Kinematics study of the deltoid in Reverse Shoulder Arthroplasty using Standard Pre and Post-Operative X-Rays

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Abstract:

For patients with deficient rotator cuff Reverse Shoulder Arthroplasty, in which the centre of rotation of the glenohumeral joint is repositioned, is a popular treatment. However, for optimal restoration of motion after RSA, the correct implant selection and positioning within the bones is critical for a successful surgical outcome. This paper examines current practice of implant insertion and predicts what would be its mechanical advantage by using a developed graphical user interface importing pre and post-operative shoulder X-rays.

Standardised X-rays of 8 shoulder griddle pre and post-operative were provided in the true anteroposterior (Grashey) view. Images were then calibrated and key geometrical parameters were identified in all images. A mathematical model for deltoid excursion and deltoid lever arm in full abduction was developed based on the mechanical model of the shoulder in order to investigate its performance (deltoid) in both native and reverse shoulders.

Results showed that the deltoid lever arm was improved in reverse shoulders for lower abductions. In higher abductions a sudden drop in the lever arm's mechanical advantage was observed. It was also observed that more deltoid excursion occurred in full abduction of reverse shoulders compared to native shoulders.

Keywords: Reverse Shoulder Arthroplasty (RSA), Deltoid, X-Ray, Kinematics

Introduction:

The Shoulder is the one of the most active joints within the human body. Utilised in the majority of daily activities either directly for the moving/carrying of objects or as a source of stability during locomotion. The Rotator Cuff muscle plays an important role in terms of dynamic stability of Glenohumeral joint and a deficient Rotator Cuff may cause pain and lack of motion in the shoulder joint [1–3].

Among all different treatments for shoulders suffering from rotator cuff tear or deficiency, the Reverse Shoulder Arthroplasty (RSA) has shown to give the best possible outcome [4–6]. Between 2012 and 2014, 11,399 shoulder replacements were recorded in the UK. Of all patients with shoulder replacement, RSA has the highest number of 4,127 primary procedures between 2012 and 2014. The majority of revisions (27.27%) were due to instability, followed by cuff insufficiency (18.78%), and infection (13.33%). Considering only reverse shoulder replacement, 37.14% of RSA revision surgeries performed are due to instability of the shoulder joint. RSA shows the highest percentage of first revisions among all type of primary shoulder replacement (42.42%). It has been reported that over a two year period (2012 to 2014) 165 revisions following the primary operation were undertaken in the UK [7]. This number is expected to rise in the coming years, as it will be for hip and knee replacement, with 11 years of follow up showing an increasing cumulative percentage probability of revisions versus years since primary operation. The cumulative revision rate of RSA in the first 18 months after primary replacement is much higher when compared to other types of shoulder replacements. This justifies the need for a better understanding with regard to sources of RSA failures.

Medialisation of Centre of Rotation (CoR) and Deltoid lengthening are cited to be the main advantages of RSA over Total Shoulder Arthroplasty (TSA) in shoulders with Rotator Cuff deficiency [8]. Different studies have shown that moving the COR medially in RSA increases the initial deltoid lever arm resulting in better mechanical advantage. This can compensate for lack of moment intensity in the shoulder joint caused by a dysfunctional rotator cuff [8].

Deltoid lengthening is also addressed as a solution to develop RSA functional outcome of surgery [9].

Biomechanical aspects of reverse shoulder systems have been studied in the past using information extracted from either shoulder images or cadaveric measurements [10, 11] to construct 2D and 3D models of the shoulder and investigate different parameters such as kinematics, involved forces and impingement [12, 13]. Most of these studies focus on the developed biomechanical model of the shoulder and currently there is no shoulder-specific imaging tool to input standard shoulder images and calculate its kinematics.

In this study some key geometrical parameters are extracted from standard X-rays of individuals pre and post-operatively in the neutral arm position. Kinematics of the Glenohumeral joint across the whole range of arm abduction is calculated and simulated based on measured initial geometries and defined kinematics equations using a graphical user interface (GUI) developed in MATLAB (Mathworks, USA).

The kinematics equations relate all independent geometrical parameters to deltoid performance across the whole range of abduction and data can be documented in a database which in the long term can be used to inform surgeons about best implant selection and positioning according to individuals shoulder morphology and dimensions.

***Methods*:**

UK National Health Service (NHS) ethical approval was obtained by the collaborating consultants before the start of this study. A NHS-approved informed consent document for human subjects was read and signed by all patients before participation in the study to allow anonymised X-ray of their shoulders to be used in this study. Eight patients (four women and four men) undergoing RSA at Royal Bournemouth Hospital, Bournemouth, UK were included in this study, with a mean age of 74.6 years (SD 5.8 years) and a mean body mass index (BMI) of 29.7 (SD 6.9). The Rotator cuff tear arthropathy was the main reason for the surgery in all of the participant's shoulders. All shoulders received the same Delta Xtend (DePuy, Warsaw, IN, USA) prosthesis [14].

The X-ray images of the shoulder were taken both pre and post-operatively in the true anteroposterior (Grashey) plane and in the plane of the scapula. Having all images in the Grashey view helps to prevent overlap of the Humeral head and Glenoid fossa [15]. Of all 8 volunteers 2 were incomplete and it did not fully comply with the inclusion criteria and for that reason the X-ray images were excluded from the study.

Imaging inclusion and exclusion criteria:

The scapular plane has a 30^{o} to 45^{o} angular offset from the Coronal plane. To provide the Grashey view while imaging, subjects are asked to rotate posteriorly by 30 to 45 degrees, such that the Scapula plane is parallel to the imaging plate [15, 16]. Although all of the images are taken in the same plane (Grashey view) following the same protocol, it is difficult to prevent overlap of the Humeral head and Glenoid fossa in healthy shoulders, and the Glenosphere and Humerus stem in reverse shoulders, due to variations in the Scapula orientation (15 degrees) between individuals. If the subject is correctly oriented to the imaging plate, the hemispherical Glenosphere should be seen as a semicircle in 2D images. In most cases, however, this does not happen (Figure 1). In this study, the amount of angular offset from the Scapular plane is determined from the calibrated 2D images by Equation 1.

$$\mathrm{Sin}(\delta) = \frac{\emptyset_p}{\emptyset_a} \qquad \text{(eq. 1)}$$

Where δ is the rotation offset from the actual Grashey view, $\emptyset_p$ is the projected diameter of the Glenosphere in the nominal Grashey view, and $\emptyset_a$ is the actual diameter of the Glenosphere.

A rotation offset of 15° is equivalent to a 3.5% error in the medial direction (as Cos(15) = 0.965). If the rotation offset from the Grashey view is more than 15°, the image is not included in the measurements.

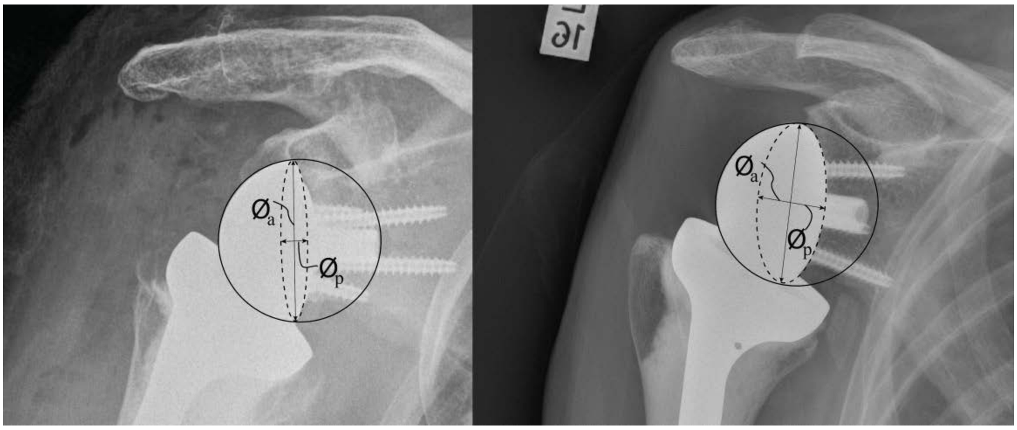

Figure 1: rotation offset calculations for two patients from the same view   left: accepted image   right: eliminated image

X-ray processing:

The initial protocol required a careful positioning and placement of a 26mm diameter steel disc in the same plane as the patient's coronal plane (in line with the shoulder) for calibration. The X-ray images are imported to the GUI in Joint Photographic Experts Group (JPEG) format. The developed GUI (Figure 2) utilising MATLAB is used to calibrate all the dimensions using the image magnification factor measured by selecting two ends of the disc in the image [8]. The COR of the Glenohumeral joint is assumed to be the centre of the native Humeral head in the intact (Native) shoulder. The centre of the Glenosphere in the reverse shoulder is assumed to be the COR which can be estimated by measuring and curve fitting the best-fit circles drawn about the predicted centre. A wider field of view of the shoulder must be taken to enable detection of the deltoid insertion point on the Humerus.

The deltoid muscle is considered as a component with adjustable length acting as a linear actuator, linking its origin and insertion [13, 17]. The deltoid fibre originates from the Inferolateral Acromion tip all the way to the middle of humeral shaft. There it is inserted into the midpoint of the deltoid tuberosity in the middle of the Humeral shaft [8, 18]. Curvature of deltoid tuberosity is differentiated visually and a curve is fitted to it. The middle of the curve is the chosen as deltoid insertion on the humerus. While the patient's arm is at neutral position [8, 10], the distance between these two points dictates the initial Deltoid length. Figure 2, shows the free body diagram representing the biomechanical model of the shoulder superimposed on the X-ray. It consists of the Deltoid muscle, Humerus and Glenohumeral joint.

The Glenohumeral joint has three full rotational degrees of freedom plus a small amount of translation displacement along all three orthogonal axes. In this study translational movement of the Humerus head is neglected and COR of Glenohumeral joint is fixed on the centre of the Glenohumeral head in the anatomic shoulder while in RSA geometries the Glenohumeral joint is totally reversed and moved, hence COR is fixed on the Scapula and is treated as the new centre of the Glenoid [14, 19, 20].

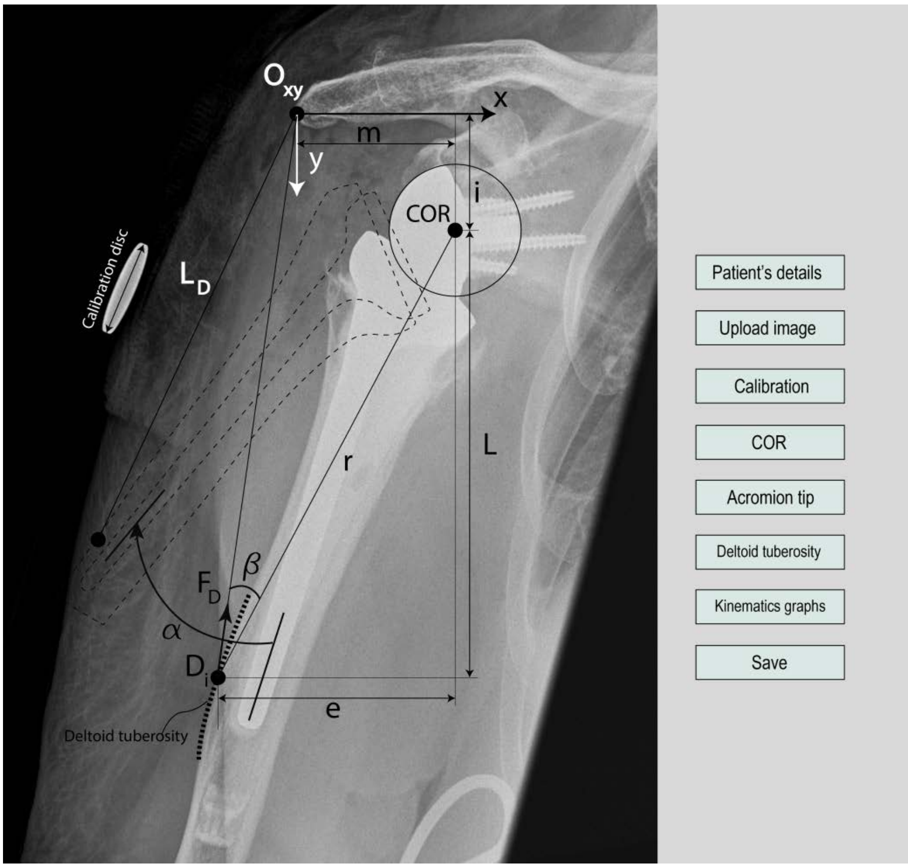

Figure 2 : Developed X-ray processing GUI - geometrical parameters affecting kinematics and dynamics of deltoid in glenohumeral joint abduction

The tip of the Acromion (origin of Deltoid) is chosen as the origin of an orthogonal 2D coordinate system ($\mathbf{O_{xy}}$) with medially oriented **x** axis and is inferiorly parallel to the bodies longitudinal axes oriented **y** axis.

As mentioned previously, standard X-Rays are provided in the Anteroposterior (Grashey) view and all the geometrical parameters are defined in the Scapular 2D plane. Hence in this study kinematics of the deltoid are investigated for abduction in the Scapular plane. All the dimensions are measured and calibrated by a calibration factor in x and y directions.

Definition of Deltoid excursion:

In the developed biomechanical model of the shoulder, the Humerus is considered as a mechanical lever arm (**r**) connecting the COR to $\mathbf{D_i}$ having a rotational degree of freedom around the COR and the Deltoid acts as a linear actuator connecting $\mathbf{O_{xy}}$ to $\mathbf{D_i}$ while providing force ($\mathbf{F_D}$) on the mechanical lever arm (**r**). The mechanical system is described in a 2D coordinate with origin of $\mathbf{O_{xy}}$.

To calculate Deltoid excursion during abduction in the scapular plane, it is assumed that the Glenohumeral joint has one rotational degree of freedom while its translation is neglected [21]. The length of the Deltoid at any given abduction angle is addressed as deltoid excursion and calculated using Equations 2 and 3

$$L_{deltoid} = \sqrt{[m - L_0 * sin(a + \tan^{-1}(e/L))]^2 + [i + L_0 * cos(a + \tan^{-1}(e/L))]^2} \quad \text{(eq. 2)}$$

$$L_0 = \sqrt{L^2 + e^2} \quad \text{(eq. 3)}$$

Where; m = horizontal (medial) distance between COR and tip of Acromion; i = vertical (inferior) distance between COR and tip of Acromion; L_0 = Initial Deltoid length at neutral arm position; L = vertical distance between COR and Deltoid insertion on Humerus; e = horizontal distance between COR and Deltoid insertion on Humerus; θ = angle of abduction in Scapular plan.

Definition of moment arm:

The generated moment in the Glenohumeral joint to abduct the arm is calculated by Equation 4.

$$M_D = F_D * r * \sin(\beta) \text{ and } \beta = a + \tan^{-1}(e/L) - \tan^{-1}\left(\frac{L_0 * sin\left(a + \tan^{-1}(e/L)\right) - m}{L_0 * cos(a + \tan^{-1}(e/L)) + i}\right) \quad \text{(eq. 4)}$$

Where; F_D = Force vector generated by Deltoid; r = Vector between COR and Deltoid insertion (Lever arm); β = angle between Deltoid force vector and lever arm.

During full arm abduction both the Glenohumeral and Scapulothoracic joint articulate together while two third of the motion (90 to 120^o) occurs at the Glenohumeral joint and one third at Scapulothoracic joint, known as Scapulohumeral rhythm [22, 23]. The deltoid is the main actuator in Glenohumeral joint articulation, meaning 90 to 120^o of arm motion is dependent on the Deltoid. As wrapping of the Deltoid around the Humerus head takes place in a limited range of low abduction its effect on Deltoid excursion and lever arm is neglected [24–27].

Results:

After Delta Xtend replacement, postoperative radiographs showed that the COR was displaced by 6 mm (SD 4 mm) inferiorly and 25 mm (SD 6 mm) medially relative to the fixed origin of the coordinate system proposed here. Also the Deltoid length was increased initially by 25 mm (SD 7 mm) due to increased Acromiohumeral distance postoperatively causing an additional 17% Deltoid initial elongation. The X-rays results are summarised in Table 1.

Medialisation of the COR is addressed as the main advantage of RSA compared to TSA due to an increase of the Deltoid moment arm. While inferior displacement of the COR associated with Deltoid lengthening leads to a better Deltoid performance after RSA [8, 13].

Table 1: Summary of 6 patient's X-ray measurements

Radiographic measurements			
Measurements	Native Shoulder	Reverse Shoulder	Change
	Mean (SD)	Mean (SD)	Mean (SD)
Deltoid initial length (mm)	137 (13)	162 (12)	25 (7)
Medial distance (mm)	11 (4)	25 (6)	13 (7)
Inferior distance (mm)	28 (2)	34 (5)	6 (4)

Based on geometrical parameters, Deltoid excursion was plotted against Glenohumeral joint abduction angle using Equations 1 and 2 both for native (pre-op) and reverse shoulders (post-op). As shown in Figure 3, Deltoid contraction in native shoulders showed a constant slope for the whole range of abduction while in the reverse shoulder, from the neutral arm position until almost 90^{o} of abduction, the deltoid contracts with a flatter gradient. At higher abduction, the Deltoid length remains constant meaning the muscle is reluctant to contract anymore.

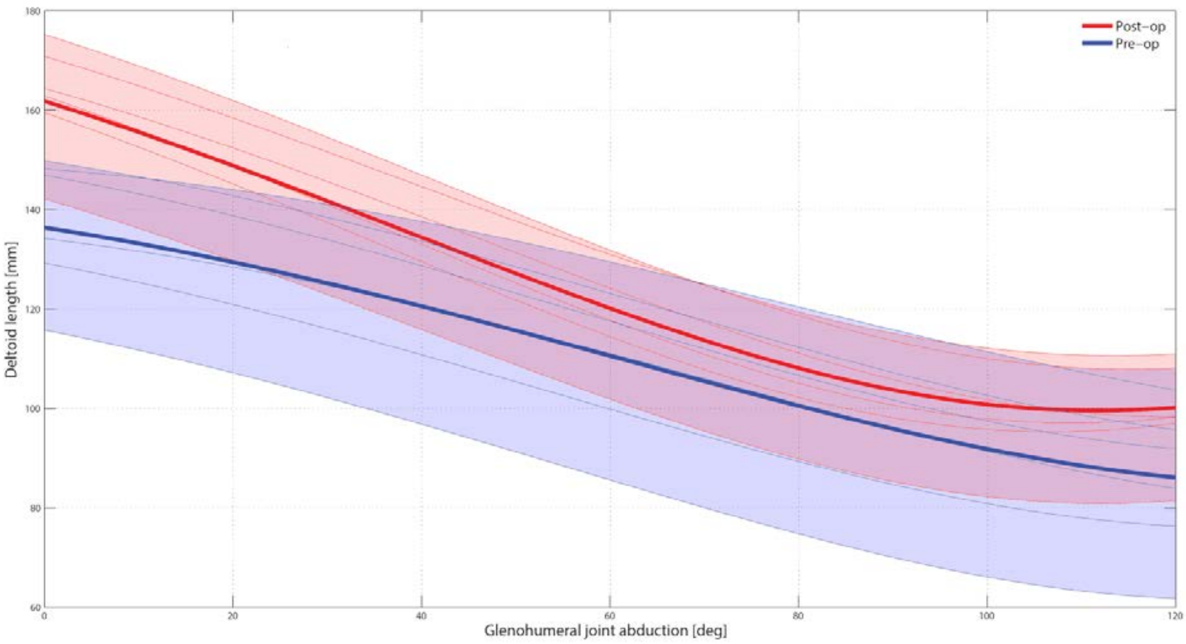

Figure 3: deltoid excursion versus Glenohumeral abduction.
Solid lines: average of all patients. Transparent ones: ±SD

Mechanical work generated in the Deltoid to abduct the arm is defined in Equation 5.

$$W = F \times d \qquad \text{(eq.5)}$$

Where **F** is muscle force and **d** is muscle excursion. Observed quasi-zero Deltoid excursion in higher abduction in the reverse shoulder is equivalent to zero displacement of the muscle in Equation 5 where no mechanical work is generated by the Deltoid and the mechanism locks.

Medialisation of the COR in reverse shoulders increased the initial lever arm of the Deltoid at the neutral arm position by 206%. However, the effect of improved lever arm in reverse shoulder is more dominant in lower abduction. In higher abductions (approximately 60^o) a sudden drop in reverse shoulder lever arm is observed. At approximately 110^o of Glenohumeral abduction the Deltoid has no lever arm and no further abduction can occur.

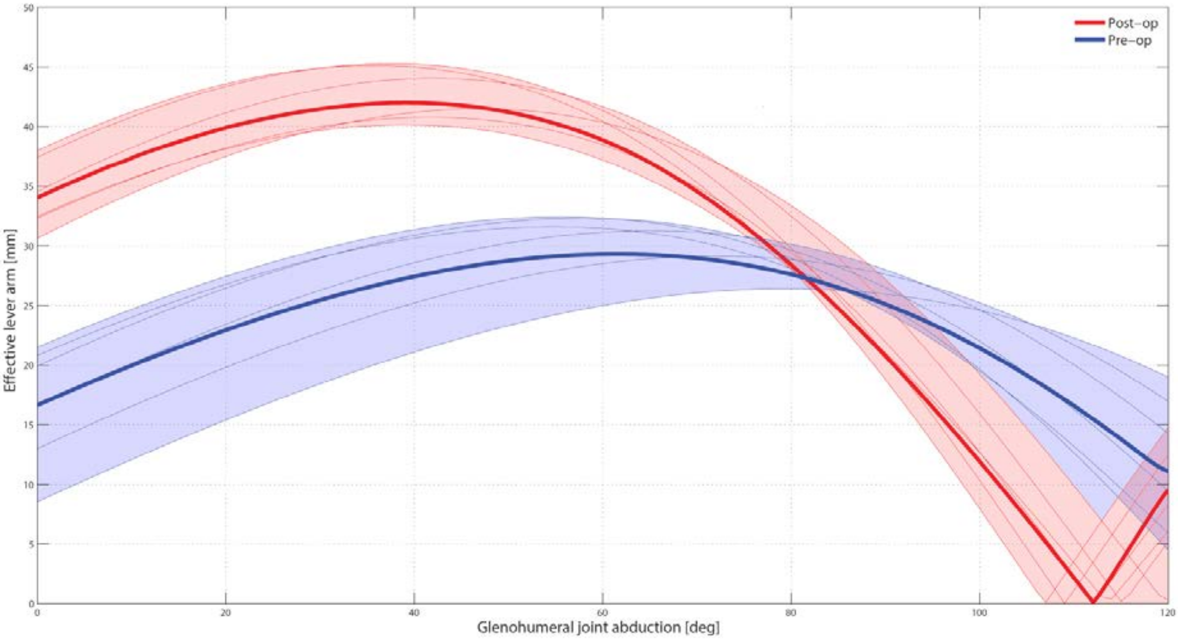

Figure 4: Deltoid effective lever arm versus Glenohumeral abduction.
Solid lines: average of all patients. Transparent ones: ±SD

Discussion:

The cumulative revision rate of RSA in the first 18 months after primary replacement is currently much worse when compared to other types of shoulder replacements. This means RSA shows the highest percentage of first revisions among all types of primary shoulder replacement with 42.42% while 27.27% of revisions are due to instability of the shoulder joint [7]. All of the above can be due to unknown (excess or insufficient) levels of initial/residual tension in the Deltoid or contact force at the joint as well as improper positioning of implants.

RSA is the most common implant option for shoulders with rotator cuff deficiency where Humeral head migration causes pain and lack of motion [4–6]. There are a large number of factors influencing the outcomes of RSA. These include the indication for surgery, surgeon's experience, characteristics of the implant, characteristics of the surgical technique, type of approach and postoperative rehabilitation, among others [6, 28].

Correct implant selection and positioning into bones play an important role in the outcome of surgery. To find the optimum implant size and right positioning for individuals, the effect of geometrical parameters on the kinematics of the shoulder pre and postoperatively needs to be investigated and better understood. The considered geometrical parameters directly affect the modified lever arm, Deltoid performance and its excursion.

Although there are some imaging and documentation protocols addressed in the literature [9, 14] the effect of anatomical and prosthetic geometrical parameters on Deltoid performance have not been well understood. In this study it is proposed that uniform and standardised X-ray images need to be obtained and analysed using a GUI developed here for detailed analysis in order to better understand the link between mechanical advantage and geometrical parameters.

A mathematical model of the shoulder joint was developed (Figure 2) that uses extracted geometrical data to calculate and simulate the differences in kinematics and mechanical advantages before and after RSA. The geometrical parameters can then be inserted into kinematics equations to calculate muscle excursion and moment lever arm for a whole range of arm abduction.

Initial COR medialisation and Deltoid lengthening is observed in all the patients. Based on the measured parameters, Deltoid excursion and moment lever arm in the Glenohumeral are plotted for the whole range of abduction. Increased moment intensity due to COR medialisation in RSA is in agreement with literature although it does not show a constant trend and drops at higher abduction angles. Deltoid lengthening in literature is addressed as initial increase of the Deltoid length in the neutral arm position while Deltoid excursion in reverse shoulders is not well studied. This study shows the Deltoid excurses more in the reverse shoulder than the native shoulder.

Initial Deltoid lengthening increases its performance due to a shift of the muscle working range to the right in Hill-type graphs (Figure 5) [29]. According to the Hill-type muscle model, each muscle is able to provide both passive and active forces according to its length while maximum available active force can be generated at initial muscle length. Available active force decreases as the muscle excurses (contracts) more and more. Arm lengthening in reverse shoulder causes initial shift of muscle stroke to the right in Hill model where bigger passive tension exists in the muscle. While COR medialisation leads to more muscle excursion in the reverse shoulder compared to the native shoulder for the same amount of abduction. Deltoid lengthening associated with medialisation of the COR causes flat gradient of muscle excursion in higher abductions where no mechanical work can be generated. Excessive muscle excursion may also damage axillary nerves [30].

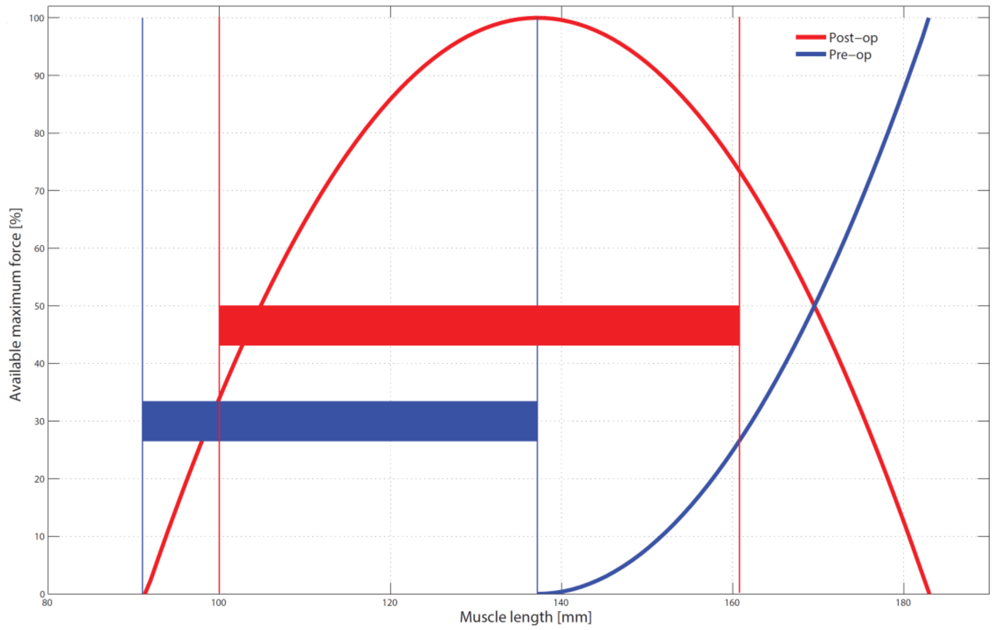

Figure 5: Available active and passive force in deltoid VS muscle length
Solid lines: average of all patients.
Horizontal bars indicate deltoid excursion in full arm abduction Blue: native shoulder, Red: Reverse shoulder

In the long term, an imaging database can be created/developed that includes geometrical and kinematic parameters and their correlation to the outcome of surgery. This database would allow for a more objective assessment of the joint mechanical advantage than the subjective process currently employed. By getting it right first time the number of revision surgeries due to mechanical failure required would be reduced due to better joint force balance and equilibrium. This database should reduce cost due to reduction in the number of revision surgeries, improve and optimise both the range of motion and the mechanical advantage resulting in a better and more deterministic surgical outcome.

Conclusion:

RSA changes geometries and kinematics of the Glenohumeral joint to improve clinical outcome as well as pain relief. However, improved range of motion varies among individuals and currently there is no tool to predict optimum prosthesis size and placement into bones with regard to individual's anatomic morphology.

Despite anatomical differences between individuals' shoulders in terms of size, joints, bone morphology and muscle quality, a healthy shoulder is expected to provide a defined range and amount of manoeuvrability. Anatomic geometries of the shoulder are changed after RSA leading to a new mechanical system with new joint kinematics. To be able to restore the same amount and range of manoeuvrability and functionality as a healthy shoulder after RSA, performance of the Deltoid is crucial. This study defines two key kinematics parameters (Deltoid excursion and Deltoid effective lever arm) that can be calculated from standard X-rays of the shoulder to investigate performance of the Deltoid on the shoulder joint pre and post-operatively.

Currently there is no assessment tool to quantify key geometrical parameters and their influence on kinematics of the shoulder in RSA. A dedicated and user-friendly GUI (developed by the authors using MATLAB), has enabled the standard shoulder X-rays of individuals to be used to extract key geometrical data of the shoulder, pre and post-operatively, to simulate, monitor and compare kinematics of the Deltoid. The kinematic equations/theories presented here relate all independent geometrical parameters to the Deltoid performance throughout the whole range of abduction. The GUI also stores this data in a database which in the long term can be used to inform surgeons about the ideal joint contact force or ideal deltoid load intensity or tension to determine the optimal position and orientation of the implant.

Kinematics of six shoulders during abduction was investigated using standard pre and post-operative X-rays and results are discussed. It must be noted that this study uses a standard X-ray of the shoulder taken in anteroposterior following the same protocol for all the patients. More geometrical parameters can be extracted from other radiographic views to investigate different deltoid sections in different motion scenarios.

Small differences in anatomic and prosthetic geometrical parameters in individuals can have a large influence on the outcome. Under these circumstances and in the absence of quantitative data (sub optimal) even the most experienced surgeon must rely on personal judgment or the most advanced prosthesis will not last or reach the anticipated or the expected life. Implant placements based on better informed and quantified data will assist surgeons to achieve the best possible results first time.

The aim is such information, in the long term will give the surgeon a means to interpolate what would be the ideal implant size and positioning on an individual's bones in order to get it right first time by creating shoulders that are not overloaded, have a good range of motion and will last the life of the user without the need for any revision surgery.

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