. 3 Micromotion distributions at the resected surface when standing up from an armchair. (a) the baseplate was in the middle of the glenoid fossa; (b) the baseplate was flush to the inferior glenoid rim; (c) the baseplate with an inferior overhang; (d) the baseplate was a 15° inferior inclination. The scapula in the case of inferior tilting (d) was superiorly rotated 15° in order to show the whole contact surface. The green circle in each picture represents the contour of the glenosphere in the reverse total shoulder arthroplasty.

Fig. 4 Maximum predicted micromotions at the bone-prosthesis interface. FP1 to FP4 refer to the four fixation positions of glenoid component in Fig. 1.

Fig. 5 Bone remodelling process in the glenoid frontal plane. F0 represents the time before the operation. F1 to F4 represent follow up stages during the bone remodelling process. FP1 to FP4 refer to the four implant positions in Fig. 1.

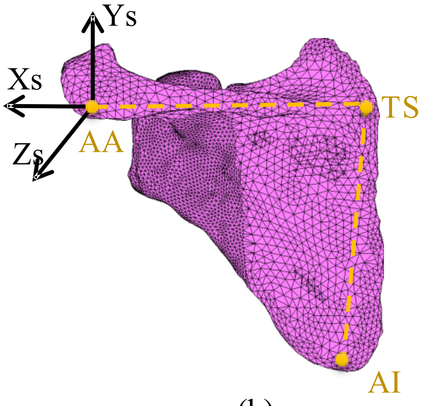
Fig. 6 Change in mean bone apparent density in the five regions of interest for each fixation position of the glenoid component. FP1 to FP4 refer to the four implant positions in Fig. 1.

Supplementary

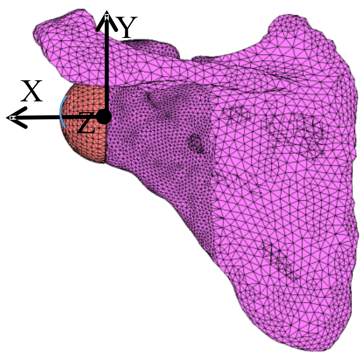
Loading Conditions used in this study

Task No.	Task	Description
Task 1	Combing hair	The largest moment arm of shear forces in the anterior region.
Task 2	Lifting a block to head height	The largest moment arm of compressive force in the posterior region.
Task 3	Lifting a block to shoulder height	Very small anteroposterior shear force.
Task 4	Hands on the lower back	The largest moment arm of shear forces in the posterior region.
Task 5	Sit-to-stand from an armchair	The largest moment arm of compressive force in the anterior region.

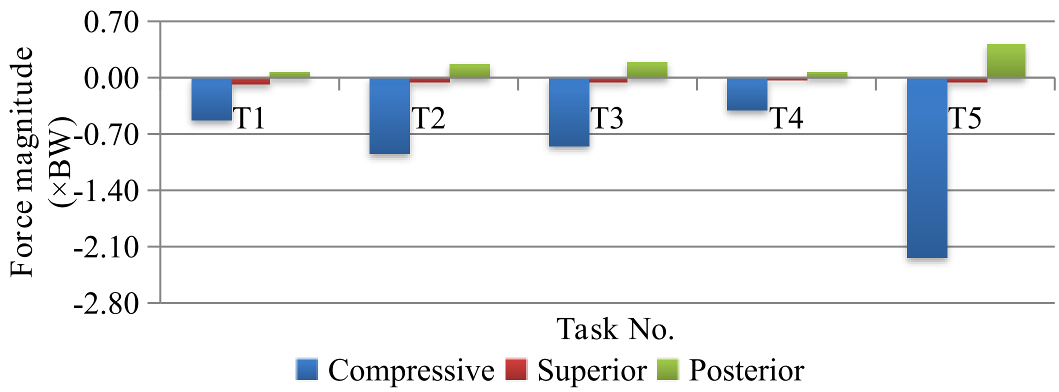
(a)



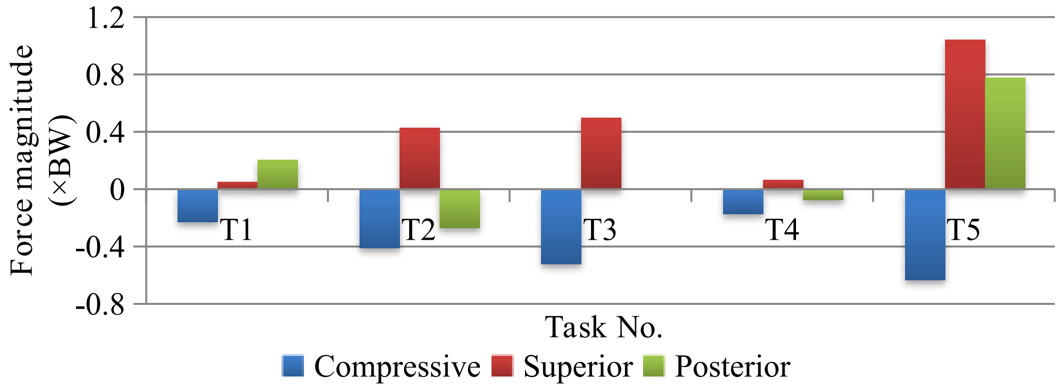
(b)



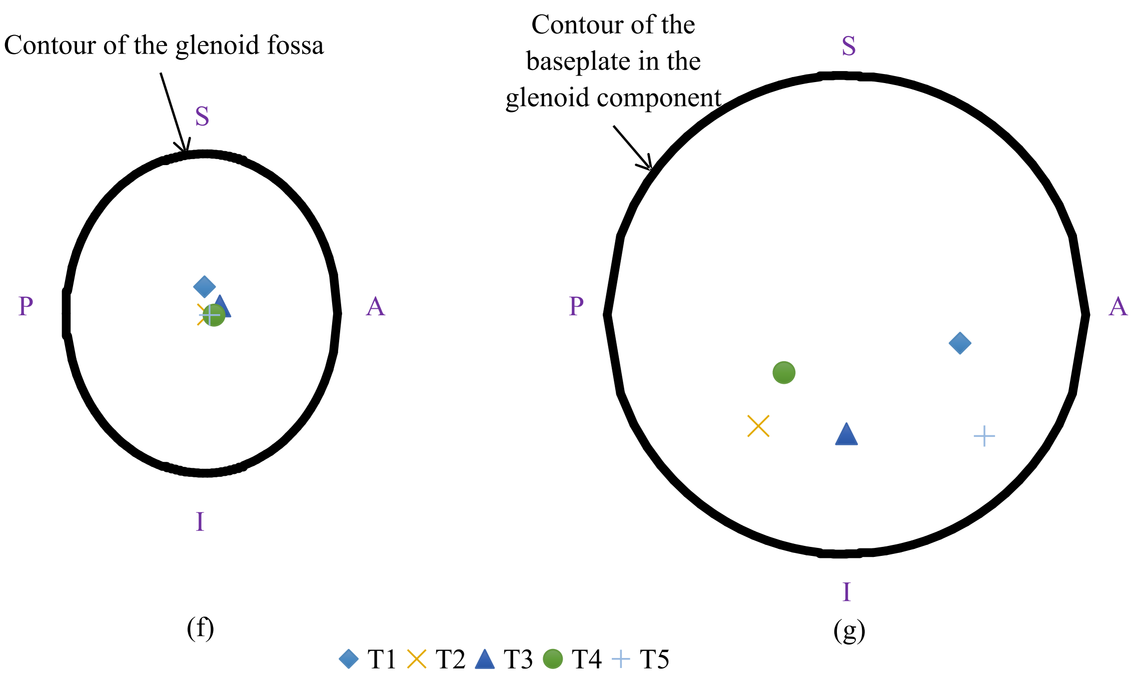
(c)


0.70
0.00
-0.70
-1.40
-2.10
-2.80
Force magnitude (×BW)
T1
T2
T3
T4
T5
Task No.
Compressive
Superior
Posterior

(d)


1.2
0.8
0.4
0
-0.4
-0.8
Force magnitude (×BW)
T1
T2
T3
T4
T5
Task No.
Compressive
Superior
Posterior

(e)


Contour of the glenoid fossa
S
P
A
I
Contour of the baseplate in the glenoid component
S
P
A
I
T1 T2 T3 T4 T5

(f) (g)

(a) Description of the five daily activities simulated in this study. (b) Coordinate system for intact scapula. AI: the inferior angle, AA: the posterior point of acromion, TS: the root of scapular spine; (c) Coordinate system for the finite element model of implanted scapula; (d) Magnitudes of glenohumeral force for a normal shoulder during the five daily activities shown in (a); (e) Magnitudes of glenohumeral force for a Delta reverse total shoulder arthroplasty during the five daily activities shown in (a); (f) Positions of loading of the glenohumeral force in a normal shoulder; (g) Positions of loading of the glenohumeral force in a Delta reverse total shoulder arthroplasty (modified from Kontaxis, 2010). T1-5: Task 1-5 in (a). A/P/S/I: Anterior/Posterior/Superior/Inferior.