ASSESMENT OF KEY PARAMETERS ON THE PERFORMANCE OF THE DELTOID MUSCLE IN REVERSE SHOULDER ARTHROPLASTY – A MODELING AND SIMULATION BASED STUDY

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Reverse Shoulder Arthroplasty (RSA), in which anatomic concavities of glenohumeral joint are inverted, is a popular treatment of arthritic shoulders with deficient rotator cuff. The correct positioning of the glenohumeral centre of rotation and initial setting of the deltoid length (Deltoid Tension) plays an important role in the outcome of the reverse shoulder arthroplasty. A study of the key literature has shown that despite common use of RSA, its biomechanical characteristics during motion are not fully understood. This study investigates the influence of some of the key parameters on the intensity of the moment in a shoulder after RSA during abduction in scapular plane. The kinematics after RSA are then compared with the anatomic shoulder kinematics and differences are discussed.

Mathematical models of both the anatomical and reverse shoulder (RS) were developed in MATLAB and in MSC ADAMS. The anatomical and RSA geometries were defined using measurements obtained from X-Ray and MRI images of the shoulder girdle.

The results show that in RSA, the intensity of the moment generated in the glenohumeral joint improves. However this improvement doesn’t show a constant trend and its intensity can dramatically decrease in higher glenohumeral joint abduction.

Keywords: Rotator Cuff, Reverse Shoulder Arthroplasty (RSA), Deltoid, Shoulder Kinematics, Simulation

1. Introduction

Reverse Shoulder Arthroplasty (RSA): A healthy shoulder has specific characteristics in terms of range of motion, strength and manoeuvrability it can provide. However, in a shoulder with rotator cuff tear deficiency, its characteristics are dramatically compromised. Rotator cuff tear arthropathy (a condition that affects both shoulder strength and stability) can result in severe pain, and difficulty in performing daily activities [1]. There are many discussions regarding shoulder implants [2,3] showing the Reverse Shoulder Arthroplasty (RSA) has emerged as an effective treatment of rotator cuff deficiencies in the shoulder. Despite its success, this procedure has been associated with a relatively high complication rate both intraoperatively [4] and postoperatively [3]. while in some cases revision surgery is needed [5]. These complications include limited range of motion, pain, hematoma formation, infection, scapular notching, instability, acromial insufficiency, and glenoid component failures. In this study we are investigating kinematics of deltoid, discussing solutions to increase effectiveness of deltoid and decrease fracture risk of acromion caused by excessive deltoid pretension.

In RSA, as shown in Fig.1, the anatomic concavities of the glenohumeral joint (GH) are inverted (by removing the humerus head and glenoid fossa). As a result, the centre of rotation is shifted medially and inferiorly relative to the glenoid fossa, increasing the effective deltoid lever arm and deltoid tension resulting in increased range of motion and pain relief [6,7,8,9,10,11].

Despite widespread use of RSA as deficient rotator cuff treatment, a limited amount of data exists regarding the functional outcome; especially with regards to the influence of biomechanical and geometrical elements of the individual's initial anatomic and postoperative prosthesis parameters. Currently there is no information on the importance of, or the link between individuals' initial, anatomical/geometry variations and the locating of the implant system during surgery on the functional outcome of RSA.

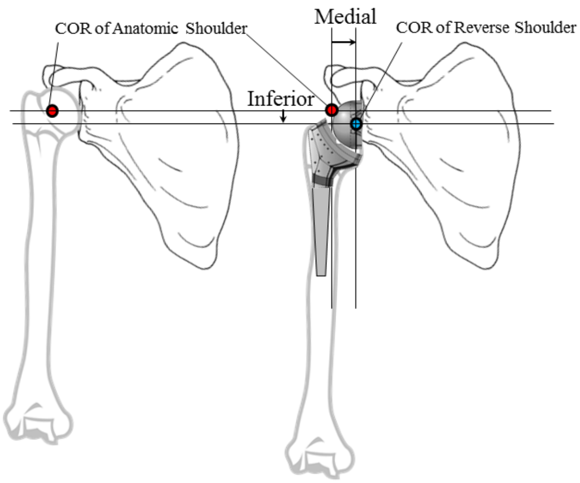

Fig.1: Anatomic shoulder (left) Vs. Reverse shoulder (right)

The purpose of this study is to compare kinematic differences between native and reverse shoulder to determine the contribution of all the factors effecting the kinematics and intensity of the total moment generated in the glenohumeral joint on the scapular plane by the deltoid during abduction in order to provide new information to inform the level of success of the surgery outcome in the long term. Both simulated normal anatomical and reverse shoulder data and the deltoid range of possible active motion and their effect on the abduction levels is studied in order to evaluate the difference in their relative kinematics. This study allows the effect of change in the centre of rotation to be linked to the deltoid muscle's excess excursion where the deltoid is no longer able to generate the required force to remain active beyond its normal operating range of contraction needed to achieve full abduction in a normal shoulder.

2. Methods

The shoulder is a very complex non-linear biomechanical system that consists of three bones (the clavicle, humerus, and scapula) and four joints (sternoclavicular, acromioclavicular, glenohumeral, and scapulothoracic) (Fig.2). Shoulder motion is generated by a combination of the motion of these four joints.

In this study a parametrised model of the shoulder is developed. The parameterised biomechanical model consists of the humerus, the scapula, deltoid muscles, deltoid insertion points, position of Centre of Rotation of Glenohumeral joint and deltoid tensioning before and after surgery based on X-Ray and MRI images before and after RSA.

Geometrical parameters of anatomic and prosthetic shoulder: X-Ray and Magnetic Resonance Imaging (MRI) images of the shoulder girdle shows a variety of morphology and dimensional differences amongst individuals [12,13,14,15].

Whilst no two individuals are the same, the normative range of motion of the arm for all healthy individuals is practically the same. However, the difference in anatomical sizes between individuals indicates there must exist an optimised relationship between relative values of these key parameters in order to obtain a defined abduction. All of these variables can play an important role in the shoulder's performance in terms of range of motion, strength and manoeuvrability. After RSA the geometry and kinematics of the glenohumeral joint will be totally changed. A standard RSA can result in different overall geometry depending on the original size of the individual and also in terms of the prosthesis size and positioning of prosthesis parts both on scapula and humerus for each patient [16,17,18] .

It is possible to extract key geometrical parameters from X-Ray and MRI images as long as they are calibrated and are taken based on a specific/standard protocol. These parameters can be used to define:

1) The origin of the deltoid on the acromion
2) The insertion points of the deltoid on the humerus
3) The centre of rotation of glenohumeral joint in 3D space
4) The available space and size of the glenoid sphere

all pre-operatively and post-operatively [19,20].

All the calculations are based on differences between native and reverse shoulder (DELTA prosthesis).

A musculoskeletal model of the shoulder was developed in MSC ADAMS software (MSC Software Corporation) including glenohumeral joint, scapula, humerus and two segments of the deltoid (anterior and middle).

XRay images of a single patient (an 82 years old female with 4 years of severe shoulder pain having massive irreparable rotator cuff tear and rotator cuff arthritis) pre and postoperatively in scapular, sagittal and transverse planes were used to prepare a 3D Computer Aided Design (CAD) model. The Images were imported into a graphical user interface (GUI), developed by the authors in MATLAB (Mathworks, USA). Key dimensions from the images, using a sphere with a known diameter for scaling, were measured.

The prosthesis parts were created in the same CAD tool, based on the dimensions of a real prosthesis. The prosthesis 3D models were inserted on shoulder griddle 3D model following standard Surgical Technique of Delta Xtend [21]

The centre of rotation (COR) of the GH joint was defined as centre of humerus spherical head in anatomic shoulder and centre of prosthesis glenoid in reverse shoulder. Both anterior and middle deltoids were modelled by linear springs connected to the origin and insertion coordinates of deltoid on scapula and humerus (Fig.3). Springs deformation was considered as muscle contraction and position and orientation of springs as deltoid force vector origin and orientation [22,9].

A mathematical model of shoulder was developed in MATLAB software. The difference between the COR of native and reverse shoulder was extracted from Saltzman *et al* [19] mentioning change of COR position from native shoulder to reverse one for DELTA prosthesis.

Deltoid resting length for both middle and anterior deltoid and their insertion and origin coordinates were extracted from Berthonnaud *et al* [23] and Fridén *et al* [24]

The model includes all the geometrical dimensions of bones, GH joint, origin and insertion coordinates of deltoid on humerus and scapula both for anatomic and reverse shoulder. The distance between origin and insertion coordinates of each muscle in 3D space was measured during arm abduction in scapular plane, as muscle length while connecting points of these coordinates represent force vector origin and direction.

All the parameters influencing intensity of moment generated in the GH joint (deltoid force, lever arm, effective lever arm) are considered as vectors while these vectors are just rotating and changing their magnitude without changing their origin position (translation of glenohumeral joint is neglected). As the studied motion is in a single plane (scapular plane), axial rotation during abduction is neglected. Using Cartesian coordinates instead of Euler angles prevents Codman's paradox [25].

Both models (musculoskeletal model of shoulder in MSC ADAMS and mathematical model in MATLAB) revealed same results.

These models were shown to be capable of creating a realistic representation of the X-Ray and MRI images obtained from previous studies [12,13,14,15,19,20]. The dimensions, coordinates, relative positions, perceived displacements, centre of rotations, trajectories, acceleration velocities and displacements can all be specified discretely and accurately allowing for future parametric optimisation.

During arm abduction the GH joint contributes 90^o to 120^o of abduction in the scapular plane while the rest is provided by the Scapulothoracic joint [26,27,28] (Fig.2). This leads to the assumption that after RSA the GH joint must be able to achieve the same range of motion. This outcome however, is not always guaranteed and the outcome varies between individuals. It is also assumed that after RSA the Scapulothoracic joint still provides 0^o to 60^o degree of abduction in the scapular plane which is independent of the deltoid function.

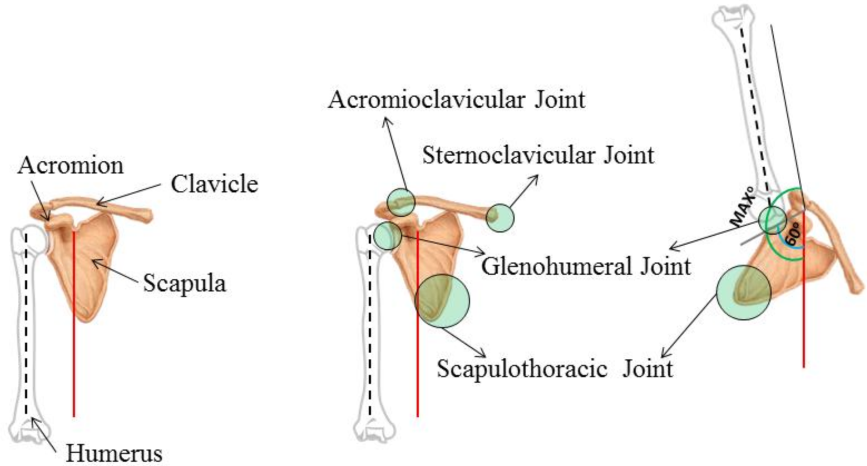

Fig.2: Shoulder Bones (left) Shoulder Joints (middle)
Scapulohumeral rhythm (right)

The wrapping of the muscle around the bone was neglected due to previous studies which indicate wrapping takes place in a limited range of motion (Low Abduction) [29,30,31,23] .

As shown in Fig.3 the fixed $\mathbf{O_{xyz}}$ coordinate system was used as a centre of rotation of the GH joint on the scapula. The arm motion was described in the scapular plane having $\boldsymbol{\theta}$ as rotation of the GH joint [14]. **m, n, p** = Distances between COR and origin of the middle deltoid on acromion along X,Y and Z axes, **L** = Distance between COR and insertion of deltoid on the Humerus, $\boldsymbol{\beta}$ = angle between moment arm and force vector of deltoid and **F** = Deltoid Force Vector.

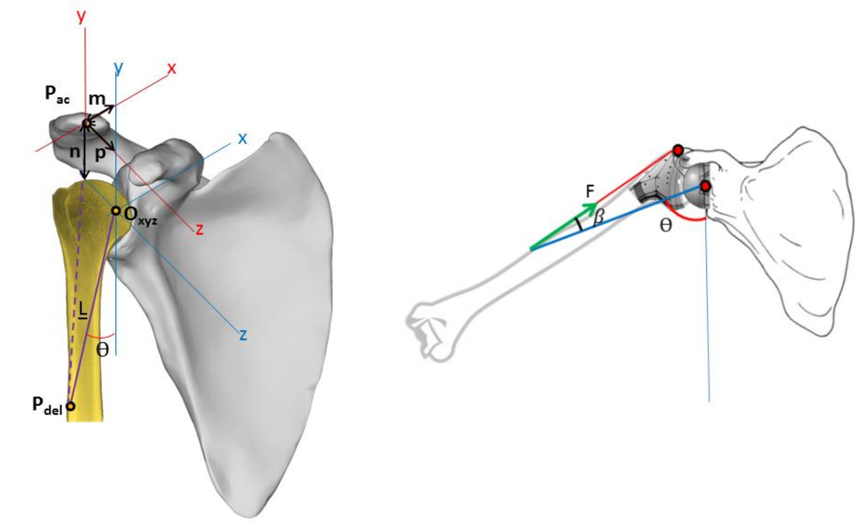

Fig.3: 3D Biomechanical Model of Shoulder (left) –Scapular Plane View (right)

3. Results

3.1. Deltoid excursion: The simulated model showed that the deltoid (Middle Deltoid, Anterior Deltoid) after RSA excurses (moves) more than the anatomic shoulder during abduction (0-120^o) (Fig.4) [1]**.** This longer excursion can cause a huge reduction in the deltoid range of available active force according to Force-Length graphs (Hill's Muscle model) [32,23] . Hill's Muscle model indicates muscles can provide the maximum force at the neutral position and a decreasing force as the muscle contracts. According to previous studies, the deltoid has it neutral length at approximately 30^o of arm abduction [33,34,35]. However, Berthonnaud *et al*. [23] assumes that the deltoid has its maximum force at its neutral position (0^o of abduction).

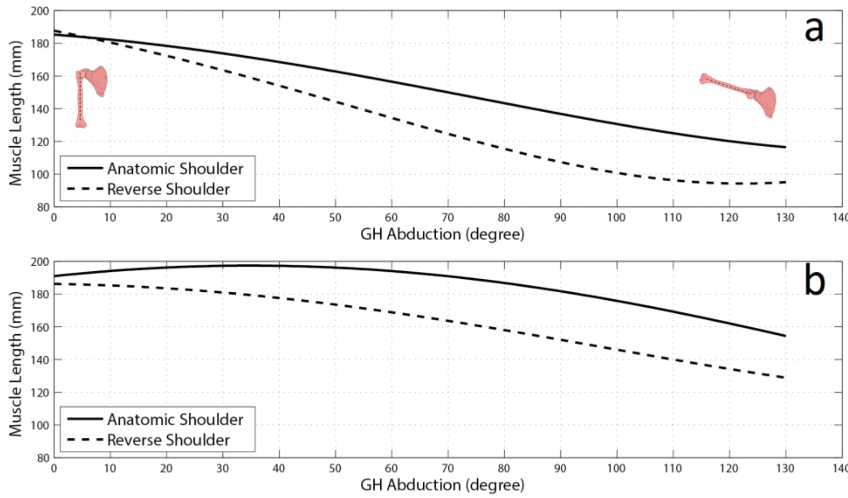

Fig.4: Deltoid Length VS Abduction of GH joint in scapular plane (a) Middle Deltoid (b) Anterior Deltoid

This accelerating contraction of the deltoid in reverse shoulder causes dramatic reduction in the available active force in it due to the muscle reaching the end of its contraction range. In some cases the deltoid may exceed its working range where it no longer can generate any force.

The Force-Length graph of the middle deltoid in the anatomic shoulder (Fig.5) shows that when the glenohumeral joint is in 0 degree of abduction, there exists little passive force in the muscle having an available active force close to its maximum. As the arm abducts more, the middle deltoid reaches its maximum available active force at approximately 30^o of abduction (where muscle reaches its neutral length). At larger angles, the available active force decreases towards zero (Maximum Abduction Angle). While in the reverse shoulder, the middle deltoid starts its excursion approximately at the same muscle length of the anatomic shoulder (0^o of abduction) but it excurses more than the anatomic one during abduction arriving almost at zero force [24]. Generally, the available maximum active force of the Middle Deltoid in reverse shoulder is less than that of anatomic shoulder during the same range of abduction angles. While for Anterior Deltoid, the reverse shoulder can provide more force than the anatomic one at the lower abduction angle. Effectively, the higher abduction angle follows the same trend as that of the Middle Deltoid (Fig.6).

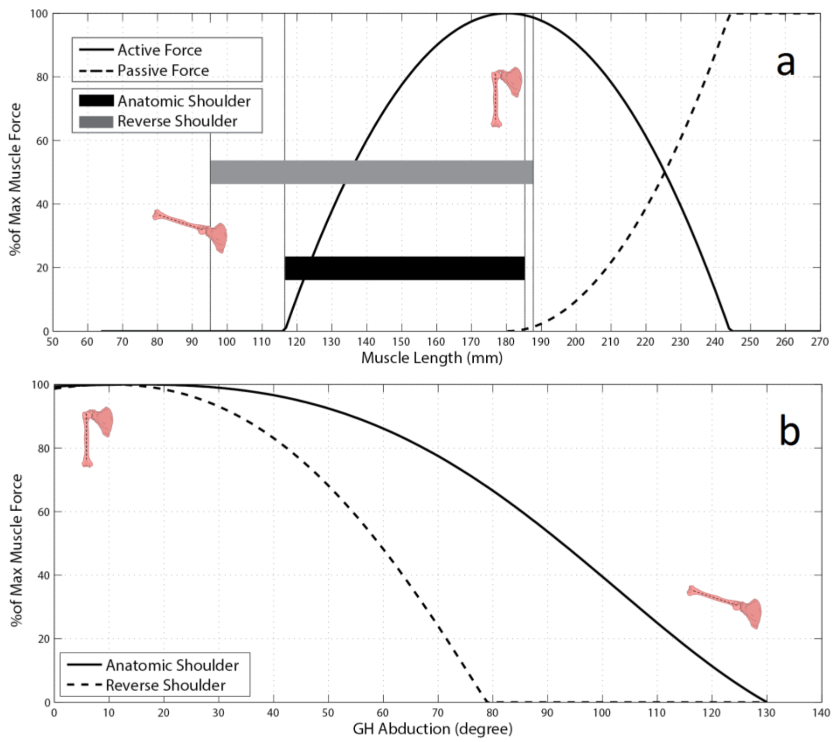

Fig.5: (a) Available active force in middle deltoid VS muscle length (b) Available active force in middle deltoid VS glenohumeral abduction angle (Horizontal bars indicate deltoid excursion in anatomic and RS from 0^o to 130^o of Glenohumeral joint abduction)

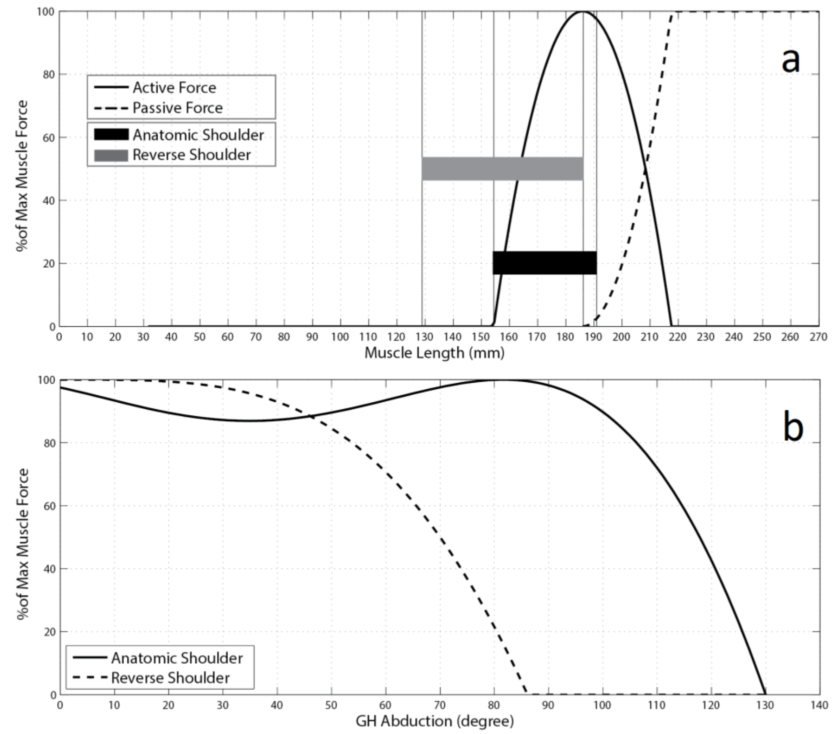

Fig.6: (a) Available active force in anterior deltoid VS muscle length (b) Available active force in anterior deltoid VS glenohumeral abduction angle
(Horizontal bars indicate deltoid excursion in anatomic and RS from 0^{o} to 130^{o} of Glenohumeral joint abduction)

3.2. The moment intensity is the function of the moment arm (distance between Centre of Rotation of the humerus and the deltoid insertions on humerus: $\underline{\mathbf{L}}$), deltoid force vectors (the vectors connecting deltoid insertion points on the humerus and origins of the deltoid on acromion: $\underline{\vec{\boldsymbol{F}}}$) and $\boldsymbol{sin}$ of the angle between the moment arm and force vector of deltoid, $\boldsymbol{sin(\beta)}$ (Fig.3). They are related by the following function [9,22,36].

$$M = F \times L \times sin(\beta)$$

Effective lever arm is the product of Moment arm: (**L)** multiplied by $\boldsymbol{sin(\beta)}$**.**

$$L_{eff} = L \times sin(\beta)$$

$$M = F \times L_{eff}$$

Plotting Effective Lever Arm (L_{eff}) versus abduction angle in anatomic shoulder and reverse shoulder shows different trends:

Middle Deltoid: This section of the deltoid experiences higher values of the effective lever arm in the reverse shoulder than in anatomic shoulders for a limited abduction angle. It then drops dramatically getting close to zero (Fig.7 (a)). At Zero degrees the glenohumeral joint mechanism is locked and cannot be abducted any more due to the loss of the effective lever arm and generates a pure compression force pulling on the arm towards the centre of rotation instead of rotating about it.

L_{eff} may not cross absolute zero in its range of motion but this increased L_{eff} shows closer (or even smaller) values compared to anatomic ones during higher abduction. This means that the provided increase of L_{eff} by medialization (Fig.1) does not provide a constant or sustained boost to rotation moment through the whole range of the motion. Previous studies mention that the lever arm in reverse shoulder is bigger than the anatomic one thanks to medialization of COR, but this investigation using a kinematic model has shown this theory can only be correct during a limited range of abduction [2,37].

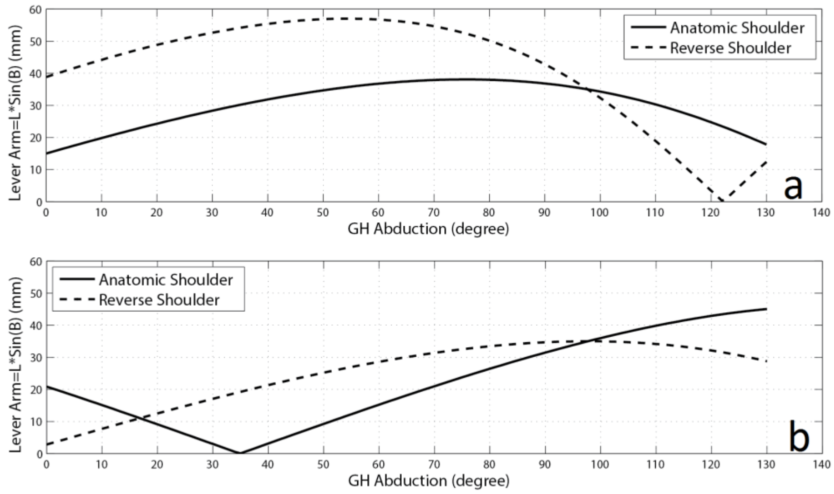

Fig.7: deltoid Effective Lever Arm VS Abduction of GH joint (a) middle deltoid (b) anterior deltoid

For example, looking at Fig.7(a), at 10 degrees of GH joint abduction the effective lever arm in anatomic shoulder has a value equal to 20 mm while the prosthetic shoulder has an effective lever arm equal to 45 mm which is more than twice that of the anatomic one of the same patient. However, at 80 degrees of glenohumeral abduction the anatomic shoulder has an effective lever arm equal to 40 mm while at this angle the prosthetic reverse shoulder is 50mm. The results show that the rate of change of the lever arm does not follow a linear trend and this medialization (Fig.1) in RS is only advantageous during a limited range of abduction.

Anterior Deltoid: As shown in Fig.7(b), in reverse shoulder, L_{eff} of the Anterior Deltoid will increase at the beginning of abduction while its effect decreases in higher abduction. Fig.7 clearly shows the effect of the change in Lever arm length and its dependency on the subtended angle (**β**). In these graphs absolute values of L_{eff} have been demonstrated. The anatomic L_{eff} graph has intersected zero effective lever arm at an approximate angle of 35^o of abduction. Regarding absolute value before this angle, L_{eff} has a negative value which means it does not assist the arm to abduct in low abduction whilst reverse shoulder has positive L_{eff} during whole abduction which is useful.

3.3. Deltoid pre-tensioning as a solution? The Deltoid length can be defined as the distance between origins of the deltoid on the acromion and its insertion points on the humerus. In reverse shoulder arthroplasty the deltoid is lengthened to increase its efficiency and it must be performed by increasing the distance between the origin of the deltoid on the acromion and its insertion point on the humerus [11,20,19,37].

There are two solutions to increase this length which are:

(1) Increasing **L (**Fig.3) (Distance between centre of rotation and insertion of deltoid on humerus). **L** depends on the position of the socket of the prosthesis on the humerus, diameter of the ball of the prosthesis and the size of the spacers used. Increasing this value will result in middle deltoid working range, a shift to the right on Force-Length graphs as shown in Fig.8 (a). As can be seen in Fig.8 (b), increased **L** is not affecting L_{eff} .The same trend is observed for Anterior Deltoid as shown in Fig.8 (c),(d) .

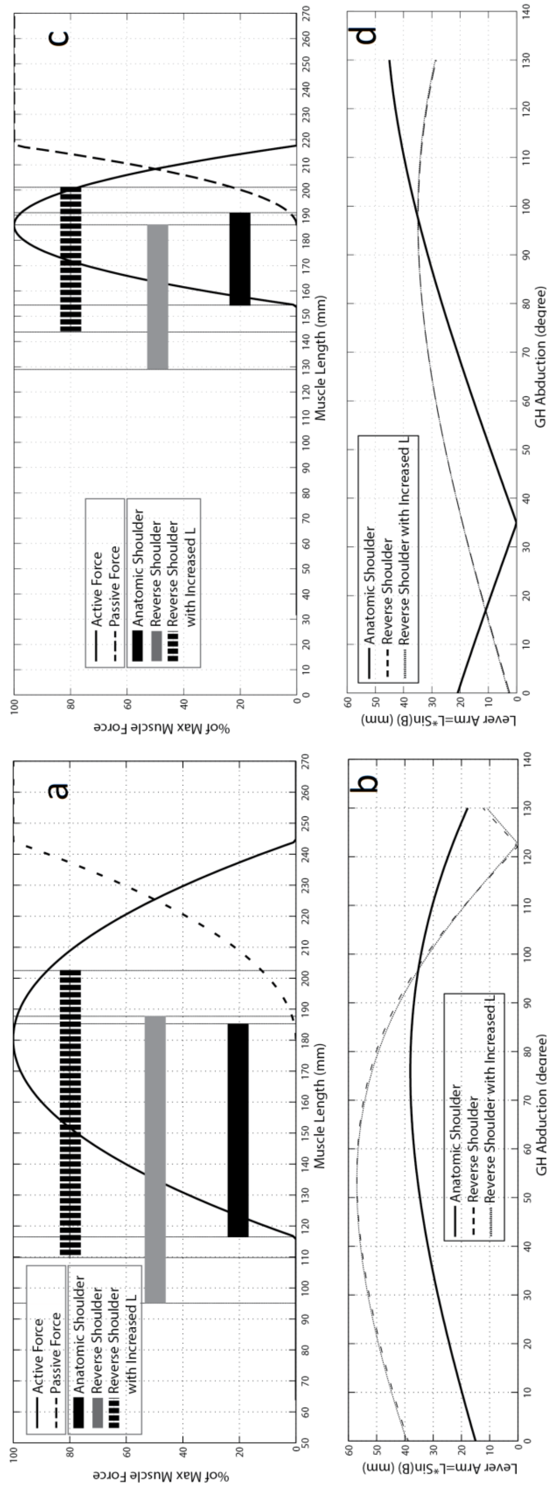

Fig.8: (a) %of Max Muscle Force VS Muscle Length in middle deltoid. Horizontal bars show Muscle Excursion. Black graph reveals passive force in muscle
(b) Effective Lever Arm VS GH Abduction
(c) %of Max Muscle Force VS Muscle Length in anterior deltoid. Horizontal bars show Muscle Excursion. Black graph reveals passive force in muscle
(d) Effective Lever Arm VS GH Abduction

(2) Increasing **n** (distance between acromion and centre of rotation) (Fig.3). This requires placing the ball of the prosthesis more inferiorly on scapula. As shown in Fig.9 (a), when the COR is moved in the reverse shoulder more inferiorly, initial middle deltoid length will be increased while more excursion of deltoid occurs during abduction with a shift in the working range of deltoid to right in the Force-Length graph. As shown in Fig.9 (b) L_{eff} trend will generally improve still showing a drop in higher abduction. Excessive movement of COR inferiorly can result in over stressing that can result in stress fracture [38,5]. Fig.9 (a),(b) shows that deltoid tensioning can optimise deltoid excursion in Force-Length graph with a developed effect on the effective lever arm. The same trend is observed for Anterior Deltoid as shown in Fig.9 (c),(d).

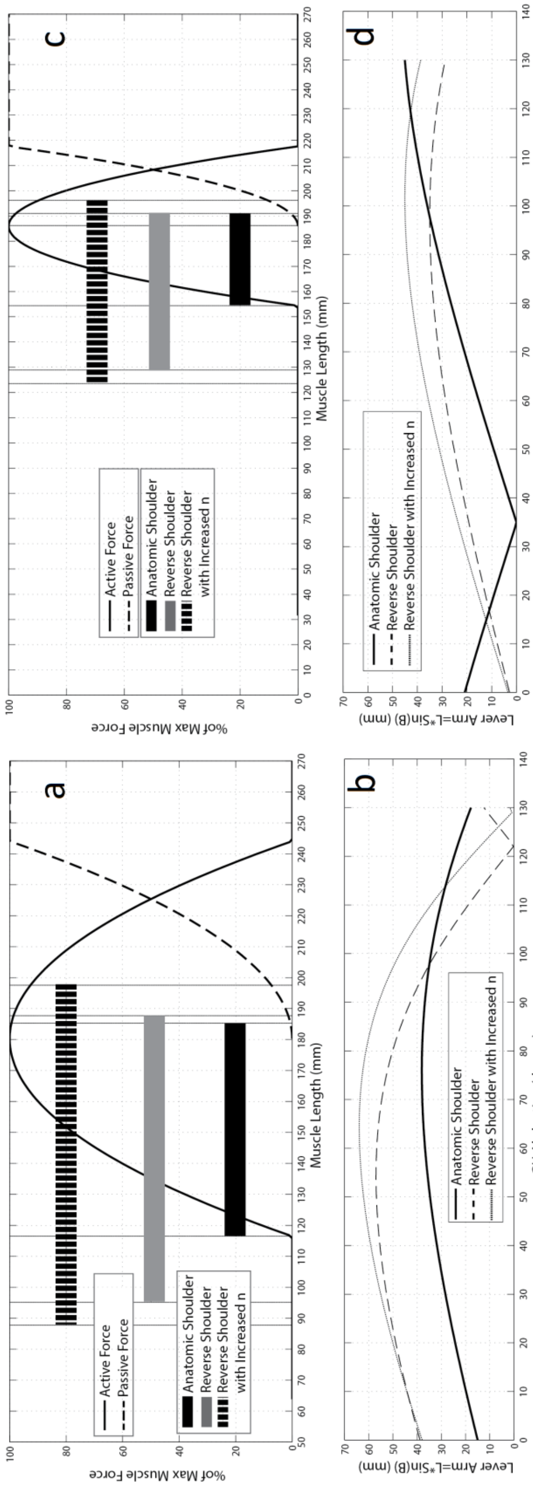

Fig.9: (a) %of Max Muscle Force VS Muscle Length in middle deltoid. Horizontal bars show Muscle Excursion. Black graph reveals passive force in muscle
(b) Effective Lever Arm VS GH Abduction
(c) %of Max Muscle Force VS Muscle Length in anterior deltoid. Horizontal bars show Muscle Excursion. Black graph reveals passive force in muscle
(d) Effective Lever Arm VS GH Abduction

3.4. Deltoid Pre-Tensioning Upper Limit in RSA, passive tension of deltoid is directly linked to the position of COR on the scapula, origin of the deltoid on the acromion and insertion point of the deltoid on the humerus.

As mentioned previously, increasing the tensioning parameters (**n** and **L**) shifts the working range of the deltoid towards the right hand side of the Force-Length graph of the muscle Fig.8 (a),(d) and Fig.9 (a),(d). However, as shown in Fig.10, the more it is shifted to the right the more passive tension in the deltoid muscle is generated which can result in loosening of the prosthesis and fracture of the acromion due to high load intensity or stress [38,5] .

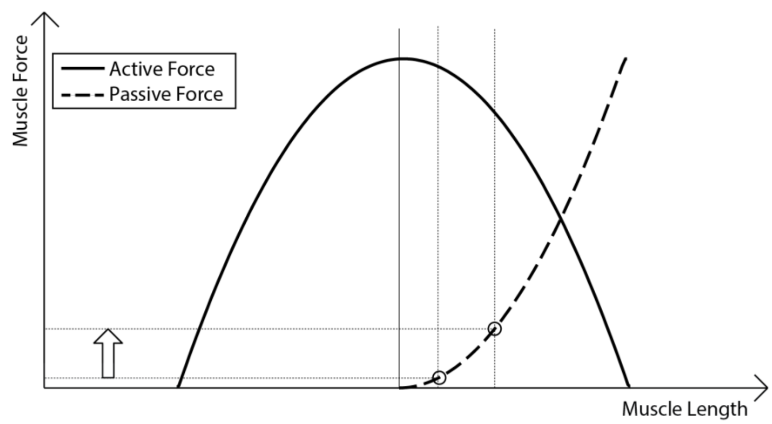

Fig.10: Muscle Force VS Muscle Length the more shift to right side, the more passive force in muscle

Active force is generated in the muscle when needed while passive force is a permanent spring effect of muscle while it is stretched (not contraction).

The results show that RSA improves the effective lever especially if the glenohumeral centre of rotation is moved both medially and inferiorly. It is also shown that because of tension of deltoid muscle its active force will be improved after RSA according to Hill's Muscle model. These two factors (improved effective lever arm and deltoid's active force) directly contribute in improvement of moment intensity of the glenohumeral joint generated by the deltoid. It must be taken into account that excessive deltoid tension could be a cause of scapula fracture. It is also shown that deltoid muscle excursion increases after RSA which could be a drawback while the deltoid reaches its maximum range of effectiveness.

4. Discussion

There are some modelling studies of reverse shoulder in the literature. Based on a cadaveric study, Schwartz *et al* [36] discusses the importance of anterior deltoid in RSA concluding after RSA surgery the anterior deltoid's moment arm increases. Kontaxis *et al* [22] and Terrier *et al* [9] studied biomechanics of RSA, based on a modeling study, and also concluded both middle and anterior deltoid moment arms increase after RSA. De Wilde *et al* [11], based on a computerised study, proves that the deltoid muscle force will be improved after RSA. Jobin *et al* [37] investigated the clinical effect of deltoid lengthening and centre of rotation medialisation concluding Deltoid lengthening improves active forward elevation after RSA for cuff tear arthropathy.

The results from this study are in agreement with all previous literature. In addition, the results provide new information regarding details of improvement of deltoid moment arm, deltoid excessive excursion after RSA and deltoid lengthening effect of increasing the deltoid's force. This study demonstrated that all of the geometrical parameters, both in normal shoulder and reverse shoulder either individually or in combination can play an important role on the outcome of the surgery for each individual [14,39,19].

A mathematical and 3D model of the anatomical shoulder and RSA were developed using data from X-Ray and MRI images. Different geometrical parameters were defined in each model (anatomic and RS) and the effect of small changes in each one (in isolation) on the overall kinematics and kinetics of the shoulder was investigated.

These parameters identify the centre of rotation of glenohumeral joint and the force vector of the deltoid knowing the origin of the deltoid on the scapula and its insertion point on the humerus both for the anatomic and RSA shoulder (Fig.3).

The behaviours of the deltoid muscle was simulated and investigated during glenohumeral joint full abduction both before and after RSA. The factors considered for comparison of the functional outcome are classified as: 1) <u>Deltoid Excursion, 2) Effective Lever Arm, 3) Deltoid Tensioning</u> and 4) <u>Deltoid Tensioning Upper Limit.</u> Also, the differences these geometrical parameters made on the outcome of the simulation were discussed.

Using the simulation, it was also possible to show the importance of the initial geometrical differences in individuals and how it can inform the placement of the implants. It also enables users to visualise the effect of lever arm beyond the range of motion possible by the deltoid contraction. This will have an effect on design of new implants glenoid to better control the lever arm length during abduction.

Using an image database of individuals' pre and post operatively, calculating the discussed kinematics parameters for each and correlating them with the outcome of surgery in long term, could inform surgeons intraoperatively about optimised placement of prosthesis to provide the maximum possible range of motion and least amount of pain. Currently, there is an on-going project to make an image database through a collaboration between Bournemouth Royal Hospital and Bournemouth University.

It should be highlighted, that these models only consider geometrical and kinematics of the glenohumeral joint while there are many other patient characteristics such as muscle fibre type, muscle volume and bones shape which have not been taken into account in this study. Therefore, the prediction of subjective outcomes (pain relief and range of motion) needs more studies including mathematical and clinical approaches together.

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