<u>Final Report on the individual Fellowship Dr. Marc Andreas Mueller</u>

<u>Grant Titel:</u> Biomechanics of the Shoulder in Rotator Cuff Lesions during simulated Normal Shoulder Motions and Pitching

<u>Date:</u> 21.10.2012

<u>1. Goals investigated and results obtained during the project</u>

1.1 Initial goal of the Project

The initial goal of the project was to investigate the effect of supra-spinatus tears and repairs on glenohumeral and scapulothoracic kinematics

Th effect of rotator cuff tears on shoulder kinematics is a matter of debate. Previous *in vivo and in vitro* studies have suggested that supraspinatus tears in isloation may not alter glenohumeral kinematics, but may affect scapulothoracic motion. However, these studies were subject to major limitations in methodology:

In vivo studies are intrinsically biased inter- and intrasubject variability to perform investigated shoulder motions. In addition, many in vivo studies use static 2D (fluoroscopic) and 3D (MRI) imaging techniques which are incapable of registering joint kinematics continuously. For continuous data registration, in vivo studies have to use skin markers as a representative of the underlying bony landmark. However, the accuracy of this technique is limited due to motion of the skin relative to the underlying bone.

On the other hand, current cadaveric models to study shoulder biomechanics isolate the glenohumeral joint. Therefore, they do not consider scapulothoracic motion and position of the clavicle. Moreover, in these models, the humerus is moved manually to a given position within a trajectory and held in place while kinematic data are registered. This methodology introduces significant errors in measurement due to its dependence on the operator and reproduction of a specific motion or position over sequential repetitions. Most importantly, the dynamic nature of the shoulder motions is simplified and neglected.

In order to over come these limitations, we intended to employ in this project a novel passive cadaveric model which was previously developped by Dr. Claudio Rosso at the Beth Israel Deaconess Medical center with support of the Swiss National Research Foundation. As explained in section 1.3, the system involves the use of a full cadaveric torso, robotic technology for trajectory implementation along with bone markers for continuous stereophotogrammetric motion analysis (**Figure 1a, b**). Complex and normal shoulder motions can be simulated in the *entire* shoulder girdle of the cadaver. Therefore this model allows studying scapulothoracic *and* glenohumeral simultaneoulsy which was the crucial methodological requirement in this project.

1.2. Additional goals investigated during the course of the project

On the arrival of Dr. Marc Andreas Mueller at the Beth Israel Deaconess Medical Center, the novel testing apparatus was fully functional. However, the apparatus had to undergo a solid validation process before any clinically relevant data could be collected. Dr. Claudio Rosso already provided data which demonstrated a high accuracy and precision of robotic actuators. Nontheless, the accuracy and precision of the camera system to capture motion trajectories had to be additionally evaluated (see section 1.4.). Furthermore, we had to show the apparatus' capability to reliably capture kinematic data and to discern intact from pathologic shoulder conditions in a broad spectrum of anthropometrically different cadavers (see section 1.5.). As a first clinically relevant project, we studied the effect of scapular malpositioning on glenohumeral kinematics (see section 1.6.). This project served as a primary model in which we learned to analyze the interaction between GH and scapulothroacic kinematics. The current complexity of the system did not allow for arthroscopic interventions in the proposed rotator cuff project. Therefore, the creation of rotator cuff tears and repairs required removal of the deltoid to access the joint. However, we first had to ensure that this additional perturbation fo the system did not alter GH kinematcs (see section 1.6). Finally, we could turn towards the initially planned study and evaluate the effect of supraspinatus tears and repairs on GH and scapulothroacic kinematics (see section 1.7.)

1.3. Testing apparatus used to achieve the goals of this project

The system consists of a lower frame housing the cadaveric torso and an upper frame with a hand actuator connected to the wrist of the cadaver. Using robotic control, the hand actuator can be moved along three linear axes (X, Y. Z) to implement any given normal or complex shoulder motion (**Figure 1**). During testing, bone embedded marker clusters inserted into the humerus, scapula, and thorax of the cadaver are tracked by five calibrated high speed cameras. Anatomical landmarks that are calibrated with respect to these technical (bone-embedded) marker clusters using a point wan are used to create coordinate systems of the thorax and the scapula. These thoracic and scapular coordinate systems serve as a reference to register scapulothoracic and GH joint kinematics respectively. In addition, the calibrated landmarks can be used along with the equations outlined by Meskers et al to locate the GH center of rotation for each instance of time.

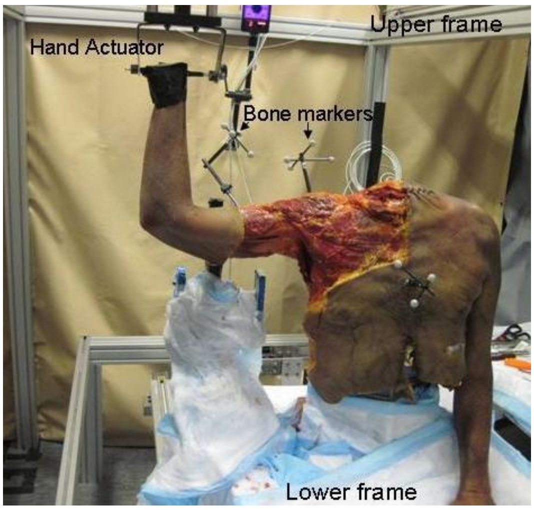

Figure 1: Testing apparatus

1.3. Evaluation of the accuracy and precision of the camera system of the testing apparatus

Methods:
The precision and accuracy of the camera system was calculated by comparing the magnitude of displacement of the hand and torso actuator through diagonal trajectories to displacement captured by the camera system. The diagonal trajectories consisted of four possible diagonals motions of the upper frame and two diagonal motions of the lower frame (that were tested in tree repeats. The retroflective marker clusters were placed on the hand actuator and the torso actuator on the base plate and their motion was tracked using the motion capturing cameras. .
Results:
The magnitude of each diagonal motion was reproducibly and accurately captured by the high speed cameras. The maximum standard deviation between the trials was 0.6 mm. The intraclass correlation coefficient calculated from the three repeats performed in each axes was consistently 1 with a high level of significance (p= 0.001).On average, the absolute error in observed magnitude of diagonal trajectories was 2.9 (± 2.2) mm for the upper frame and 7.0 (± 4.0) mm for the lower frame with percent errors of 0.0%.

1.4. Evaluation of the Robotic Apparatus for the Analysis of passive GH Joint Kinematics

Methods:
In order to streamline the validation of our system in respect to the capability to capture kinematic data in intact and pathologic shoulder conditions, we restricted the analyses to the measurements of GH joint translations, as they can be considered as clinically most relevant and at the same time the most difficult to measure. In order to cover the full spectrum of specimen sizes and shapes that can be tested in the apparatus, we included two shoulders of two anthropometrically different cadavers in this study. Likewise, we tested two characteristic shoulder pathologies, i.e. scapular winging, supraspinatus tears that are representative of other pathologies which are either distant or intrinsic to the GH

joint. For both types of these shoulder pathologies, GH translations were captured while the shoulders were subjected to three trials of humeral elevation.

Results:
The trajectories of GH translations obtained from the same cadaver were highly reproducible for a given condition. The standard deviations (SD) and intraclass correlation coefficients (ICC) calculated from the three sequential trials that were performed for each condition ranged from 0.16mm-0.64mm and from 0.77 to 0.97 respectively. Both ICCs and SDs were not significantly different between the conditions and the two cadavers tested. The system was consistently able to distinguish GH translations captured in intact shoulders from those recorded in pathologic shoulder conditions. (example, see **figure 2**). Nonetheless, although motion patterns of a given condition were repeatable in both cadavers, the absolute X-Y-Z coordinates of a given trajectory substantially differed between the two cadavers. This phenomenon may be explained by differences in tissue elasticity and the absence of muscle control in a passive cadaveric system. Yet, the inter-specimen variability implied that results of subsequent clinical studies must be subjected to paired statistical test.

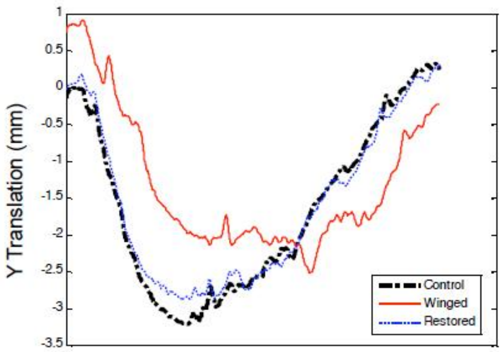

Figure 2: GH Translations captured after implementation and restoration of scapular winginging

1.5. The effect of scapular winging on GH kinematics

This first clinical project served as a model to understand the interactions between GH and scapulothoracic kinematics. Scapular winging is a common scapulothoracic disorder in pitchers. There is a current controversy if athletes with scapular winging are subject to increased anterior GH translations with consecutive instability. Thus, the goal of this study was to test, if scapular winging leads to a significant increase of anterior GH translations.

Methods: Six shoulders of three skinned, fresh frozen cadaveric torsos were tested in this study. The shoulders were subjected to three trials of an abbreviated throwing motion (ATM) (**Figure 3**) before and after simulation of scapular winging with a wedge put under the inferior angle of the scapula. During each motion, GH translations and scapular rotations were plotted over time. The difference between GH translations and scapular rotations captured in winged and non-winged shoulders was studied at specific points of the ATM motion as well as in the whole segment in between these points (**Figure 3**). In order to express the overall GH translations and scapular rotations occurring in a motion segment, the area under the curve (AUC) of a given trajectory was calculated.

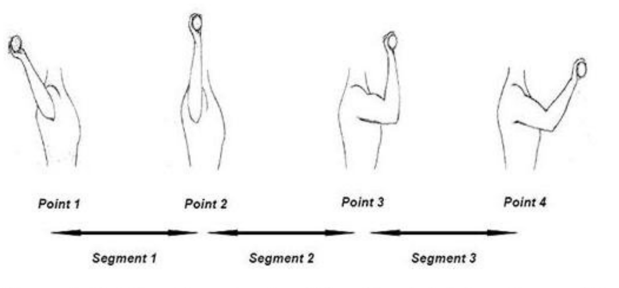

Figure 3: Points and segments of the abbreviated throwing motion

Results: Implementation of scapular winging led to a significant increase of scapular flexion and lateral rotation in all segments of the motion (P=0.001-0.025 and P=0.004-0.012, respectively). From maximal external rotation to neutral rotation (segment 1), scapular winging was associated with an increase of scapular internal rotations (AUC 170 ± 21 versus 145± 39 degrees*seconds, P= 0029) *and* anterior GH translations (AUC 14.5±11 versus 28.4±14.9mm*seconds, P= 0008). In conclusion, we could demonstrate that an increase of scapular internal rotation as seen with scapular winging is associated with a significant increase of anterior GH translations.

1.5. The effect of deltoid removal on GH Translations in a passive cadaveric system

For testing of shoulder pathologies intrinsic to the GH joint, the deltoid needs to be removed in the current testing set up. In this study we therefore evaluated if removal of the deltoid leads to a significant increase of GH translations in simulated normal shoulder motions and pitching.

Methods: Both shoulders of three fresh-frozen human torsos were tested in an intact specimen and after complete removal of the deltoid in three consecutive trials of abduction and abbreviated throwing motion (ATM). Differences of GH translations were again analysed by comparing absolute trajectoires at specific points of the motion as well as the area under the curve calculated within specific motion segments.

Results: Removal of the deltoid only lead to a significant increase of medio-lateral GH translations ($p = .003$) at 30-60° of abduction with values of 0.9 ± 0.4 mm.
No other significant different trajectories between the intact specimen and after deltoid removal could be found. In conclusion, we showed that deltoid removal does not to cause a clinically relevant change in abduction and an abbreviated throwing motion. These findings suggest that the bulk effect might play only a minor role in passive glenohumeral stabilization. Moreover, we concluded that the deltoid can be removed in subsequent studies that investigate pathologic conditions of the GH joint without additional alterations of the results.

1.5. The effect of deltoid removal on GH Translations in a passive cadaveric system

Methods: Six deltoid deficient shoulders from three skinned cadaveric torsos were enrolled in this study. Each deltoid deficient shoulder was first subjected to three trials of humeral elevation in the scapular plane and to an abbreviated throwing motion. The same motions were replicated after the creation of 1cm/3cm full thickness supraspinatus tear and after reapir of the supraspinatus tear in double row technique (**Figure 4**). Like in the two aformentionned studies, differences of GH translations and scapulothoracic rotations were analysed by comparing absolute trajectories at specific points of the motion as well as the area under the curve calculated within specific motion segments. Due to technical reasons, we had to refrain from the initially planned testing of partial tears and from the registration of tendon strains.

Results: The data analyses is still ongoing. However, current results suggest that for both motion tested, there was no significant differences between GH translations and scpulothoracic rotations either captured in deltoid deficient shoulders or in shoulder with 1cm/3cm supraspinatus tears and double row repairs. These data support the hypothesis that the supraspinatus does not provide passive stability of the GH joint. In addition, any alteration of the scapulothroacic kinematics observed in patients with rotator cuff tears may not be due to the lesion itself, but more secondary to pain experienced by the patient.

<u>2. Conferences:</u>

The following abstracts were accepted for the Orthopedic Research Society congress in San Francisco, February 2012:

1.) Evaluation of a robotic apparatus for the analysis of passive glenohumeral joint kinematics
2.) Design and Manufacture of A Novel System to Simulate the Real Time Biomechanics of Basic and Pitching Shoulder Motion using a Cadaveric Model

The following presentation was held at the SGOT congress 2012 in Basel:

1.) The effect of scapular winging on glenohumeral translations

The following abstract was accepted at the DKOU congress in Berlin 2012:

1.) Evaluation of a robotic apparatus for the analysis of passive glenohumeral joint kinematics

3. Publications

The following mansucripts were written based on the generated data with Dr.Marc Andreas Mueller either as a coauthor (1), second author (2,3) or **first author (4)** (all manuscripts have been submitted).

1. Design and Manufacture of A Novel System to Simulate the Real Time Biomechanics of Basic and Pitching Shoulder Motion using a Cadaveric Model. Accepted in Bone and Joint Research
2. Evaluation of a robotic apparatus for the analysis of passive glenohumeral joint kinematics, under Review in Bone and Joint Research
3. The role of the deltoid muscle in basic and pitching shoulder motions using a cadaveric model, under Review in C
4. **The effect of scapular winging on glenohumeral translations, accepted in Journal of Shoulder and elbow surgery**
5. The effect of supraspinatus tears and repairs on glenohumeral translations in simulated pitching motion; manuscript in preparation phase.

In some manuscripts (2,3) authroship was committed to Dr. Claudio Rosso as an apprecciation of his previous work to develop the methodology used in this project.