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

NAVID ASLANI

Department of Design and Engineering, Faculty of Science and Technology, Bournemouth University, Talbot Campus, Fern Barrow, Poole, Dorset, BH12 5BB, UK
naslani@bournemouth.ac.uk

SIAMAK NOROOZI

Department of Design and Engineering, Faculty of Science and Technology, Bournemouth University, Talbot Campus, Fern Barrow, Poole, Dorset, BH12 5BB, UK
snoroozi@bournemouth.ac.uk

RICHARD HARTLEY

Bournemouth Royal Hospital, Bournemouth, UK
rrhhbmc@me.com

MIHAI DUPAC

Department of Design and Engineering, Faculty of Science and Technology, Bournemouth University, Talbot Campus, Fern Barrow, Poole, Dorset, BH12 5BB, UK
mdupac@bournemouth.ac.uk

PHILIP SEWELL

Department of Design and Engineering, Faculty of Science and Technology, Bournemouth University, Talbot Campus, Fern Barrow, Poole, Dorset, BH12 5BB, UK
psewell@bournemouth.ac.uk

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 previous 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 abduction.

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

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 an arthritic shoulder with rotator cuff tear deficiency, characteristics are dramatically compromised. Rotator cuff tear arthropathy (a condition that affects both shoulder strength and stability that occurs when there is severe shoulder arthritis) can result in severe pain, and difficulty in performing daily activities [1]. There are many discussions about shoulder implants [2,3] showing the Reverse Shoulder Arthroplasty (RSA) has emerged as a an effective treatment of rotator cuff deficiencies in the shoulder. Despite its success, this procedure has been associated with a relatively high complication rate.

In RSA, as shown in Fig.1, the anatomic concavities of the glenohumeral joint are inverted (by removing the humerus head and Scapula fossa) to resolve the superior humeral head migration as a treatment of arthritis in shoulders with rotator cuff deficiency, reducing pain and providing an acceptable range of motion [4,5].

The procedure shifts the centre of rotation medially relative to the glenoid fossa to increase the effective lever arm and inferiorly Fig.1 to tension the deltoid and improve its function [6,7,8]. 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 post operation prosthesis parameters. Currently there is no information on the importance of, or the link between individuals’ initial, anatomical/geometry variations or differences and the locating of the implant system during surgery on the functional outcome of RSA.

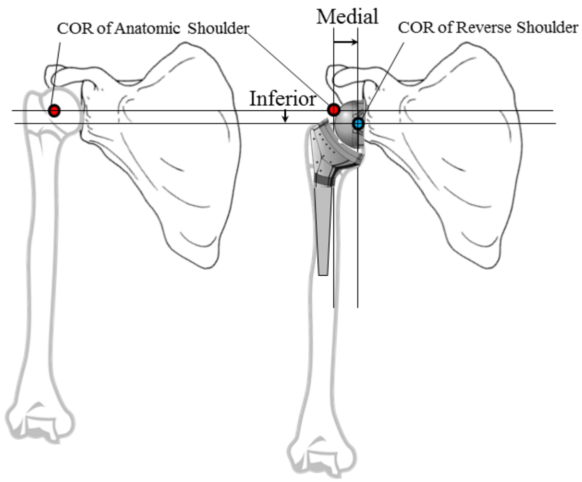

Fig.1: Anatomic shoulder (left) Vs. Reverse shoulder (right)

Using a simulation it was 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.

Geometrical parameters of anatomic and prosthetic shoulder: X-Ray and MRI images of the shoulder girdle shows a variety of morphology and dimensional differences amongst individuals [9,10,11,12].

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 [13,14,15] .

Regarding information that can be extracted from X-Ray and MRI images before and after surgery, it is possible to extract some key geometrical parameters from such 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 [16,17].

The purposes of this study is to compare kinematic differences and to determine the contributions 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. This case study investigates and compares both simulated normal anatomical and reverse shoulder in order to evaluate the difference in their relative kinematics and the deltoid range of possible active motion and their effect on the abduction levels. 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.

This study demonstrated that all of the geometrical parameters, both in normal shoulder and reverse shoulder (RS) either individually or in combination can play an important role on the outcome of the surgery for each individual [11,18,16].

1. Methods

A musculoskeletal model of shoulder was developed in MSC ADAMS software including glenohumeral joint, scapula, humerus and two segments of deltoid (anterior and middle). Centre of rotation of 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 [19,6].

A mathematical model of shoulder was developed in MATLAB software including 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, as muscle length while connecting points of these coordinates represent force vector origin and direction.

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

These models were shown to be capable of creating a realistic representation of the X-Ray and MRI image obtained from previous studies [9,10,11,12,16,17]. The dimensions, coordinates, relative positions, perceived displacements and centre of rotations, as well as trajectories and acceleration, velocities and displacements can all be specified discretely and accurately allowing for future parametric optimisation.

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.

The parameterised biomechanical model consists of the humerus, the scapula, deltoid muscles, deltoid insertion points, position of Centre of Rotation (COR) of Glenohumeral joint (GH) and deltoid tensioning before and after surgery based on X-Ray and MRI images before and after RSA.

During arm abduction the Glenohumeral joint contributes 90^o to 120^o of abduction Fig.2. This leads to the assumption that after RSA the glenohumeral joint must be able to achieve the same range of motion. This outcome however, is not always guaranteed and the outcome varies between individuals. This variation in the outcome after RSA is what prompted this investigation. It is also assumed that after RSA the scapulothoracic joint still provides 0^o to 60^o degree of abduction which is independent of the deltoid function [20,21,22].

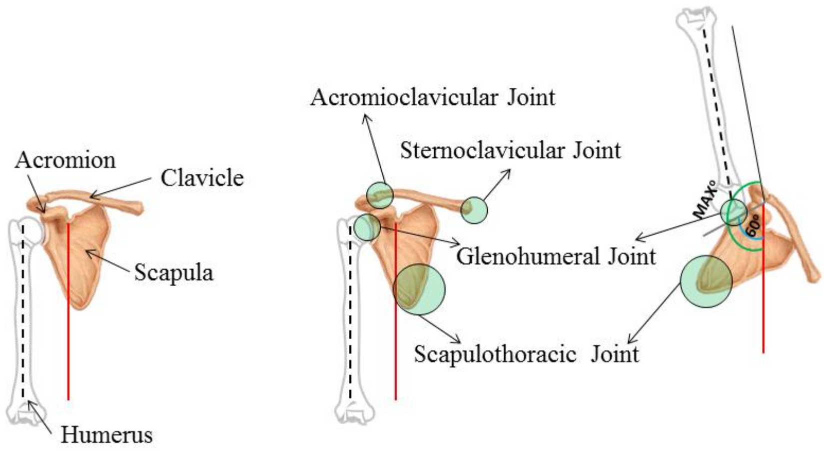

Fig.2: Shoulder Bones (left) Shoulder Joints (middle)
Scapulohumeral rhythm: in a full abduction of arm just around 120 degree of abduction is provided by glenohumeral joint and the rest by scapulothoracic joint (right)

The origin (Centre of rotation), insertion coordinate and length of bones and muscles were determined from anatomical and prosthetic measurements of X-Ray and MRI images studies [9,10,11,12,16,17] .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) [23,24,25,26] .

As shown in Fig.3 the fixed $\mathbf{O_{xyz}}$ coordinate system was used as a centre of rotation of the glenohumeral joint on the scapula. The arm motion was described in the scapular plane having $\boldsymbol{\theta}$ as rotation of the glenohumeral joint [11]. **m, n, p** = Distances between COR (Centre of Rotation) and origin of middle deltoid on acromion along X,Y and Z axes, **L** = Distance between COR and Insertion of deltoid on Humerus, $\boldsymbol{\beta}$ = angle between moment arm and force vector of deltoid and **F** = Deltoid Force Vector.

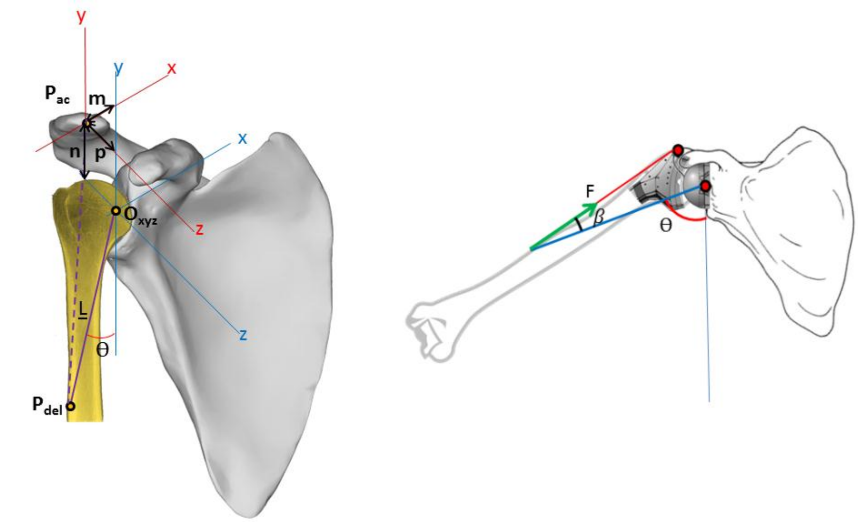

Fig.3: 3D Biomechanical Model of Shoulder (left) –Scapular Plane View (right)

2. Results and discussion

2.1. Deltoid excursion: The simulated model showed that the deltoid (all three sections: Middle Deltoid, Anterior Deltoid, Posterior 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) [27,26] . 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 [28,29,30] . However, Berthonnaud *et al*. [26] assumes that the deltoid has its maximum force at its neutral position (0^o of abduction).

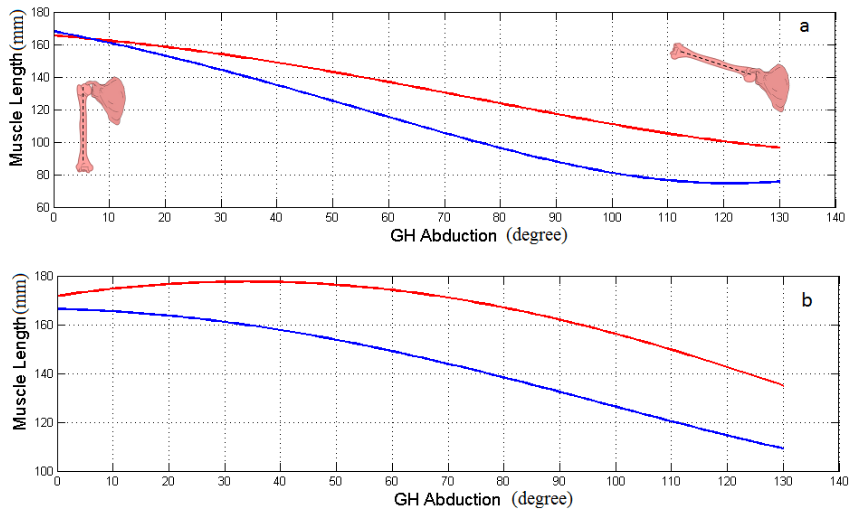

Fig.4: Deltoid Length VS Abduction of GH joint (a) Middle Deltoid (b) Anterior Deltoid
red: anatomic / blue: reverse shoulder

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.

As shown in Fig.5, in Force-Length graph of middle deltoid, in anatomic shoulder, when GH 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 around 30^o of abduction (where muscle reaches its neutral length). After that 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 at 0^o of abduction but it excurses more than the anatomic one during abduction arriving almost at zero force [31]. 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.

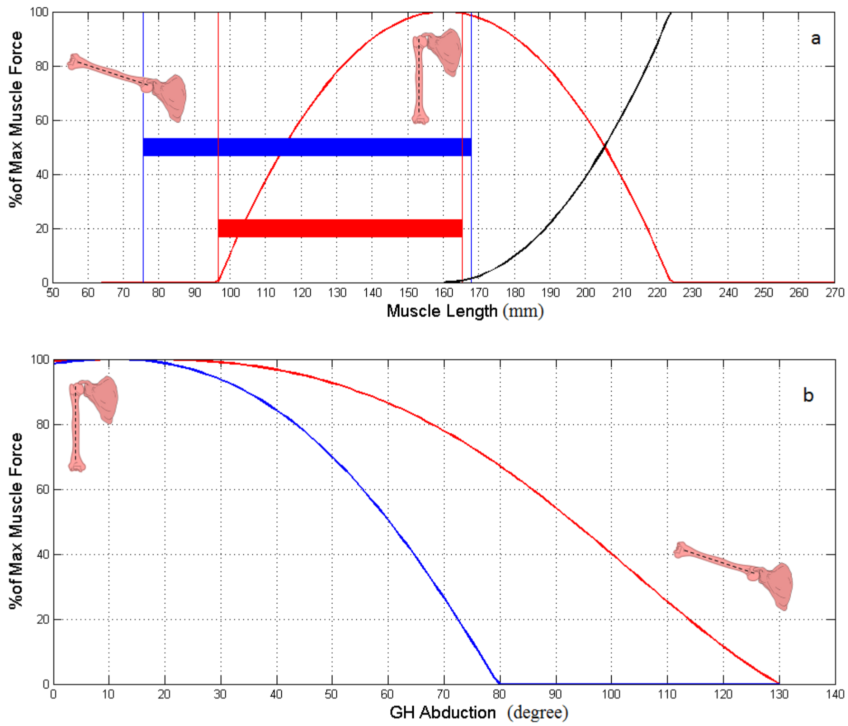

Fig.5: (a) Available active force in middle deltoid VS muscle length (b) Available active force in middle deltoid VS glenohumeral abduction angle
red: anatomic / blue: reverse shoulder / black: passive force in muscle
(Horizontal bars indicate deltoid excursion in anatomic and RS from 0^o to 130^o of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

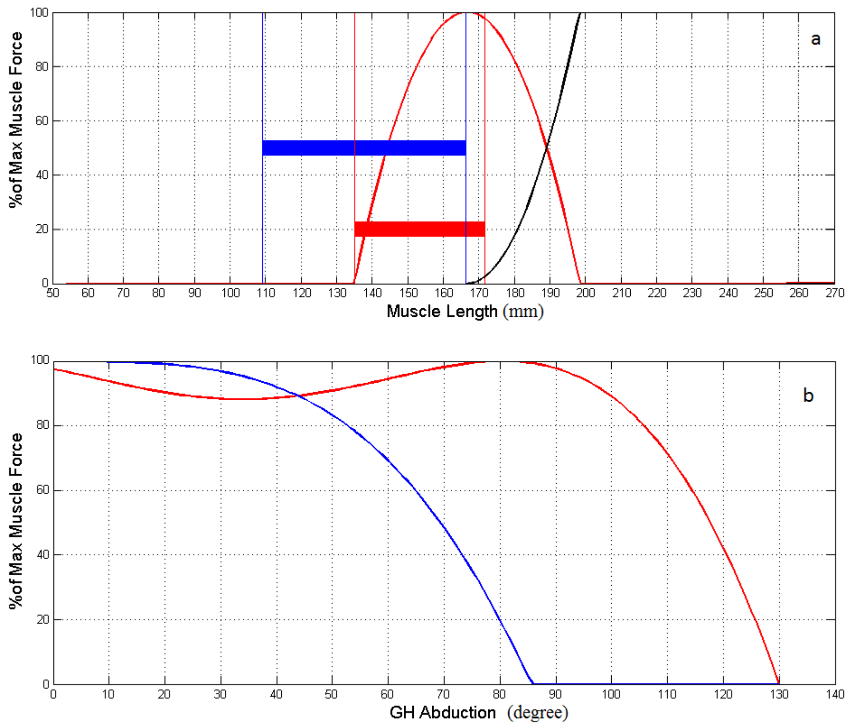

Fig.6: (a) Available active force in anterior deltoid VS muscle length (b) Available active force in anterior deltoid VS glenohumeral abduction angle
red: anatomic / blue: reverse shoulder / black: passive force in muscle
(Horizontal bars indicate deltoid excursion in anatomic and RS from 0^o to 130^o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

2.2. The moment intensity is the function of the moment arm (distance between Centre of Rotation of the humerus and the deltoid insertions on humerus: **L**), deltoid force vectors (the vectors connecting deltoid insertion points on the humerus and origins of the deltoid on acromion: $\vec{F}$) 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 [6,19, 32].

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

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}) VS abduction angle in anatomic shoulder and reverse shoulder shows different trends:

Middle Deltoid: This section of the deltoid experiences higher value of the effective lever arm in the reverse shoulder than in anatomic shoulders for a limited abduction angle. After that it drops dramatically getting close to zero Fig.7(a). Zero degree means the glenohumeral joint mechanism is locked and cannot be abducted any more due to the loss of the effective lever arm and generation of 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 less) values compared to anatomic ones during higher abduction. This means that 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 [2,33].

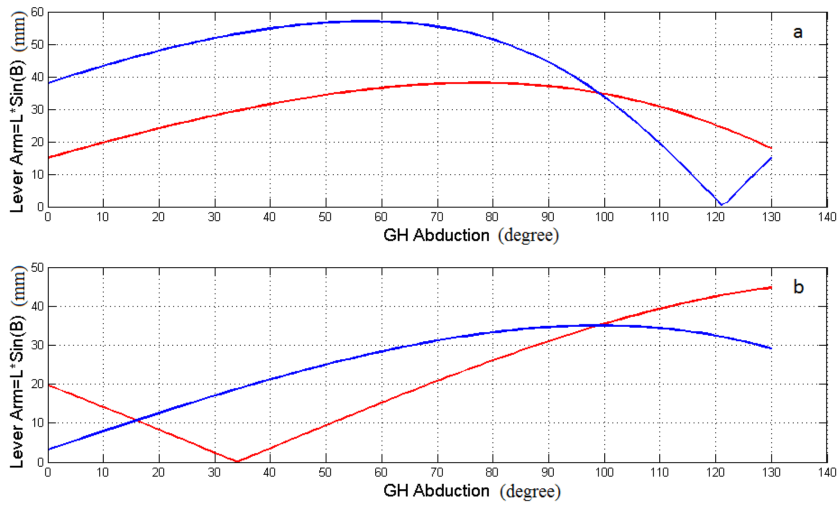

Fig.7: deltoid Effective Lever Arm VS Abduction of GH joint (a) middle deltoid (b) anterior deltoid
red: anatomic / blue: reverse shoulder

For example, looking at Fig.7(a), at 10 degree of glenohumeral 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 43 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 medicalization 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 angle around 35^o of abduction and regarding absolute value before this angle L_{eff} has had a negative value which means it does not assist the arm to abduct in low abduction while reverse shoulder has positive L_{eff} during whole abduction which is useful.

2.3. 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 [8,17,16,33].

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) .

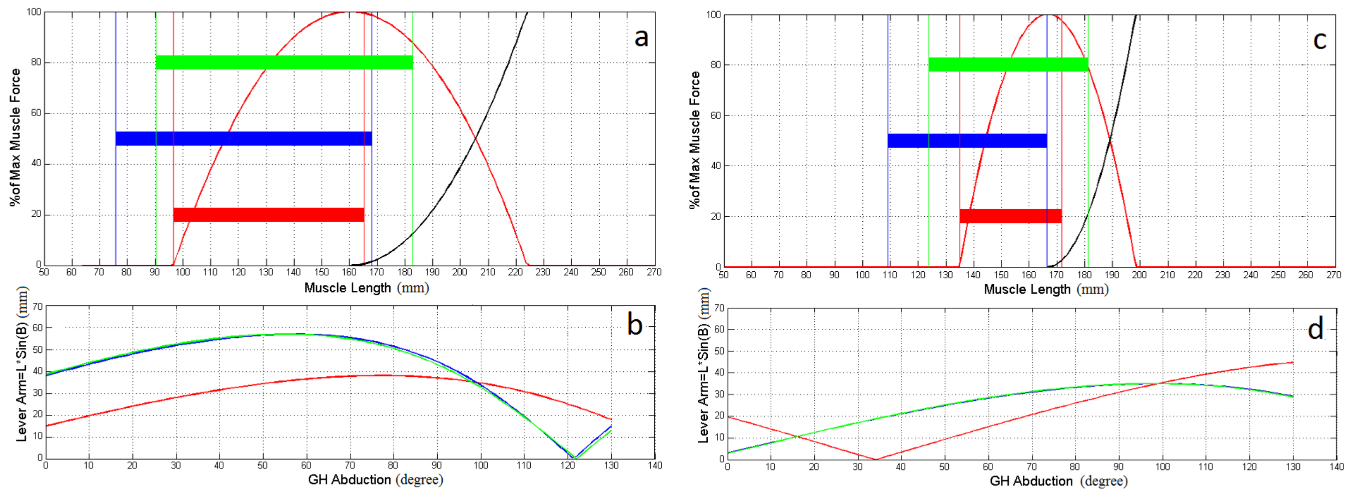

Fig.8: (a) %of Max Muscle Force VS Muscle Length in middle deltoid.
Horizontal bars show Muscle Excursion. Black graph reveals passive force in muscle
(b) Effective Lever Arm VS GH Abduction
(c) %of Max Muscle Force VS Muscle Length in anterior deltoid.
Horizontal bars show Muscle Excursion. Black graph reveals passive force in muscle
(d) Effective Lever Arm VS GH Abduction
Red: Anatomic / Blue: Reverse Shoulder / Green: Reverse Shoulder with Increased L

(2) Increasing **n** (distance between acromion and centre of rotation) Fig.3. This requires placing the ball of prosthesis more inferiorly on scapula. As shown in **Error! Reference source not found.**(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 **Error! Reference source not found.**(b) L_{eff} trend will generally improve still showing a drop in higher abduction. Excessive moving of COR inferiorly can result over stressing that can result in stress fracture [34,35]. **Error! Reference source not found.**(a),(b) show 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 **Error! Reference source not found.**(c),(d).

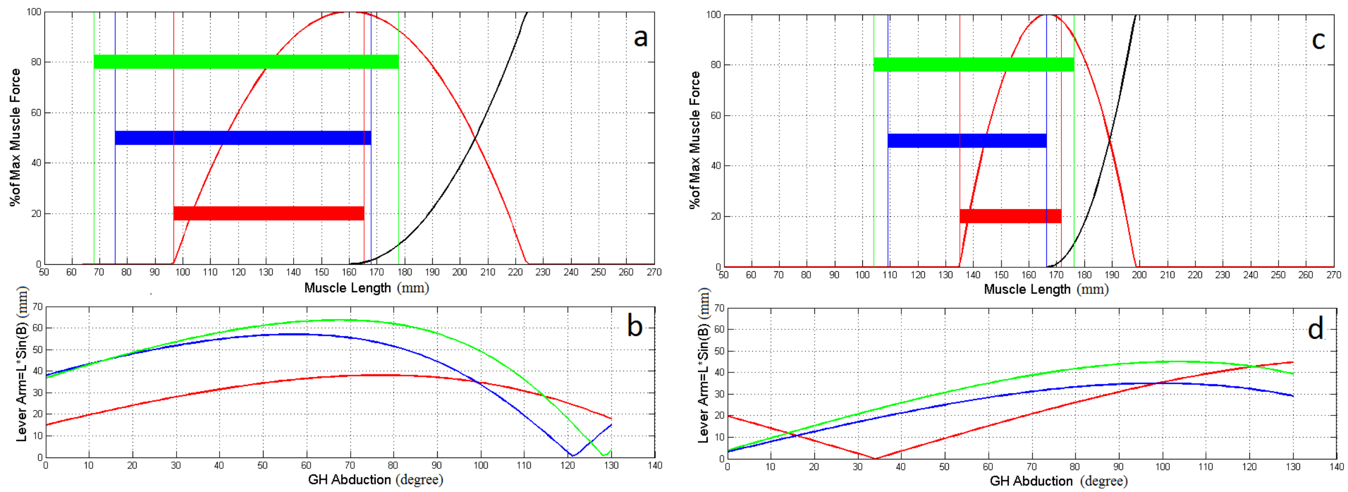

Fig.9: (a) %of Max Muscle Force VS Muscle Length in middle deltoid.
Horizontal bars show Muscle Excursion. Black graph reveals passive force in muscle
(b) Effective Lever Arm VS GH Abduction
(c) %of Max Muscle Force VS Muscle Length in anterior deltoid.
Horizontal bars show Muscle Excursion. Black graph reveals passive force in muscle
(d) Effective Lever Arm VS GH Abduction
Red: Anatomic / Blue: Reverse Shoulder / Green: Reverse Shoulder with Increased n

2.4. 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 **Error! Reference source not found.**(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 created which can result in pain when the arm is in the neutral position. This can also results in loosening of the prosthesis and fracture of the acromion due to high load intensity or stress values as a result of high passive or residual force in deltoid due to pre-tensioning [34,35] .

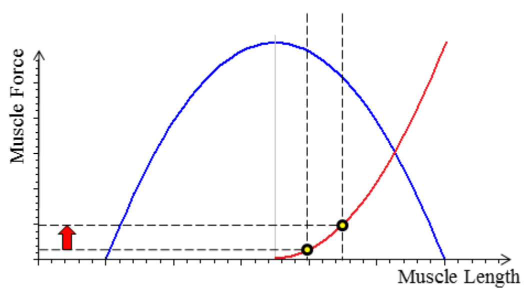

Fig.10: Blue: Active Force VS Muscle Length Red: Passive Force VS Muscle Length
the more shift to right side, the more passive force in muscle

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

2.5. Effect of Changes (differences) in Anatomic and Prosthetic Parameters: Small differences in anatomic and prosthetic geometrical parameters Fig.11 in individuals can have a large influence on the outcome. For example, Fig.12 shows the effect of small changes in acromion distance of the same shoulder before and after RSA [9,10,36] .

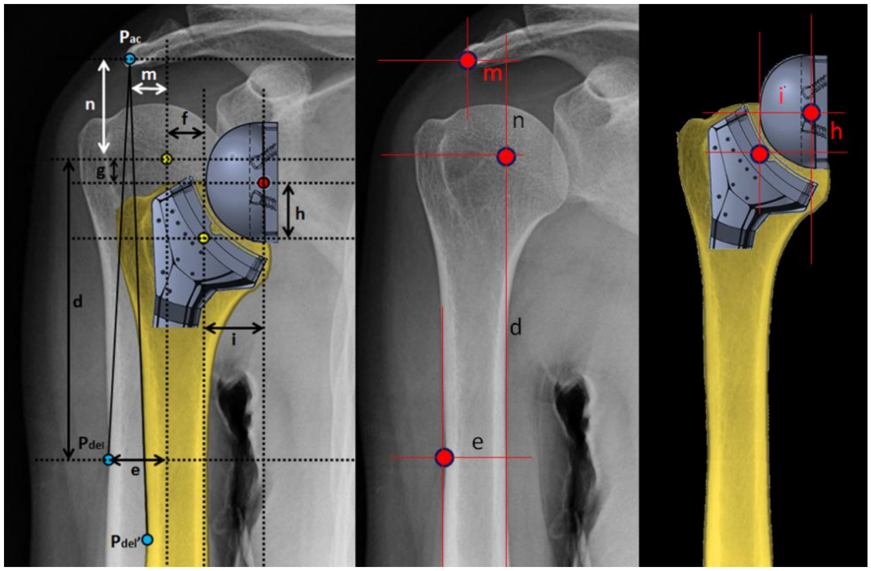

Fig.11: Defined geometrical parameters in scapular plane.
m,n,e,d: Anatomic Shoulder parameters

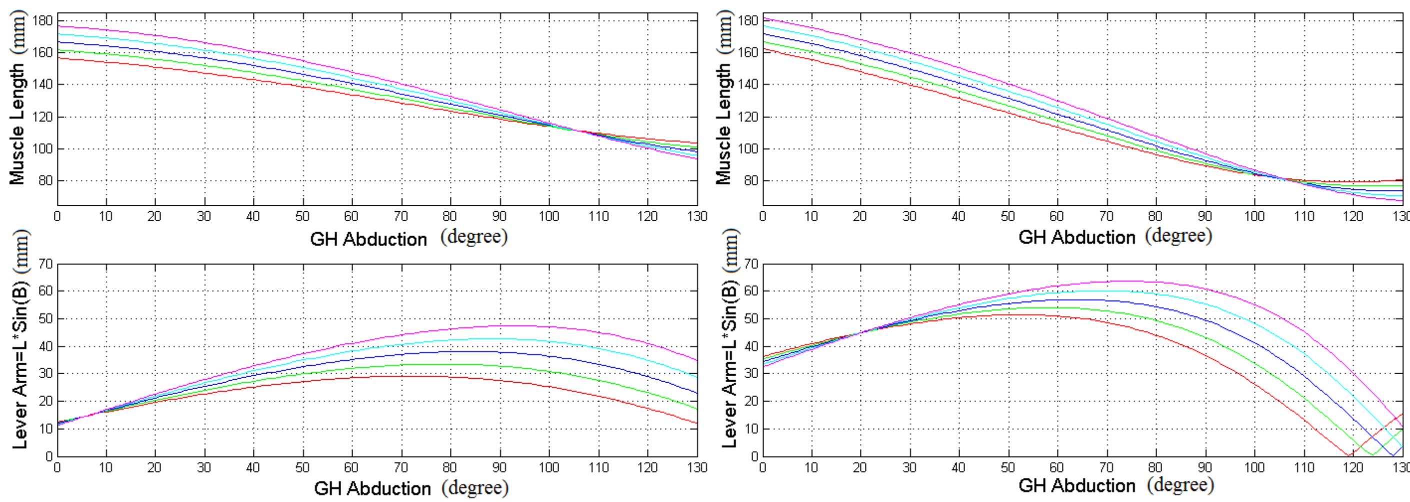

Fig.12: Small differences in **n** (**n**=15,17,19,21,23,25 mm) can cause big differences in muscle excursion and Effective Lever Arm during GH abduction

Left: Anatomic Shoulder Right: Reverse Shoulder

(Arrows show increasing trend of n from15 to 25 mm)

3. Discussion and results

A mathematical and 3D model of the anatomical and RSA were developed using data from X-Ray and MRI images coming from previous studies.

Different geometrical parameters were defined in each model (anatomic and RS) Fig.11 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 origin of the deltoid on the scapula and its insertion point on the humerus both for the anatomic and RS 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) Deltoid Excursion, 2) Effective Lever Arm, 3) Deltoid Tensioning and 4) Deltoid Tensioning Upper Limit. Also, the differences these geometrical parameters made on the outcome of the simulation were discussed.

In conclusion, regarding the fact that small differences in anatomic and prosthetic parameters can affect dramatically the outcome of RSA, the development of a structured approach/procedure for measurement is needed. This would enable all measurement on all patients to be taken on similar or identical planes to allow a more objective comparison of the Pre and post op range of motion to be conducted. Also, to set the procedure for development of a database and imaging techniques would allow better superposition of images that allows RS to be located on the original image in order to take measurement for various locations. Using a database of such images and optimisation of kinematic graphs, the optimal decision could be made for individuals to have possible maximum range of motion and least amount of pain.

4. REFERENCES

1. Meyer, D. C., Rahm, S., Farshad, M., Lajtai, G. & Wieser, K. Deltoid muscle shape analysis with magnetic resonance imaging in patients with chronic rotator cuff tears. *BMC Musculoskelet Disord* **14,** 247 (2013).

2. Jazayeri, R. & Kwon, Y. W. Evolution of the reverse total shoulder prosthesis. *Bull. NYU Hosp. Jt. Dis.* **69,** 50–5 (2011).

3. Flatow, E. L. & Harrison, A. K. A history of reverse total shoulder arthroplasty. *Clin. Orthop. Relat. Res.* **469,** 2432–9 (2011).

4. Nam, D. *et al.* Reverse total shoulder arthroplasty: current concepts, results, and component wear analysis. *J. Bone Joint Surg. Am.* **92 Suppl 2,** 23–35 (2010).

5. Sanchez-Sotelo, J. Total shoulder arthroplasty. *Open Orthop. J.* **5,** 106–14 (2011).

6. Terrier, a, Reist, A., Merlini, F. & Farron, A. Simulated joint and muscle forces in reversed and anatomic shoulder prostheses. *J. Bone Joint Surg. Br.* **90,** 751–6 (2008).

7. Kuechle, D. K. *et al.* The relevance of the moment arm of shoulder muscles with respect to axial rotation of the glenohumeral joint in four positions. *Clin. Biomech. (Bristol, Avon)* **15,** 322–9 (2000).

8. De Wilde, L., Audenaert, E., Barbaix, E., Audenaert, A. & Soudan, K. Consequences of deltoid muscle elongation on deltoid muscle performance: a computerised study. *Clin. Biomech. (Bristol, Avon)* **17,** 499–505 (2002).

9. Kircher, J. *et al.* Is there an association between a low acromion index and osteoarthritis of the shoulder? *Int. Orthop.* **34,** 1005–10 (2010).

10. Gu, G. & Yu, M. Y. Novel Physiotherapies Imaging Features and Clinical Significance of the Acromion Morphological Variations. 2–5 (2013). doi:10.4172/2165-7025.S2-003

11. Frankle, M. a, Teramoto, A., Luo, Z.-P., Levy, J. C. & Pupello, D. Glenoid morphology in reverse shoulder arthroplasty: classification and surgical implications. *J. Shoulder Elbow Surg.* **18,** 874–85 (2009).

12. Werner, C. M. L. *et al.* Intermethod agreement and interobserver correlation of radiologic acromiohumeral distance measurements. *J. Shoulder Elbow Surg.* **17,** 237–40 (2008).

13. Gutiérrez, S., Comiskey, C. a, Luo, Z.-P., Pupello, D. R. & Frankle, M. a. 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,** 2606–15 (2008).

14. Gutiérrez, S., Keller, T. S., Levy, J. C., Lee, W. E. & Luo, Z.-P. Hierarchy of stability factors in reverse shoulder arthroplasty. *Clin. Orthop. Relat. Res.* **466,** 670–6 (2008).

15. Anglin, C., Wyss, U. P. & Pichora, D. R. Shoulder prosthesis subluxation: Theory and experiment. *J. Shoulder Elb. Surg.* **9,** 104–114 (2000).

16. Saltzman, M. D., Mercer, D. M., Warme, W. J., Bertelsen, A. L. & Matsen, F. a. A method for documenting the change in center of rotation with reverse total shoulder arthroplasty and its application to a consecutive series of 68 shoulders having reconstruction with one of two different reverse prostheses. *J. Shoulder Elbow Surg.* **19,** 1028–33 (2010).

17. Lädermann, A. *et al.* Influence of arm lengthening in reverse shoulder arthroplasty. *J. Shoulder Elbow Surg.* **21,** 336–41 (2012).

18. Hoenecke, H. R., Tibor, L. M. & D'Lima, D. D. Glenoid morphology rather than version predicts humeral subluxation: a different perspective on the glenoid in total shoulder arthroplasty. *J. Shoulder Elbow Surg.* **21,** 1136–41 (2012).

19. Kontaxis, a. & Johnson, G. R. The biomechanics of reverse anatomy shoulder replacement – A modelling study. *Clin. Biomech.* **24,** 254–260 (2009).

20. Lee, S. K., Yang, D. S., Kim, H. Y. & Choy, W. S. A comparison of 3D scapular kinematics between dominant and nondominant shoulders during multiplanar arm motion. *Indian J. Orthop.* **47,** 135–42 (2013).

21. Ludewig, P. M., Hassett, D. R., Laprade, R. F., Camargo, P. R. & Braman, J. P. Comparison of scapular local coordinate systems. *Clin. Biomech. (Bristol, Avon)* **25,** 415–21 (2010).

22. Matsuki, K. *et al.* Dynamic in vivo glenohumeral kinematics during scapular plane abduction in healthy shoulders. *J. Orthop. Sports Phys. Ther.* **42,** 96–104 (2012).

23. Klepps, S. *et al.* A cadaveric study on the anatomy of the deltoid insertion and its relationship to the deltopectoral approach to the proximal humerus. *J. Shoulder Elb. Surg.* **13,** 322–327 (2004).

24. Moser, T. *et al.* The deltoid, a forgotten muscle of the shoulder. *Skeletal Radiol.* **42,** 1361–75 (2013).

25. Johnson, G. R., Spalding, D., Nowitzke, A. & Bogdukt, N. MODELLING THE MUSCLES AND COORDINATE IMPLICATIONS OF THE SCAPULA DATA AND FUNCTIONAL. *J. Biomech.* **29,** (1996).

26. Berthonnaud, E., Morrow, M., Herzberg, G., An, K.-N. & Dimnet, J. Biomechanical Model Predicting Values of Muscle Forces in the Shoulder Girdle During Arm Elevation. *J. Mech. Med. Biol.* **10,** 643–666 (2010).

27. Millard, M., Uchida, T., Seth, A. & Delp, S. L. Flexing computational muscle: modeling and simulation of musculotendon dynamics. *J. Biomech. Eng.* **135,** 021005 (2013).

28. FLAVIO ALMEIDA SALLES, A. Z. F. Isokinetic evaluation of eighteen male patients submitted to surgical corretion of acute acromioclavicular luxation with a minimum two-year follow-up. *ACTA ORTOP BRAS* **10,** 19–24 (2002).

29. Terrier, A. *et al.* A musculoskeletal shoulder model based on pseudo-inverse and null-space optimization. *Med. Eng. Phys.* **32,** 1050–6 (2010).

30. Terrier, A., Reist, A., Vogel, A. & Farron, A. Effect of supraspinatus deficiency on humerus translation and glenohumeral contact force during abduction. *Clin. Biomech. (Bristol, Avon)* **22,** 645–51 (2007).

31. Fridén, J. & Lieber, R. L. Quantitative evaluation of the posterior deltoid to triceps tendon transfer based on muscle architectural properties. *J. Hand Surg. Am.* **26,** 147–55 (2001).

32. Schwartz, D. G. *et al.* The anterior deltoid's importance in reverse shoulder arthroplasty: a cadaveric biomechanical study. *J. Shoulder Elbow Surg.* **22,** 357–64 (2013).

33. Jobin, C. M. *et al.* Reverse total shoulder arthroplasty for cuff tear arthropathy: the clinical effect of deltoid lengthening and center of rotation medialization. *J. Shoulder Elbow Surg.* **21,** 1269–77 (2012).

34. Schamblin, M. *et al.* In vitro quantitative assessment of total and bipolar shoulder arthroplasties: a biomechanical study using human cadaver shoulders. *Clin. Biomech. (Bristol, Avon)* **24,** 626–31 (2009).

35. Boileau, P. *et al.* Revision surgery of reverse shoulder arthroplasty. *J. Shoulder Elbow Surg.* **22,** 1359–70 (2013).

36. Kappe, T., Cakir, B., Lippacher, S., Reichel, H. & Elsharkawi, M. Intraarticular lesions in calcifying tendinitis: incidence and association with the acromion index. *Arch. Orthop. Trauma Surg.* **131,** 325–9 (2011).