International Orthopaedics (SICOT)
DOI 10.1007/s00264-015-2984-3

ORIGINAL PAPER

Effect of humeral stem design on humeral position and range of motion in reverse shoulder arthroplasty

Alexandre Lädermann[1,2,3] · **Patrick J. Denard**[4,5] · **Pascal Boileau**[6] · **Alain Farron**[7] · **Pierric Deransart**[8] · **Alexandre Terrier**[9] · **Julien Ston**[9] · **Gilles Walch**[10]

Received: 27 June 2015 / Accepted: 24 August 2015
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Abstract

Purpose The impacts of humeral offset and stem design after reverse shoulder arthroplasty (RSA) have not been well-studied, particularly with regard to newer stems which have a lower humeral inclination. The purpose of this study was to analyze the effect of different humeral stem designs on range of motion and humeral position following RSA.

Methods Using a three-dimensional computer model of RSA, a traditional inlay Grammont stem was compared to a short curved onlay stem with different inclinations (155°, 145°, 135°) and offset (lateralised vs medialised). Humeral offset, the acromiohumeral distance (AHD), and range of motion were evaluated for each configuration.

Results Altering stem design led to a nearly 7-mm change in humeral offset and 4 mm in the AHD. Different inclinations of the onlay stems had little influence on humeral offset and larger influence on decreasing the AHD. There was a 10° decrease in abduction and a 5° increase in adduction between an inlay Grammont design and an onlay design with the same inclination. Compared to the 155° model, the 135° model improved adduction by 28°, extension by 24° and external rotation of the elbow at the side by 15°, but led to a decrease in abduction of 9°. When the tray was placed medially, on the 145° model, a 9° loss of abduction was observed.

Conclusions With varus inclination prostheses (135° and 145°), elevation remains unchanged, abduction slightly decreases, but a dramatic improvement in adduction, extension and external rotation with the elbow at the side are observed.

Keywords Reverse total shoulder arthroplasty · Inlay and onlay design · Reverse tray · Impingement · Humeral offset · Arm position · Range of motion · Complications

Study design: basic science study; computer modeling

✉ Alexandre Lädermann
alexandre.laedermann@gmail.com

1 Division of Orthopaedics and Trauma Surgery, La Tour Hospital, Rue J.-D. Maillard 3, 1217 Meyrin, Switzerland

2 Faculty of Medicine, University of Geneva, Rue Michel-Servet 1, 1211 Geneva 4, Switzerland

3 Division of Orthopaedics and Trauma Surgery, Department of Surgery, Geneva University Hospitals, Rue Gabrielle-Perret-Gentil 4, 1211 Geneva 14, Switzerland

4 Southern Oregon Orthopedics, Medford, OR, USA

5 Department of Orthopaedics and Rehabilitation, Oregon Health & Science University, Portland, OR, USA

6 Department of Orthopaedic Surgery and Sports Traumatology, Hôpital de L'Archet-University of Nice Sophia-Antipolis, 151, Route de St Antoine de Ginestière, 06202 Nice, France

7 Division of Orthopaedics and Trauma Surgery, Department of Surgery, Centre Hospitalier Universitaire Vaudois, Lausanne, Switzerland

8 Tornier SA, Montbonnot Saint-Martin, France

9 Laboratory of Biomechanical Orthopedics, Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland

10 Department of Orthopaedics, Shoulder Unit, Santy Orthopaedic Center and Jean Mermoz Hospital, Lyon, France

Published online: 18 September 2015

Introduction

Clinically, the Grammont reverse shoulder arthroplasty (RSA) led to predictable pain relief and restoration of active elevation in patients with rotator cuff insufficiency [1]. However, several complications or adverse effects have been reported including scapular notching [2], excessive arm lengthening [3, 4], and violation of greater tuberosity bone stock. Additionally, the non-anatomic design of this stem prevents convertibility to or from an anatomic total shoulder arthroplasty (TSA).

To address these problems, several authors have proposed changes in the Grammont design, including humeral cup position and offset, stem design, and humeral inclination [5–7]. Decreasing humeral inclination, that is moving to a more vertical or anatomic inclination, has been shown to increase adduction, which decreases the risk for scapular notching [8]. However, this change also increases humeral offset, which may decrease abduction by leading to impingement of the greater tuberosity upon the acromion and of the lesser tuberosity upon the coracoid.

While the traditional inlay Grammont RSA had a straight stem, some newer designs have a curved stem with or without an eccentric onlay humeral tray (Fig. 1). The goal of the curved stem modification is to preserve tuberosity bone stock, decrease the risk of greater tuberosity fracture, preserve the remaining rotator cuff insertion, optimize ease of insertion, preserve metaphyseal stability, and lastly, to offer intra-operative or post-operative ability to convert between TSA and RSA. While appealing, a curved stem and onlay system both increase offset of humerus and decrease the acromiohumeral distance (AHD) which may lead to acromial impingement with abduction. Finally, eccentricity of a modular onlay humeral tray may impact range of motion (ROM) and humeral position, since offsetting the tray superiorly moves the humerus medially and inferiorly, whereas offsetting the tray inferiorly moves the humerus laterally and superiorly in relation to the scapula (Fig. 2). Our hypothesis was that a curved stem design with an eccentric onlay tray and a lower inclination would increase humeral offset and alter ROM compared to a classic Grammont design.

The purpose of this study was thus to evaluate the effect of (1) stem design, (2) inclination and (3) eccentric tray position on humeral position and ROM in a virtual RSA model.

Materials and methods

Computer model and prosthetic scenarios

A three-dimensional (3D) computer model was developed from computed tomography (CT) images of a cadaveric shoulder without any sign of pathology (www.virtualskeleton.ch). The CT included the entire scapula and humerus as well as a

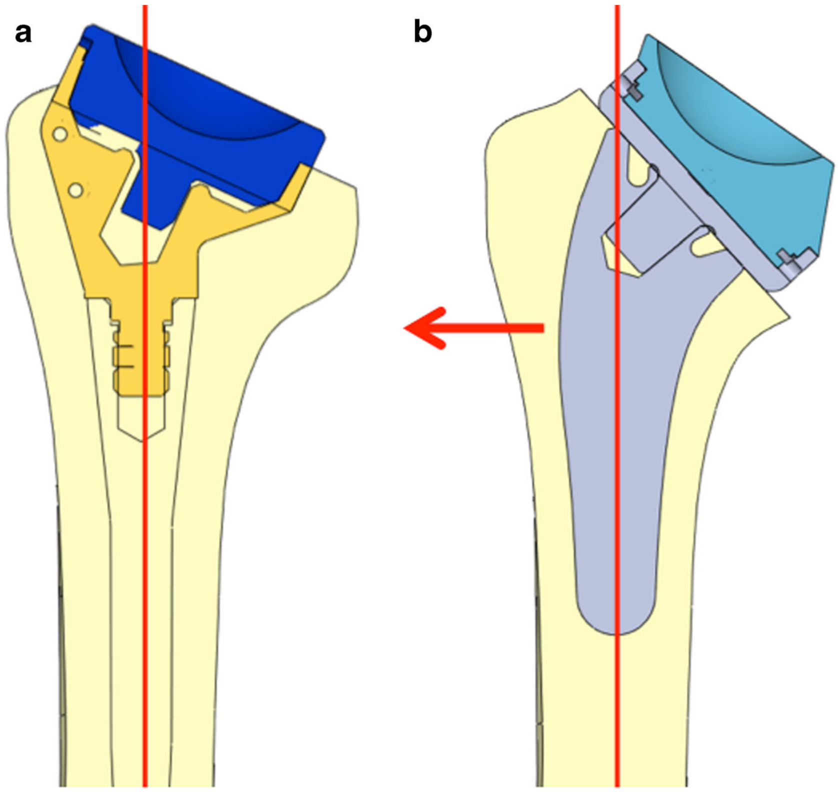

Fig. 1 **a** Traditional inlay Grammont RSA with a straight stem. **b** Example of a new design with a curved stem and an onlay humeral tray. The *red line* passes through the center of the stem. Note that the center of the polyethylene is more medial with the curved stem which results in lateralization of the humerus (*red arrow*)

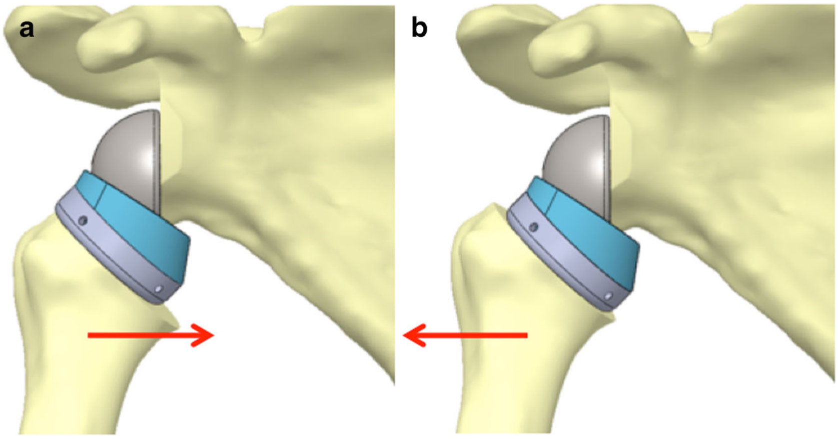

Fig. 2 A modular onlay humeral tray which is may be **a** concentric, **b** have low offset (1.5 mm), or **c** high offset (3.5 mm)

portion of the thoracic ribs. The scapula, humerus, and ribs were segmented using Amira (Visage Imaging, Berlin, Germany). A 3D reconstruction of the bone surface was obtained with Geomagic Studio (Geomagic, Morrisville, NC, USA). The reconstructed bone surface was then superimposed to the CT slices to assess the precision of the reconstruction. The reconstructed scapula, humerus, and ribs were then imported into the computer-aided design (CAD) software SolidWorks (Dassault Systèmes SolidWorks, Concord, MA, USA) to virtually perform an RSA. The virtual RSA was performed under the supervision of two shoulder surgeons (A.L. and G.W.), who agreed on component positioning. In order to limit the analysis to the humeral configuration, a standardised glenoid component was used. The scapula was prepared according to the recommended surgical technique to obtain neutral inclination and version. A 29-mm circular baseplate (Aequalis Reversed; Tornier SAS, Montbonnot, France) was implanted at the inferior edge of the glenoid surface and a 36-mm glenosphere with a centre of rotation at the glenoid surface was placed over the baseplate.

Stem design

For the first model, the humerus was virtually prepared according to the recommended surgical technique to accommodate a traditional Grammont-style stem (Aequalis Reversed; Tornier) at 20° of retroversion [9–11]. The humeral cut of the Grammont RSA positions the humeral component at the top of the humeral head as previously recommended [4]. A 9-mm stem combined with a 36-mm epiphysis and a +6-mm polyethylene humeral insert was used. The final construct had a humeral inclination of 155° (inlay 155°) (Fig. 3a). For the other five models, the humerus was prepared to accommodate a newer short curved anatomical stem (Aequalis Ascend Flex; Tornier) at 20° of retroversion [9–11]. The humeral cut was performed close to the anatomic neck of the humerus. A size-4 stem was used because this corresponds to 9 mm for the Grammont RSA.

Humeral inclination

Different angled polyethylene humeral inserts were applied to the humeral tray of the new stem to obtain onlay inclinations of 155° (Fig. 3b), 145° (Fig. 3c), and 135° (Fig. 3d). A concentric (1.5-mm) humeral tray with a standard +6-mm polyethylene insert was used for each of the three inclinations.

Eccentric tray position

For the 145° implant, a 3.5-mm eccentric humeral tray was also positioned at the two extreme positions along the supero-inferior axis of the humeral cut in order to maximize (infero-medial position) or minimize (supero-lateral position) lateralization (Fig. 3e and f).

The scapula and humerus were positioned to a rest position, according to van Andel et al. [12], and using the recommended joint coordinates system [13]. For each of the six configurations, humeral offset and AHD were measured in the frontal plane based on 2D representations. Although the model allowed 3D assessment, the measurements were made in 2D so that they would be clinically applicable to plain radiographs. Humeral offset was calculated by measuring the horizontal distance from the centre of rotation of the humeral cup to the most lateral aspect of the greater tuberosity (Fig. 4). AHD was calculated by measuring the vertical distance from the infero-lateral aspect of the acromion to the most supero-lateral aspect of the greater tuberosity (Fig. 4).

Kinematic simulation and impingement

For each of the six configurations, as well as the native shoulder, glenohumeral ROM was evaluated by simulating four standardized motions: abduction-adduction, forward flexion-extension, external-internal rotation with the elbow at 10° of abduction and with the elbow at 90° of abduction. According to the International Society of Biomechanics, abduction, flexion and internal rotation were noted positively. Conversely, adduction,

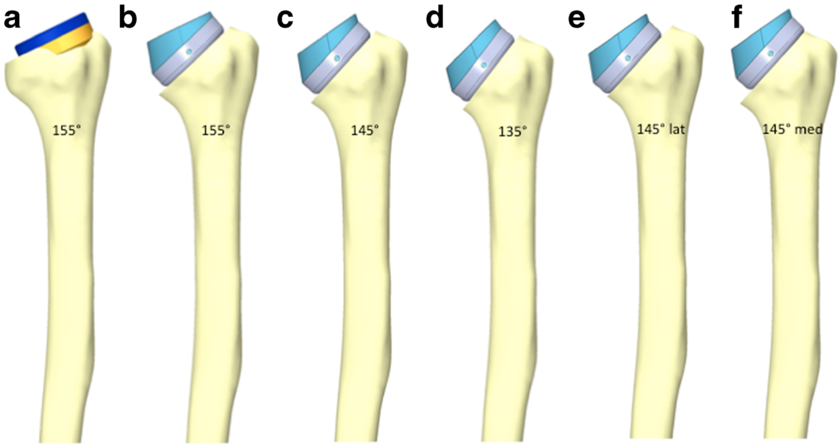

Fig. 3 The six humeral configurations evaluated. **a** Grammont-style 155° inlay straight stem; **b** 155° onlay curved stem with a concentric tray; **c** 145° onlay curved stem with a concentric tray; **d** 135° onlay curved stem with concentric tray; **e** 145° onlay curved stem with an infero-medial eccentric tray (*lat* lateralized); **f** 145° onlay curved stem with a supero-lateral eccentric tray (*med* medialized)

extension and external rotation were noted negatively. All of the motions had a resolution of 1° and were performed in a quasi-static way. The measurements were made by one observer. The two extreme positions of each ROM were evaluated and reported with the corresponding angle (Fig. 5a and b). Inferior impingement was defined as polyethylene contact with the scapular pillar (Fig. 5c). In cases in which no impingement was observed, the maximal native shoulder ROM value was retained. In cases of polyethylene contact, the type of impingement was further classified as *abutment-type* when ROM could not be substantially improved even after simulating polyethylene or bone wear, or a *friction-type* when ROM could be substantially improved by simulating polyethylene or bone wear as clinically observed in notching (Fig. 5d).

Statistical analysis

Linear regression analysis was conducted between humeral offset and ROM, as well as between the AHD and ROM. If no linear regression was established, correlation analysis was conducted. Additionally, for the onlay design, any linear regression related to the final construct inclination was verified.

Results

Influence of stem design on humeral position and ROM

Humeral offset varied by 9 mm, with the smallest offset occurring with the Grammont inlay 155° model and largest occurring with the onlay 135° model (Table 1). Compared to the inlay design, the onlay humeral design with the same 155° inclination increased humeral offset by 6.6 mm. AHD varied by 9.8 mm with the smallest occurring with the onlay 135° model and the largest occurring with the Grammont inlay 155° (Table 1). Compared to the inlay design, the onlay humeral design with the same 155° inclination decreased the AHD by 4.1 mm. Compared to the onlay

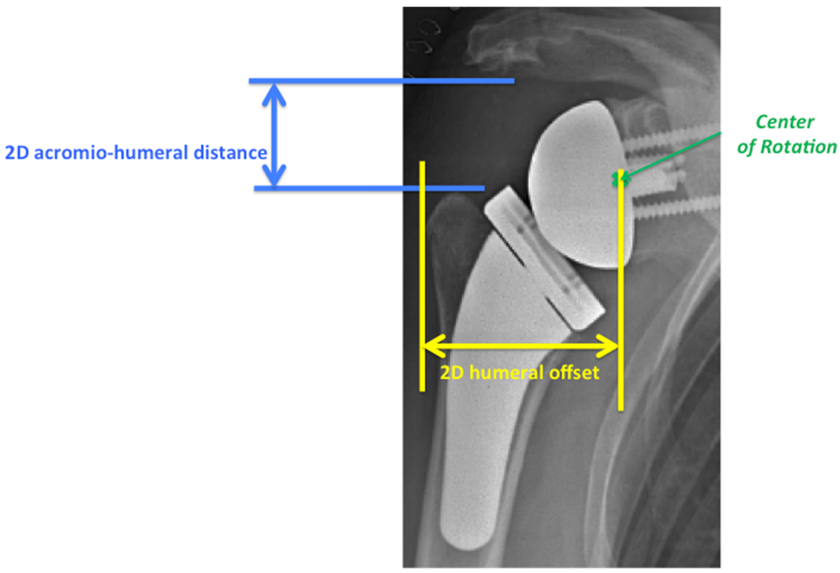

Fig. 4 Humeral offset is the horizontal distance from the center of the polyethylene cup to the most lateral aspect of the greater tuberosity. The acromiohumeral distance (AHD) corresponds to the vertical distance from the infero-lateral aspect of the acromion to the most supero-lateral aspect of the greater tuberosity

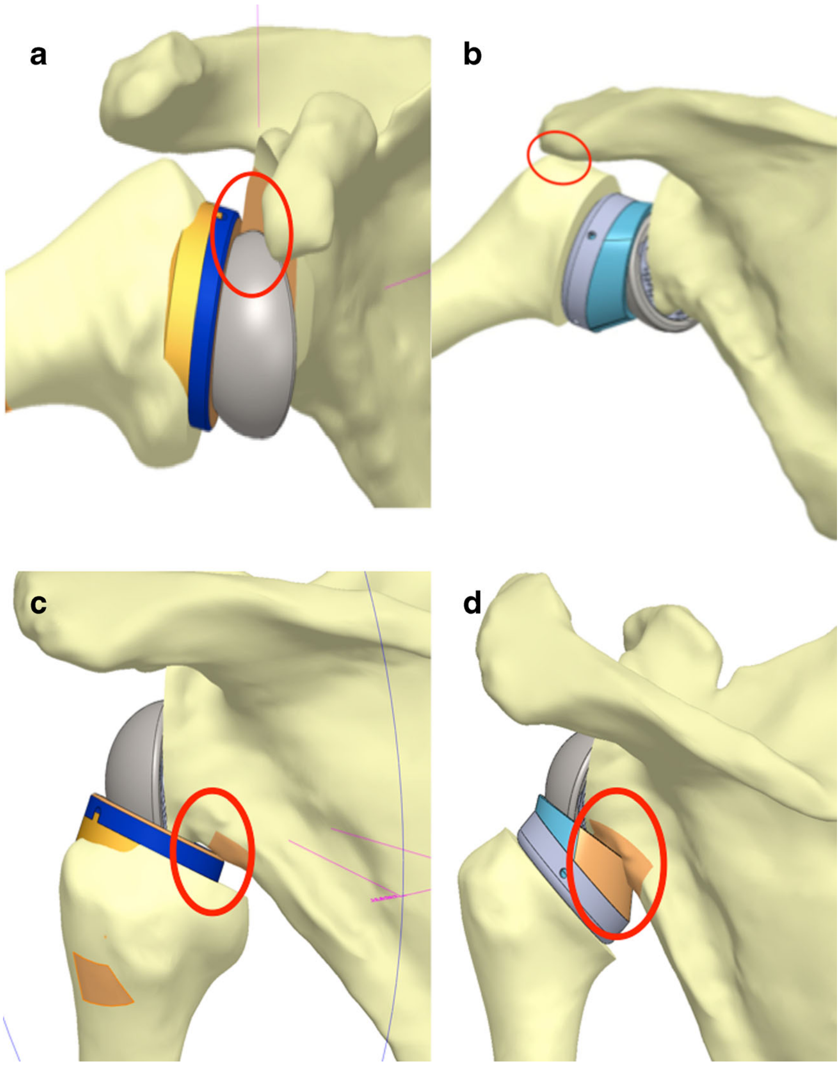

Fig. 5 Measurement of range of motion and types of impingements. Note the abutment-type impingements: **a** the polyethylene with the posterior glenoid; **b** the greater tuberosity with the acromion. **c** A friction-type impingement found for the external rotation of the arm at the side; **d** this could be substantially improved by simulating polyethylene or bone wear as clinically observed in notching

155° model, with the inlay 155° model there was a 10° decrease (77.8° to 67.9°) in abduction and a 5° (range, −15.3° to −20.2°) increase in adduction (Table 2). Additionally, with 155° onlay, flexion increased by 3.3° (range, 105.9-109.2°) and extension increased by 1.9° (range, −6.8° to −8.7°). Internal rotation with elbow at the side was similar among the configurations with no restrictions compared to the native shoulder, while external rotation increased 3.8° with the onlay design. Both configurations achieved native internal and external rotation at 90° of abduction.

Influence of humeral inclination on humeral position and ROM

Within the onlay design, inclination had a smaller influence, with humeral offset only increasing by 3.3 mm when moving from 155° to 135°. Nevertheless, an inverse linear regression

Table 1 Humeral position in relation to the six different prosthetic configurations

	Humeral offset (mm)	Acromiohumeral distance (mm)
Inlay 155°	26.6	29.0
Onlay 155°	33.2	24.9
Onlay 145°	34.2	23.1
Onlay 135°	35.5	19.2
Onlay 145° medial eccentric tray	33.3	26.4
Onlay 145° lateral eccentric tray	35.1	19.7

Table 2 Standardized range of motion for the native shoulder and the six different prosthetic configurations

	Abduction in degrees	Adduction in degrees	Flexion in degrees	Extension in degrees	Internal rotation at 0° in degrees	External rotation at 0° in degrees	Internal rotation at 90° in degrees	External rotation at 90° in degrees
Native shoulder	106.6	−48.7	129.2	−46.0	99.0	−59.7	116.5	−43.0
Inlay 155°	77.8	−15.3	105.9	−6.8	99.0	−15.8	116.5	−43.0
Onlay 155°	67.9	−20.2	109.2	−8.7	99.0	−19.6	116.5	−43.0
Onlay 145°	65.0	−42.8	112.1	−18.7	99.0	−28.1	116.5	−43.0
Onlay 135°	59.5	−48.7	110.5	−32.5	99.0	−34.2	116.5	3.4
Onlay 145° medial	69.6	−42.8	112.1	−18.7	99.0	−28.1	116.5	−43.0
Onlay 145° lateral	60.4	−42.8	111.7	−18.7	99.0	−28.1	116.5	−1.9

was found between humeral offset and the different inclinations of the onlay design (R^2 = −0.994). Within the onlay design, inclination had a slightly larger influence, with the AHD decreasing by an additional 5.7 mm when moving from 155° to 135°. As for humeral offset, a linear regression was found between AHD and the different inclinations of the onlay design (R^2 = 0.958). Within the onlay design there was a strong linear regression between inclination and abduction (R^2 = 0.970), adduction (R^2 = 0.997), extension (R^2 = 0.992), and external rotation with the elbow at the side (R^2 = 0.991) (Table 2). There was a 12.4° (range, 67.9–59.5°) decrease in abduction and a 28.5° (range, −20.2° to −48.7°) increase in adduction with a 135° inclination compared to a 155° inclination. No design restored native abduction, and only the 135° model achieved native adduction. Flexion increased by 1.3° and extension increase by 23.8° with the 135° inclination compared to the 155° inclination. External rotation with elbow at the side increased 14.6° (range, −19.6° to −34.2°) with the 135° inclination. No constructs with elbow at the side achieved external rotation of the native shoulder. At 90° of abduction, all inclinations achieved native shoulder motion in internal rotation. However, a large deficit was observed in external rotation for the 135° model in contrast to the 145° and 155° models which achieved native ROM.

Influence of humeral eccentric tray position on humeral position ROM

Similar to inclination, the eccentric tray position had little influence with humeral offset only increasing by 1.8 mm when moving from the supero-lateral position to the infero-medial position. AHD decreased by 6.7 mm when moving from the most medial configuration to the most lateral configuration. There was a 9.2° (range, 69.6–60.4°) decrease in abduction when the eccentric tray was rotated from a supero-lateral position to an infero-medial position (Table 2). Conversely, no influence was observed on adduction, flexion, extension, or external rotation with the elbow at the side. While internal rotation 90° of abduction did not vary by position, a deficit was observed for the infero-medial position of the eccentric tray.

Type of impingement

Limitation in abduction comes from an *abutment-type* impingement (Table 3). But while with the original Grammont inlay design this abutment occurred between the polyethylene humeral cup and the glenoid face (Fig. 5a), with the onlay design this *abutment* occurred between the humeral bone and the acromion (Fig. 5b). Such bone-to-bone abutment was also the cause of limited external rotation of the arm at 90° of abduction observed for the 135° onlay model as well as the supero-lateral configuration of the onlay design at 145°. *Abutment* of the polyethylene humeral insert with the scapular pillar was observed in adduction (Fig. 5c) for all configurations except the 135° onlay. Conversely, in the other configurations, the limited extension was due to a *friction-type* impingement (Fig. 5d). Such friction-type impingements were also found for external rotation with the arm at the side in all configurations.

Discussion

RSA with a traditional Grammont design greatly improved the ability to treat patients with rotator cuff disorders. However, with this design, scapular notching is commonly observed and increases in frequency and severity as follow-up lengthens [2]. Moreover, reliable improvement in internal and external rotation is not observed [14]. A variety of changes in prosthetic design have been proposed to address these issues. On the humeral side, onlay designs with a more anatomic inclination and curved stem have been introduced. In addition to decreasing notching and improving rotation, such designs are intended to facilitate prosthetic convertibility and preserve tuberosity bone stock. However, the consequences of such changes have not been thoroughly analyzed independently from the glenoid side. The goal of this study was, therefore, to analyze the consequences of specific humeral component design changes on humeral position and ROM.

Humeral offset was heavily influenced by prosthetic design. The onlay stem in this study led to a 7-mm increase in

Table 3 Impingement for the six different prosthetic configurations

	Abduction	Adduction	Extension	External rotation arm at side	External rotation arm at 90° abduction
Inlay 155°	Abutment	Abutment	Friction	Friction	
	PE to bone	PE to bone	PE to bone	PE to bone	
Onlay 155°	Abutment	Abutment	Friction	Friction	
	bone to bone	PE to Bone	PE to bone	PE to bone	
Onlay 145°	Abutment	Abutment	Friction	Friction	
	bone to bone	PE to bone	PE to bone	PE to bone	
Onlay 135°	Abutment		Abutment	Friction	Abutment
	bone to bone		PE to bone	PE to bone	bone to bone
Onlay 145° medial	Abutment	Abutment	Friction	Friction	
	bone to bone	PE to bone	PE to bone	PE to bone	
Onlay 145° lateral	Abutment	Abutment	Friction	Friction	Abutment
	bone to bone	PE to bone	PE to bone	PE to bone	bone to bone

*PE*polyethylene

humeral offset compared with the traditional inlay Grammont prosthesis. On the other hand, by changing inclination from 155° to 135° within the onlay design, humeral offset only increased by about 2 mm. Similarly, position of the eccentric metallic tray altered humeral offset by less than 2 mm. Therefore, humeral offset is affected more by the curved stem design than by inclination or tray position. In this study, humeral offset had a linear regression with abduction (R^2 = 0.883) and a weaker linear regression with flexion and external rotation with the arm at the side (R^2 = 0.748 and R^2 = 0.707 respectively).

AHD was influenced by all of the humeral factors examined in this study. AHD decreased by 4 mm going from the 155° inlay Grammont stem to a 155° onlay stem. Within the onlay design, AHD decreased a further 6 mm going from 155° to 135°. Finally with the 145° stem, AHD varied by 7 mm within the two extreme offset positions allowed by the humeral tray. Previous studies have shown that arm lengthening (reflected by AHD) is related to improvement in forward flexion following RSA with a Grammont style prosthesis [15, 16]. The current study supports this concept as we observed a strong linear regression (R^2 = 0.961) between AHD and abduction. One clinical study did not find any relationship between arm lengthening and forward flexion following RSAs with a 135° inclination design [17]. However, they did not compare different configurations as done in the current study and they used varying glenosphere offsets. While arm lengthening improves forward flexion, it has also been shown to be a risk factor for nerve injury after a Grammont style prosthesis [18]. On the other hand, there are no reports of post-operative neurologic impairment related to excessive humeral offset following RSA.

In this study, the 135° model led to a substantial limitation of external rotation with the arm at 90° abduction. This finding is important as such external rotation is a major factor in the ability to perform activities of daily activities such as hair care and facial grooming. While both the 135° and 145° models increased humeral offset, the 145° model was closer to the AHD observed with a Grammont RSA. It appears that increased AHD limits bony abutment in external rotation with the arm in abduction. Therefore, the 145° onlay stem may represent the optimal compromise in ROM, with limited change in humeral position compared to a traditional Grammont RSA.

The present study demonstrates, as previously observed by Nyffeler et al. [19] and Virani et al. [20], that adduction is limited by abutment between the inferior polyethylene abutment and the scapular pillar, whereas abutment in abduction may occur either between the superior polyethylene and the glenoid or between the acromion and the greater tuberosity. With a Grammont RSA we observed that abduction was limited by abutment of the polyethylene insert with the glenoid surface. However, humeral offset via an onlay stem shifted abduction abutment to the acromion and greater tuberosity (Fig. 5b). Such abutment likely explains the decreased abduction observed with lateralizing humeral components in this study. Similarly, other studies have noted that abduction with an RSA decreases as humeral inclination becomes more anatomic [5, 20]. Conversely, with a 135° or 145° inclination we noted a dramatic improvement in adduction compared to the Grammont prosthesis. Additionally, our study showed that external rotation at the side and extension are dramatically improved with a more anatomic inclination angle. This finding is important as external rotation with the elbow at the side and extension led to *friction* between the scapular pillar and the polyethylene insert (Fig. 5d). This friction phenomenon does not limit ROM but likely contributes to progressive polyethylene wear and scapular notching. Therefore, a more anatomic inclination angle may decrease notching not only by decreasing abutment in adduction, but also by improving rotation and extension. Virani et al. [20] also found external rotation is optimized with a more anatomic humeral inclination as well as a large glenosphere implanted inferiorly. In a recent study, Berhouet et al. [9] demonstrated that glenoid lateralization and a 42-mm sphere size significantly improved internal and external ROM. Other authors reported that inferior translation and glenoid lateralization improved rotation significantly [21, 22]. Since inferior impingement between the polyethylene and the scapula is systematic with the arm at the side, another potential way to limit friction and notching in external rotation would be to create a notch in the polyethylene inferiorly between 3 and 9 o'clock as has been done in some prostheses (e.g., Arrow and SMR). Similarly to Berhouet et al. [23], we observed that the tray position had no influence on the adduction and forward flexion, but had an impact on abduction and on external rotation with the arm at 90° abduction.

Strengths and limitations

To our knowledge, this is the first study which specifically investigates the combined effect of stem design (inlay vs onlay), humeral inclination angle, and eccentric tray position on humeral position and ROM independent of glenoid configuration. However, there are several limitations to this study. First, the computer model was developed from one cadaveric shoulder without any sign of pathology. This unique morphological study prevented us from analyzing patient-related factors that may impact post-operative ROM. Normal or pathologic changes related to human scapular morphology may also lead to significant differences [24]. Another limitation of this study is the omission of soft tissue tension which can restrict ROM, particularly in revision or post-traumatic cases. Thirdly and finally, the goal of our study was limited to analyzing the influence of humeral offset and inclination angle and was not to analyze the influence of the glenoid configuration. Therefore we cannot comment about the influence of glenoid size or position regarding notching and ROM. However, previous studies have explored these factors, and based on this, we chose to focus on the humeral side to gain a better understanding of the influence of new humeral designs. Future work should investigate whether glenoid offset or humeral offset has a similar impact on ROM and muscles tension.

Conclusion

Humeral stem design and humeral inclination change ROM after RSA. Compared to a classic Grammont prosthesis, by using varus inclination prostheses (135° and 145°) forward flexion remains unchanged and abduction decreases, but a dramatic improvement in adduction, extension, and external rotation with the elbow at the side is observed. However, only the 145° construct maintains external rotation with the arm at 90° of abduction. While both 135° and 145° increased humeral offset, the 145° prosthesis was closer to AHD observed with a Grammont RSA. Therefore, the 145° onlay stem may represent the optimal compromise in ROM, with limited change in humeral offset compared to a traditional Grammont RSA.

Conflicts of interest Two authors (G.W., P.B.) of this study received royalties from Tornier. One author (P.J.D.) is a paid consultant for Arthrex. One author (P.D.) of this study is employee and held stock from Tornier.

References

1. Wall B, Nove-Josserand L, O'Connor DP, Edwards TB, Walch G (2007) Reverse total shoulder arthroplasty: a review of results according to etiology. J Bone Joint Surg Am 89:1476–1485. doi:10.2106/JBJS.F.00666
2. Mélis B, DeFranco M, Lädermann A, Mole D, Favard L, Nerot C, Maynou C, Walch G (2011) An evaluation of the radiological changes around the Grammont reverse geometry shoulder arthroplasty after eight to 12 years. J Bone Joint Surg (Br) 93:1240–1246. doi:10.1302/0301-620X.93B9.25926
3. Lädermann A, Edwards TB, Walch G (2014) Arm lengthening after reverse shoulder arthroplasty: a review. Int Orthop 38:991–1000. doi:10.1007/s00264-013-2175-z
4. Lädermann A, Williams MD, Mélis B, Hoffmeyer P, Walch G (2009) Objective evaluation of lengthening in reverse shoulder arthroplasty. J Shoulder Elb Surg 18:588–595. doi:10.1016/j.jse.2009.03.012
5. Gutierrez S, Levy JC, Frankle MA, Cuff D, Keller TS, Pupello DR, Lee WE 3rd (2008) Evaluation of abduction range of motion and avoidance of inferior scapular impingement in a reverse shoulder model. J Shoulder Elb Surg 17:608–615. doi:10.1016/j.jse.2007.11.010
6. Skikumaran U, Salari N, Garzon-Muvdi J, Skolasky R, Peterson S, Tantisricharoenkul G, McFarland EG (2013) Prosthetic design of reverse total shoulder arthroplasty contributes to scapular notching and instability. Twelveth InternationalCongress of Shoulder and Elbow Surgery, April 10-13, Nagoya, p 180
7. Trouilloud P, Gonzalvez M, Martz P, Charles H, Handelberg F, Nyffeler RW, Baulot E, Duocentric G (2014) Duocentric(R) reversed shoulder prosthesis and Personal Fit(R) templates: innovative strategies to optimize prosthesis positioning and prevent scapular notching. Eur J Orthop Surg Traumatol 24:483–495. doi:10.1007/s00590-013-1213-2
8. Gutierrez S, Comiskey CA, Luo ZP, Pupello DR, Frankle MA (2008) Range of impingement-free abduction and adduction deficit after reverse shoulder arthroplasty. Hierarchy of surgical and implant-design-related factors. J Bone Joint Surg Am 90:2606–2615. doi:10.2106/JBJS.H.00012
9. Berhouet J, Garaud P, Favard L (2013) Evaluation of the role of glenosphere design and humeral component retroversion in avoiding scapular notching during reverse shoulder arthroplasty. J Shoulder Elb Surg. doi:10.1016/j.jse.2013.05.009
10. Gulotta LV, Choi D, Marinello P, Knutson Z, Lipman J, Wright T, Cordasco FA, Craig EV, Warren RF (2012) Humeral component retroversion in reverse total shoulder arthroplasty: a biomechanical study. J Shoulder Elb Surg 21:1121–1127. doi:10.1016/j.jse.2011.07.027

11. Stephenson DR, Oh JH, McGarry MH, Rick Hatch GF III, Lee TQ (2011) Effect of humeral component version on impingement in reverse total shoulder arthroplasty. J Shoulder Elb Surg 20:652–658. doi:10.1016/j.jse.2010.08.020
12. van Andel CJ, Wolterbeek N, Doorenbosch CA, Veeger DH, Harlaar J (2008) Complete 3D kinematics of upper extremity functional tasks. Gait Posture 27:120–127. doi:10.1016/j.gaitpost.2007.03.002
13. Wu G, Siegler S, Allard P, Kirtley C, Leardini A, Rosenbaum D, Whittle M, D'Lima DD, Cristofolini L, Witte H, Schmid O, Stokes I (2002) ISB recommendation on definitions of joint coordinate system of various joints for the reporting of human joint motion—part I: ankle, hip, and spine. International Society of Biomechanics. J Biomech 35:543–548
14. Sirveaux F, Favard L, Oudet D, Huquet D, Walch G, Mole D (2004) Grammont inverted total shoulder arthroplasty in the treatment of glenohumeral osteoarthritis with massive rupture of the cuff. Results of a multicentre study of 80 shoulders. J Bone Joint Surg (Br) 86:388–395
15. Jobin CM, Brown GD, Bahu MJ, Gardner TR, Bigliani LU, Levine WN, Ahmad CS (2012) Reverse total shoulder arthroplasty for cuff tear arthropathy: the clinical effect of deltoid lengthening and center of rotation medialization. J Shoulder Elb Surg 21:1269–1277. doi:10.1016/j.jse.2011.08.049
16. Lädermann A, Lubbeke A, Collin P, Edwards TB, Sirveaux F, Walch G (2011) Influence of surgical approach on functional outcome in reverse shoulder arthroplasty. Orthop Traumatol Surg Res 97:579–582. doi:10.1016/j.otsr.2011.04.008
17. Schwartz DG, Cottrell BJ, Teusink MJ, Clark RE, Downes KL, Tannenbaum RS, Frankle MA (2014) Factors that predict postoperative motion in patients treated with reverse shoulder arthroplasty. J Shoulder Elb Surg 23:1289–1295. doi:10.1016/j.jse.2013.12.032
18. Lädermann A, Lubbeke A, Melis B, Stern R, Christofilopoulos P, Bacle G, Walch G (2011) Prevalence of neurologic lesions after total shoulder arthroplasty. J Bone Joint Surg Am 93:1288–1293. doi:10.2106/JBJS.J.00369
19. Nyffeler RW, Werner CM, Gerber C (2005) Biomechanical relevance of glenoid component positioning in the reverse Delta III total shoulder prosthesis. J Shoulder Elb Surg 14:524–528. doi:10.1016/j.jse.2004.09.010
20. Virani NA, Cabezas A, Gutierrez S, Santoni BG, Otto R, Frankle M (2013) Reverse shoulder arthroplasty components and surgical techniques that restore glenohumeral motion. J Shoulder Elb Surg 22:179–187. doi:10.1016/j.jse.2012.02.004
21. Li X, Knutson Z, Choi D, Lobatto D, Lipman J, Craig EV, Warren RF, Gulotta LV (2013) Effects of glenosphere positioning on impingement-free internal and external rotation after reverse total shoulder arthroplasty. J Shoulder Elb Surg 22:807–813. doi:10.1016/j.jse.2012.07.013
22. Mizuno N, Denard PJ, Raiss P, Walch G (2012) The clinical and radiographical results of reverse total shoulder arthroplasty with eccentric glenosphere. Int Orthop 36:1647–1653. doi:10.1007/s00264-012-1539-0
23. Berhouet J, Kontaxis A, Gulotta LV, Craig E, Warren R, Dines J, Dines D (2015) Effects of the humeral tray component positioning for onlay reverse shoulder arthroplasty design: a biomechanical analysis. J Shoulder Elb Surg 24:569–577. doi:10.1016/j.jse.2014.09.022
24. Berhouet J, Garaud P, Slimane M, Nicot J, Banah J, Waynberger E, Favard L (2014) Effect of scapular pillar anatomy on scapular impingement in adduction and rotation after reverse shoulder arthroplasty. Orthop Traumatol Surg Res 100:495-502. doi:10.1016/j.otsr.2014.03.021