Comparison of Muscle Coordination in Two Patient Specific Shoulder Models

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Abstract

The shoulder provides mobility to the upper limb and is thus necessary for lots of activities. Consequently injuries in the shoulder joint affect the patient in his daily life. The study of shoulder pathologies is however difficult : each patient has his individual anatomy and his own lifestyle which have an impact on his shoulder biomechanical pattern. This is why patient specific shoulder models are necessary to explore precise and specific features of the patient's shoulder joint.
The goal of this project was to analyse the impact of individual anatomy on the shoulder muscle coordination. To do this, we built two patient specific musculoskeletal models. The first one was based on MRI scans of a male volunteer, the second one on MRI scans of a female volunteer. We observed both models to predict similar muscle force patterns and joint reaction forces. However, the models predicted variations in muscle force intensity, that were related to the anatomic changes.

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Contents

1 Introduction

The shoulder includes three bones, the clavicle, the scapula and the humerus held together with the thorax by muscles. The shoulder joint is a ball and socket joint which needs to be mobile enough for the wide range actions of the arm, but is also actively stabilized my muscles to allow for actions such as lifting, pushing and pulling [Veeger and van der Helm(2007)]. The large range of motion provided by the shoulder would be impaired in case of shoulder damage and would affect the patient's in his daily activities. To investigate pathologies or injuries related to the shoulder joint, knowledge about the shoulder biomechanics is crucial.

Theoretically the most accurate way to have access to this information would be to surgically implant force sensors in order to directly measure the forces exerted. This technique is invasive and expensive requiring surgery and rehabilitation. Moreover it raises ethical issues due to the risks of the surgery, the pain and the rehabilitation for healthy subjects. Finally these sensors might hinder the subject in his natural movements because of the pain, hence the results might be questionable. This technique is therefore not applicable in humans.

Modeling the shoulder via numerical methods, on the other hand reduces risks and costs compared to in vivo experiments. Furthermore various hypotheses can be explored, since all states and variables are accessible and can be modified.

For this reason shoulder numerical models have been developed [J.Yang and Rajulu(2010)] but few are patient specific. Yet, each patient has his own lifestyle, performing a lot of different activities along his life. Moreover each patient has his specific bones anatomy, his individual muscular volume and his own muscle coordination resulting in a different biomechanical pattern in the shoulder. Most of the already existing patient specific models are used for shoulder replacement [P. Schuller-Götzburg and Resch(2008)]. They are intended to develop patient specific implants, plan and simulate surgery and predict the surgery outcome.

In this project we seek to determine with patient specific shoulder models how the individual anatomy influences shoulder muscle coordination.

In this work, we used an already existing musculoskeletal shoulder model based on in vivo scans of a male volunteer. We implemented a second anatomic data set for this shoulder model based on in vivo scans of a female volunteer. The shoulder model could thus compute muscle activities and joint reaction forces for both anatomic data sets using the same algorithms and hypothesis for muscle force estimation. An abduction movement was performed with the male and female data set and the muscle forces and joint loads were evaluated and compared.

2 Materials and Methods

2.1 Male Shoulder Model

The existing shoulder model is based on in vivo MRI scans of a male subject aged 27 years old showing no sign of shoulder pathology. The right shoulder MRI scans of the subject were obtained at the CHUV (Centre Hospitalier Universitaire Vaudois), in Lausanne. The model was implemented into Matlab (Version 2014, Mathworks, USA) at the Laboratory of Biomechanical Orthopedics (LBO), EPFL [D. Ingram and Farron(2012)].
The MRI scans were first imported into Amira (version 5.4.5, FEI Visualization Sciences Group, Bordeaux and Zuse Institute, Berlin) to reconstruct the scapula, the clavicle, the humerus and the thorax of the subject. As the ulna and the radius bones do not appear in the MRI scans they were approximated with cylinders using anthropometric data [Duyar and Pelin(2010)].
In the Matlab model, bones are assumed rigid and the articulations are defined as perfect spherical joints. The muscles are modelled as frictionless and massless cables. The more cables, the more the muscle is similar to the real muscle but the more time it takes to compute the results. The model has 42 muscles whose origin and insertion are defined with splines of 3 points. Since some muscles have curved shapes that cannot be designed with straight cables, via-points and wrapping objects were added. Via-point are splines on the trajectory of the muscles. The muscles cables go from the origin splines through the via-points splines and end up in the insertion splines. Wrapping objects are cylinders around which the muscles cables wrap giving to the muscle a curved shape. In addition to the muscles, anatomic landmarks are necessary for the model to be able to compute forces.
The Matlab model uses an optimisation-based method. It requires kinematic input data (a given movement of the arm) and uses an inverse dynamic approach and an optimization criteria to compute the muscles forces. The model needs inverse dynamics to get the joint torques and estimate the solution space for the given movement. An algorithm of optimization is then applied to minimize a cost function. Through the minimization of the cost function, which is the sum of the squared muscles stress, the model is able to predict the muscles forces.

2.2 Female Shoulder Model

We implemented a second anatomic data set for the shoulder model. In vivo MRI scans of a 26 years old female subject showing no sign of shoulder pathology were used to create this new anatomic data set. Magnetic resonance imaging (MRI) is a non invasive medical imaging technique used in radiology to get visualisations in 2 or 3 dimensions of the interior of a body and investigate the anatomy. The MRI scanner needs magnetic fields and radio waves to produce images in the 3 anatomical planes (sagittal, coronal and transverse) of the inside of the body. The subject is lying down still while the scans were taken.

The female shoulder MRI scans were imported in Amira. The scans segmentation was performed by marking the different bones regions on the scans, using interpolation between slices when possible. The humerus, scapula, clavicle and thorax including the spine and ribs could then be reconstructed and visualized.

The origin, via-points and insertion of the muscles are represented by splines of 3 points. These points were identified and set on the bones reconstruction according to [Gray(1918)]. The wrapping objects are cylinders around which the muscles cables wrap, modelling the curved shape of the muscles. They were placed in the trajectory of the muscles using [Gray(1918)]. The settings of the anatomic landmarks on the bones was based on the literature [G. Wu(2005)]. We provided this new anatomic data set to the Matlab model which will compute the same algorithms but using the female specific anatomical data.

In this project, we focused on an abduction movement from 0 to 120 degrees in the scapular plane. The main muscles recruited for this movement are the deltoids (anterior, middle and posterior deltoids) and the muscles of the rotator cuff (the supraspinatus, infraspinatus and subscapularis) which stabilize the joint. We set the number of cables for these muscles to 3. The number of cables for the other muscles were let to 1 as they are not involved much in the movement and we want to avoid a too heavy simulation. The muscles activities and the joint reaction force were computed for both models. The muscles activities were plotted in percentage of their theoretical maximal force taken from the literature [Garner(2000)]. Comparing the results from the male and female models we were able analyze the impact of the individual anatomy on the muscle coordination.

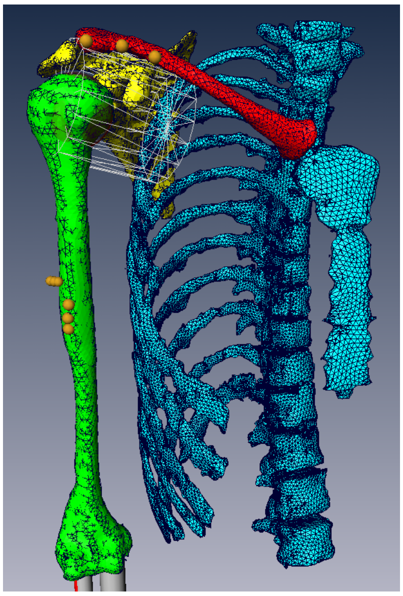

Figure 2.1: **Female shoulder reconstruction in Amira** : Origin points, via-points, insertion points and wrapping object modelling the anterior deltoid muscle

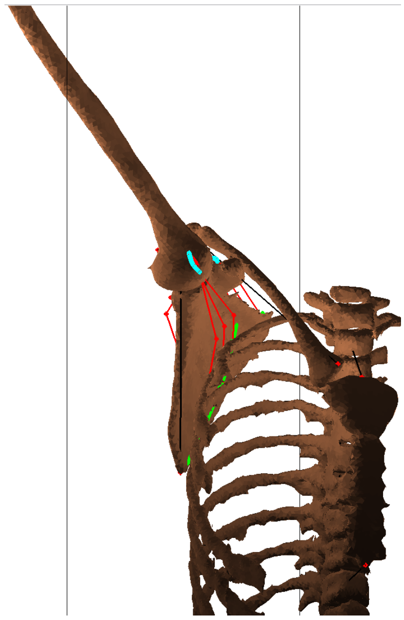

Figure 2.2: **Matlab female shoulder model**: Rotator cuff muscles modeled with 3 cables

3 Results

The comparison between the rotator cuff and deltoid muscles activities for the male and female model are plotted in percentage of their maximal force along the degrees of abduction of the arm (figures 3.1 and 3.2). Both joint reaction forces are plotted in percentage of bodyweight in figure 3.3.

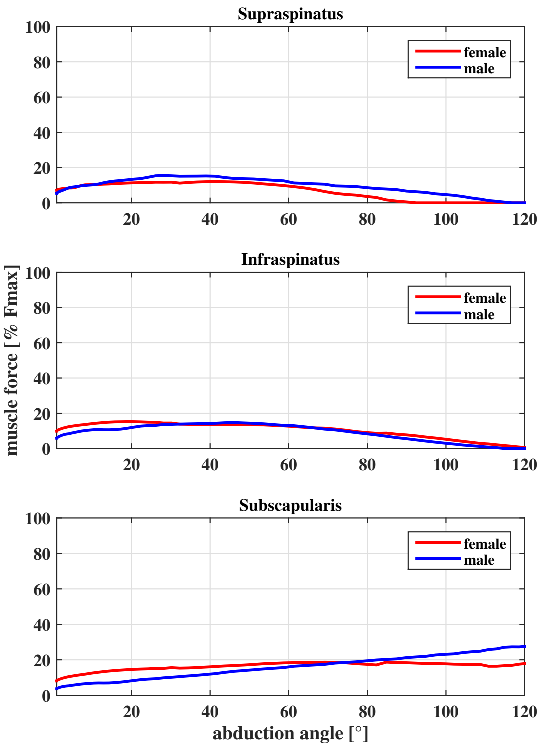

Figure 3.1: Supraspinatus, infraspinuatus and subscapularis rotator cuff muscles activities during an abduction movement of 120° exhibit similar behavior in the male and female models.

Similarities can be seen between the rotator muscles activation for the male and female models (figure 3.1). The supraspinatus and infraspinatus muscle curves are quasi superimposed indicating an almost identical muscle activation. The female subscapularis muscle curve diverge somewhat from the male one but reflects a similar behavior.

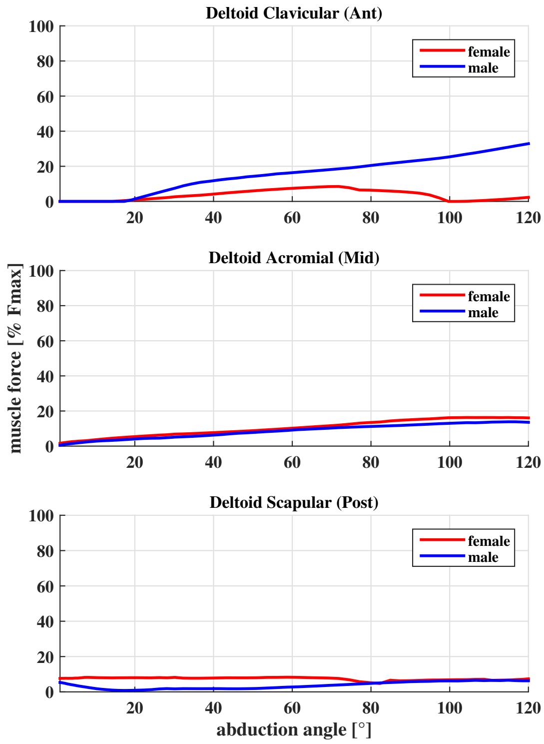

Figure 3.2: The middle and posterior deltoid muscles activities during an abduction movement of 120° show comparable patterns in the male and female models, however the anterior deltoid muscle activation differs.

The middle and posterior deltoid muscles have a comparable pattern of activities between the models. The female posterior deltoid muscle activity curve is slightly higher until almost 80° of abduction but joined next the male curve for the end of the movement. However the female anterior deltoid muscles has a lower activation compared to the male one (figure 3.2). Thus the specific anatomy of the female subject induced a variability in the anterior deltoid muscle activity.

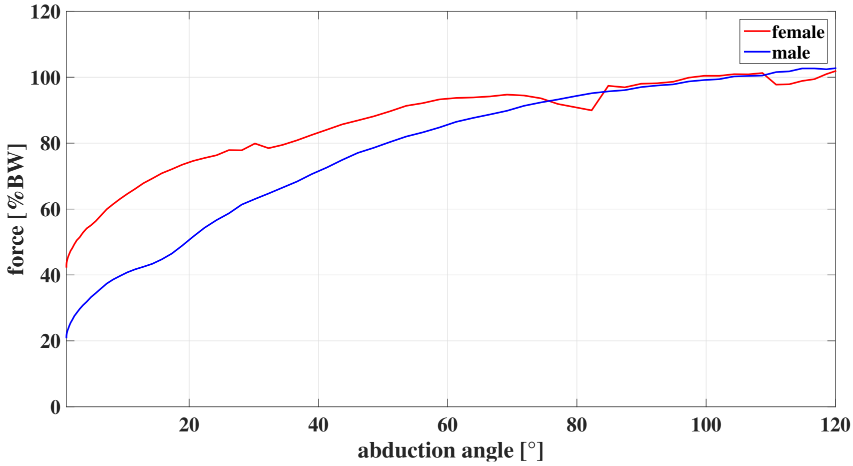

Figure 3.3: In the female model the shoulder joint reaction force is higher at the beginning of the abduction movement compared to the male model.

At the beginning of the movement the female shoulder joint reaction force is about twice higher than the male joint reaction force. It stays higher until around 75° of abduction then crosses the male curve before superimposing on it from 85° to 110° where it finally decreases a little. The individual anatomy of the female subject shoulder joint thus gave rise to a higher force. However both joint reaction forces exhibit a comparable behavior.

4 Discussion

In this work, we analysed the impact of individual anatomy on muscle coordination in the shoulder. To do this, we used two musculoskeleltal shoulder models based on in vivo MRI scans of a male and a female volunteer. Both models computed muscle and joint reaction forces for an abduction movement in the scapular plane. We observed variations in predicted forces.

The rotator cuff muscles include the supraspinatus, the infraspinatus and the subscapularis muscles. They act to stabilize the shoulder, and seem to follow a comparable behavior independently of the subject's anatomy.

The deltoid muscles are the main actors of the abduction movement. The middle and posterior deltoid muscles have more or less the same level of activation in both models. The male deltoid anterior muscle however is more recruited than the female one. This increase of activity could be explained by a smaller lever arm resulting in a higher muscle force. Also the male clavicle might be farther from the shoulder joint or have a significant different shape compared to the female clavicle. This specific anatomical feature could result in a different muscle activity since the anterior deltoid muscle originates in the clavicle. The specific male anatomy induced thus a higher activation of the anterior deltoid muscle.

Even following the same behavior as the male joint reaction force, the female joint reaction force is higher than the male one at the beginning of the abduction movement which is to be related to the anatomic change.

The joint reaction forces obtained were compared with those collected from instrumented prosthesis (files S2R_270306_1_86 and S8R_161208_1_31 from database OrthoLoad [Bergmann(2008)]). The patients having instrumented prosthesis are much older than our subjects. They may have arthrosis which would alter the way they move the arm as they are trying to ease the pain. Yet our results are in the same range of values as those obtained from the OrthoLoad database.

The estimated male deltoid muscles forces were compared to EMG measurements of the male subject deltoid muscles (see figure 6.1) for an abduction movement. Even tough it is difficult to extrapolate EMG data to muscle forces, the general pattern of muscles activation could still be recognized and were found to be similar.

Our patient specific shoulder model is thus able to bring out the general pattern of muscles activation as well as small differences depending on the male or female anatomy.

Yet the patients specific anatomical data need to be retrieved from manual MRI scan processing and muscles definitions which is time consuming and represents the main drawback of patient specific models. However there are algorithms that would automatically reconstruct the bones from MRI scans. Efficient techniques taking advantages of (semi-)automatic image processing techniques exist for the knee cartilage

[J. Carballido-Gamio(2005)] and should be evaluated and adapted for the shoulder joint.
Besides, our model contains limitations that need to be taken into consideration.
The first limitation of our model is the difficulty in predicting the stabilising muscles coactivation [D. Gagnon(2001)]. As the model simulates a perfect movement, stabilising muscles are often underestimated. However the shoulder joint needs to be stabilised. The optimization criteria tries to provide a solution to the muscle coactivation problem by minimising a physiological cost function which is the sum of the squared muscles stress. But there are other different cost functions based on mechanical, energetic or metabolic hypothesis [A Erdemir(2007)] that have been proposed.
Furthermore the specific anatomy of the subject includes not only the bones but also the muscles. The muscle is a complex biological and chemical entity having non linear and visco-elastic properties. The muscular volume and maximum activity (used to plot the muscles forces in figures 3.1 and 3.2) are related to the patients' activities or sport performance and could affect the muscles activation. Yet in our model the muscles are reduced to cables which have no mass and are not subject to friction. Their volume is not taken into account making overlapping possible. The approximation of the ulna and the radius with cylinders need to be mentioned but since we are interested in shoulder forces the ulna and radius have little influence as they are far from the shoulder joint.
However the general behavior of the muscles activation could still be extracted from our shoulder model despite the approximate design of the muscles and the difficulty to precisely solve the indeterminate problem of muscle coactivation. The model was successful in computing both female and male general patterns of activation of the muscles as well as the variations of activities and forces depending of the subject specific anatomy.

5 Conclusion

To conclude, both models predicted a general activation of the muscles as well as variabilities depending on the anatomy. These variabilities highlighted the necessity of patient specific shoulder models to investigate more accurately the patient's individual muscles forces. Comparisons between young and old subjects could also be evaluated to further investigate the impact of the anatomy on the muscle coordination. Finally implementing muscle models simulating more accurately the muscles behavior could make the model more precise in its muscle forces prediction.

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6 Additional Figure

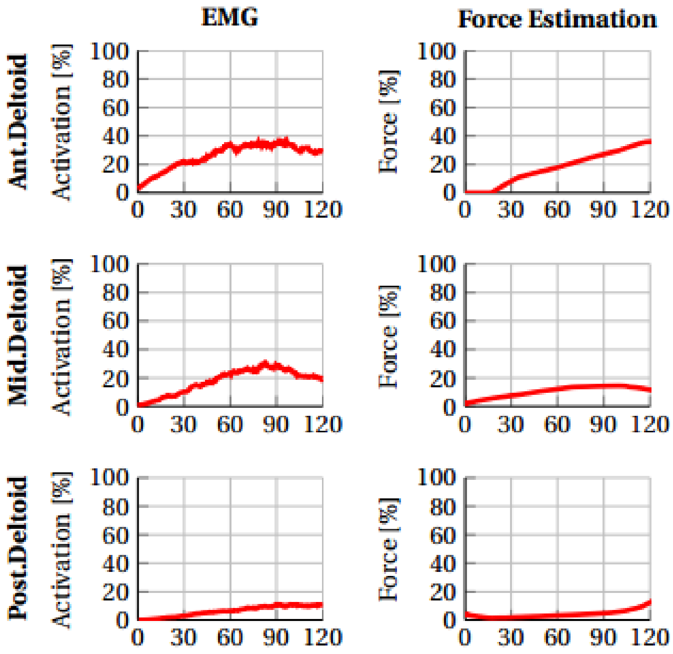

Figure 6.1: Comparison of EMG measurements of the male subject anterior, middle and posterior deltoid muscles during abduction in the scapula plane with estimated muscle force from the male shoulder model. The muscle activation was normalized to a maximum voluntary contraction