MSC. THESIS - UNPUBLISHED MANUSCRIPT

The effects of fatigue on Scapulothoracic kinematics during total shoulder abduction.

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Abstract

Introduction: Recently, scapular muscle fatigue during an elevation task was found to alter scapular kinematics. Muscle fatigue may be a key factor in the development of shoulder and neck discomfort and pain. Shoulder girdle muscle fatigue has been shown to alter scapulothoracic kinematics. However it is unclear whether muscle fatigue results in increased or decreased scapular upwards rotation.

Aim: The focus of this study is to examine the effects of shoulder muscle fatigue on the 3-dimensional scapular kinematics during arm elevation, using the Qualisys motion capture system. We aim to examine whether an upwards displacement of the humerus, increased anterior tilting of the scapula and increased upwards rotation will result from fatigue, kinematic changes suspected to cause a shortening of the subacromial space and leading to the development of shoulder pain.

Methods: Nine healthy subjects took part in the study and data for six subjects completing five repetitions of elevation and lowering in the scapular plane abduction was obtained, before and after a fatigue protocol. Maximum voluntary isometric contraction force which served as a measure of local muscle fatigue in this study was measured with the subjects standing on a force plate performing maximum voluntary isometric contractions of the shoulder while pushing up against a strap attached to the floor besides the force platform. Realtime 3-dimensional kinematics was recorded during the repetitons of shoulder elevation using a Qualisys Motion capture system.

Results: There was a significant drop in force between conditions indicating local muscle fatigue. The results of this study indicate that overall muscular fatigue of the shoulder affects scapulothoracic and glenohumeral kinematics. There was a significant effect of fatigue for Anterior/posterior tilt of the scapula after the fatiguing exercise, with a mean increase of 4.13°and a maximal increase of 7.73°anterior tilt however small, this represented a change in rotation of almost 45%.

Conclusion: This study showed that small but potentially clinically significant changes in scapular kinematics were found after a shoulder fatigue protocol. An increase in scapular anterior tilt, humeral internal rotation, flexion and abduction in the early phases of shoulder elevation was found after fatigue

Keywords: Scapular position; Pain; Overhead Athlete; Shoulder

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1 Introduction

Shoulder pain is frequently reported in individuals who use their arms in a repetitive manner during work or recreational activities [McBeth & Jones, 2007]. In sports medicine the term "athlete's shoulder" Has found its way into the literature in the last two decades [Doyscher *et al.* , 2014, Walker-Bone *et al.* , 2004, Micheli, 2010], and the shoulder pathologies of overhead athletes has become a special term in clinical sports medicine [Doyscher *et al.* , 2014, Micheli, 2010]. The term shoulder impingement describes pain in the shoulder region as a result of mechanical 'impingement' of the rotator cuff as it passes under the coraco-acromial ligament [Neer & Welsh, 1977, Khan *et al.* , 2013]. Rotator cuff disorders are considered to be among the most common causes of shoulder pain and disability encountered in both primary and secondary care, with subacromial impingement syndrome in particular being the most common disorder, resulting in functional loss and disability, of the shoulder [Michener *et al.* , 2003]. The concept of shoulder impingement syndrome is attributed to Charles Neer following his paper published in 1972 [Neer, 1972]. The term shoulder impingement itself however now belongs to a group of terms that essentially describes pain in the shoulder region as a result of mechanical 'impingement' of the rotator cuff as it passes under the coraco-acromial ligament. If left untreated rotator cuff impingement may proceed to partial or complete rotator cuff tendon rupture [Neer & Welsh, 1977, Khan *et al.* , 2013].

The causes of shoulder pain and dysfunction in the overhead athlete are controversial [Burkhart *et al.* , 2003, Grainger, 2008, Heyworth & Williams, 2009, Kvist & Bang, 2015], with several proposed theories relating to the various pathological changes observed, including subacromial impingement [Neer & Welsh, 1977] [Borstad & Ludewig, 2005] [Smith *et al.* , 2006], Instability [Jobe *et al.* , 1989], tendon tension overload [Park *et al.* , 2002], internal impingement [McFarland *et al.* , 2006, Walch *et al.* , 1992], physical load factors [Walker-Bone *et al.* , 2004], and fatigue [Joshi *et al.* , 2011]. The common precursor is that underlying mechanisms lead to alterations in the positioning of the shoulder during loading, and that the biomechanical consequences of that altered positioning may be the overloading of certain structures of the shoulder [Comerford & Mottram, 2001] [Joshi *et al.* , 2011] [Park *et al.* , 2002, Walker-Bone *et al.* , 2004]. Scapular muscle fatigue during an elevation task was found to alter scapular kinematics [McQuade *et al.* , 1995] [McQuade *et al.* , 1998b] [Ebaugh *et al.* , 2006]. Muscle fatigue may be a key factor in the development of shoulder and neck discomfort and pain [Sundelin, 1993, Sundelin & Hagberg, 1992]. Several factors, such as arm position, repetitive work with and without pauses, torque level, and work pace, have been investigated to determine their effects on muscle fatigue and discomfort [Sundelin, 1993] [Hagberg, 1981] [Gerdle *et al.* , 1993] [Tsai *et al.* , 2003].

McQuade et al found that shoulder fatigue directly affects the way in which the scapula moves concomitantly with the humerus. Fatigue tends to result in destabilization of the scapula or compensatory increased rotation primarily in the midrange to end range of arm elevation which alters the scapulohumeral rhythm [McQuade *et al.* , 1995]. Jobe et al stated that because stability and function are so interrelated, almost all sports injuries to the shoulder are related in some way to instability [Jobe *et al.* , 1989, Jobe *et al.* , 1990, McQuade *et al.* , 1995]. Athletic performance and precision of movements may deteriorate with muscular fatigue [Lephart & Jari, 2002, McQuade *et al.* , 1995, Kocher *et al.* , 1993]. A current clinical belief is that when weakness is present in the scapular musculature this will affect normal scapular positioning [Paine & Voight, 2013, McQuade *et al.* , 1995]. It has been suggested that if excess motion of the scapula occurs, this might place increased stress on the glenohumeral capsular structures and lead to increased glenohumeral instability. Abrams reported that pitchers throwing with "a malpositioned scapula" resulted in "overstressing the rotator cuff to complete the throw" [Abrams, 1991, McQuade *et al.* , 1995]. Malpositioning of the scapula for any given

arm configuration may also influence the instantaneous center of shoulder rotation, which could significantly alter moments of force generated about the shoulder [McQuade *et al.* , 1995].
In a recent 2 year prospective study on scapular positioning and shoulder pain in 113 overhead athletes Struyf et al (2014) [Struyf *et al.* , 2014] observed, that the athletes who developed shoulder pain demonstrated, significantly less upward scapular rotation at 45°and 90°of shoulder abduction in the frontal plane. Several other studies have shown correlations between reduced scapular mobility in overhead athletes and shoulder pain [Atalar *et al.* , 2009], [Struyf *et al.* , 2009], [Kvist & Bang, 2015]. In a study of the effects of local muscle fatigue, McQuade et al found that the scapulohumeral rhythm decreased, by an increase in scapular upwards rotation, as the muscles fatigued[McQuade *et al.* , 1995]. This increased scapular motion may be a compensatory response to rotate the acromion up ward and backward out of the way to decrease the possibility of subacromial impingement. The increased scapular motion may also represent an attempt to increase the length of the deltoid or supraspinatus to maintain an efficient length-tension relationship or to increase the moment arm of the deltoid to compensate for reduced deltoid muscle force-generating potential [McQuade *et al.* , 1995]. McQuade et al also correlated changes in median power frequency with changes in the scapulohumeral rythm, implying an association between the local muscular dynamics and the joint kinematics. However a direct cause-and-effect inferences were not justified because the kinematic changes seen may also be related to other muscular dynamics [McQuade *et al.* , 1995]. For example, if the rotator cuff was fatigued, this might have resulted in a reduced ability of the rotator cuff muscles to prevent the deltoid from pulling the head of the humerus superiorly into an impingement position under the subacromial arch [McQuade *et al.* , 1995].
The infraspinatus and teres minor muscles are considered the primary external rotators of the glenohumeral joint. [Pratt, 1994]. Additionally, these 2 muscles have been studied and described as having other functions with respect to the glenohumeral joint, such as contributing to arm abduction [Colachis & Strohm, 1971, Kuechle *et al.* , 1997, Howell *et al.* , 1986], prevention of anterior joint instability [Cain *et al.* , 1987, Kronberg *et al.* , 1990, Otis *et al.* , 1994], and production of force couples around the glenohumeral joint for dynamic stabilization [Inman *et al.* , 1944, Itoi *et al.* , 1996, Thompson *et al.* , 1996]. Simultaneous contraction of the rotator cuff muscles produces a moment that assists in arm elevation as well as a downward-directed joint reaction force that acts to neutralize the upward shear force produced by the deltoid muscle contraction. This dual function is facilitated by the wide tendinous insertions of these muscles above and below the humeral head's center of rotation [Sharkey *et al.* , 1994]. Due to the multiple functions of the infraspinatus and teres minor muscles at the glenohumeral joint, a deficiency of these 2 muscles may result in problems other than just causing weakness in shoulder external rotation [Tsai *et al.* , 2003]. Alterations in the normal kinematic patterns, were the subluxating shear forces created, in addition to the desired actions, by the purposeful motion of the large external muscles, cause superior humeral head translation and scapula reorientation, thereby reducing the subacromial space, is a suspected mechanism in leading to a condition were over time Impingement and attrition syndromes would be common consequences [Perry, 1983, Hudson, 2010].

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2 Aim

The focus of this study is to examine the effects of shoulder muscle fatigue on the 3-dimensional scapular kinematics during arm elevation, using the Qualisys motion capture system. We aim to examine whether an upwards displacement of the humerus, increased anterior tilting of the scapula and increased upwards rotation will result from fatigue, kinematic changes suspected to cause a shortening of the subacromial space and leading to the development of shoulder pain[Ebaugh *et al.* , 2006] [McQuade *et al.* , 1998a]. The mechanisms involved in leading to impingement syndrome are likely to be a multifactorial in origin. Any cause which leads to a dysfunction of either glenohumeral and/or scapulothoracic movement may lead to subacromial impingement also in athletes where repetitive overhead activity is required [Jobe *et al.* , 1989] [Doyscher *et al.* , 2014].

Struyf et al. reviewed the literature in scapular positioning between unimpaired shoulders and in shoulder impingement. They found differences between these groups and although the literature was inconsistent regarding scapular resting position. During shoulder elevation, they found most researchers agreed that the scapula tilts posteriorly and rotates both upward and externally. In patients with shoulder impingement however they found that there was a decreased upward scapular rotation, a decreased posterior tilt, and a decrease in external rotation [Struyf *et al.* , 2014]. Shoulder girdle muscle fatigue has been shown to alter scapulothoracic kinematics [McQuade *et al.* , 1995, McQuade *et al.* , 1998a, Ebaugh *et al.* , 2006]. However it is unclear whether muscle fatigue results in increased [McQuade *et al.* , 1998a, Ebaugh *et al.* , 2006] or decreased scapular upwards rotation [McQuade *et al.* , 1995, Tsai *et al.* , 2003]. McQuade et al reported results from a pilot study on four subjects looking at the effects of fatigue on the scapulohumeral rythm [McQuade *et al.* , 1995] and found that two out of the four subjects there seemed to be an increase in the scapulohumeral ratio following fatigue. The study was limited by the small sample size, relied on static measurement techniques and didn't consider the nonlinearity of the scapulohumeral rythm. McQuade et al followed up their study taking these limitations into account using dynamic measurement techniques, a larger sample size and accounting for the nonlinearity of the scapulohumeral rythm, however here they found that the scapulohumeral rythm decreased as the muscles fatigued [McQuade *et al.* , 1998b]. Tsai et al. included the effects of muscle fatigue on scapular tilt and external rotation where they found decreased posterior tilt, and external rotation after the external rotator muscles were fatigued [Tsai *et al.* , 2003]. Ebaugh et al reported changes in upward rotation that were more than twice those reported in the 1998 McQuade et al study [Ebaugh *et al.* , 2006] [McQuade *et al.* , 1998a]. This may be due to the fact that their fatigue protocol consisted of several tasks compared to the one in the McQuade et al study. Although the findings of Ebaugh et al related to scapular upward rotation was in agreement with those of the 1998 McQuade et al study [Ebaugh *et al.* , 2006] [McQuade *et al.* , 1998a], the direction of change was opposite to that reported in the 1995 McQuade et al study and the more recent findings of Tsai et al [Tsai *et al.* , 2003]. Both of these studies reported less upward rotation of the scapula after the shoulder muscles had been fatigued[McQuade *et al.* , 1995], [Tsai *et al.* , 2003]. Although there seem to be evidence linking fatigue to kinematic changes of the shoulder some controversy remain regarding the nature of these kinematic changes and their implications. Most of the aforementioned studies of scapular kinematics used the Polhemus Fastrak magnetic tracking device [Ebaugh *et al.* , 2006] [McQuade *et al.* , 1998a] [Tsai *et al.* , 2003], this system set the gold standard in motion tracking years ago, however Polhemus systems are not certified for medical or bio-medical use. We wanted to use the Qualisys Motion Capture system since Qualisys is certified according to ISO 9001:2015 and compliant with Medical Device Directive 93/42/EEC and the system allows users to perform 2D, 3D and 6DOF capture of data in real-time, with minimal latency.

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The focus of this study is examining the possiblity of using the Qualisys Motion Capture system on the shoulder to study the possible link between fatigue and kinematic changes in the form of Scapular reorientation or changes in the glenohumeral rhythm, Upwards displacement of the humerus or increased anterior tilting of the scapula. Finding new ways to examine Fatigue related mechanism, suspected in shortening the subacromial space and leading to the development of shoulder pain, could help lead to better understanding of the pathology of shoulder pain and prevention of injury in overhead athletes.

3 Methods

Nine healthy subjects took part in the study and completed five repetitions of elevation and lowering in the scapular plane abduction, before and after a fatigue protocol involving bouts of shoulder elevation in the frontal and scapular plane with the resistance of a dumbell. Maximum voluntary isometric contraction force which served as a measure of local muscle fatigue in this study was measured with the subjects standing on a force plate performing maximum voluntary isometric contractions of the shoulder while pushing up against a strap attached to the floor besides the force platform. Realtime 3-dimensional kinematics was recorded during the repetitons of shoulder elevation using a Qualisys Motion capture system.

3.1 Equipment

- Force Plate (AMTI, AUC LBNR 08954,Serial No: 4009, Model No: OR6-7-1000)
- Force Plate Reciever (Advanced Mechanical Technology, Inc. AMTI,Model No: MCA6,Serial No: 3763)
- 8 Motion Capture Cameras (Qualisys Oqus PRODNR: 310 4041 000)
- DAQ (National Instruments Model: BNC-2090, Part NO: 183468A-01 Rev: 1_,Serial NO: C3D668)
- Calibration kit (Qualisys:Type 130440, Wandkif 750, Qualisys AB Sweden)
- Computer with Qualisys Track Manager software (DELL PRECISION T3400)
- Tracking markers

3.2 MVIC

A Force Plate (AMTI) was used to record the resistive force generated during an isometric contraction of the shoulder muscles. The resistive force represented a measure of muscle strength, and was used as a basis for establishing the presence of fatigue. Additionally, this measure was used to determine the amount of weight each subject would lift during the fatigue protocol. The subjects were standing upright on the force platform with the arms extended out along the side of the body at a 45°angle, holding onto the handle the subjects were instructed to keep their elbows and knees straight, and trunk upright using only shoulder elevation to pull on the handle. Subjects performed a maximal voluntary isometric contraction (MVIC) by pulling up against the handle for 5 s. This was repeated three times with a 30 s rest between trials. Shoulder muscle strength was determined by averaging the maximum resistive force from a 1 s time period (3.5-4.5 s) from each trial. MVIC force measures were used as indicators of local muscle fatigue [De Luca, 1993] [Lindstrom *et al.* , 1977][Ebaugh *et al.* , 2006].

3.3 Study procedure

Nine subjects took part in this study with a mean age 26.22 ± 3.77 height 178.78 ± 7.61 and weight 75.67 ± 10.84. The subjects was informed about the study, and a written consent was signed, and subject information was collected: age, height, level of activity and if they had any old injuries. Then 22 kinematic markers was placed on the following places..

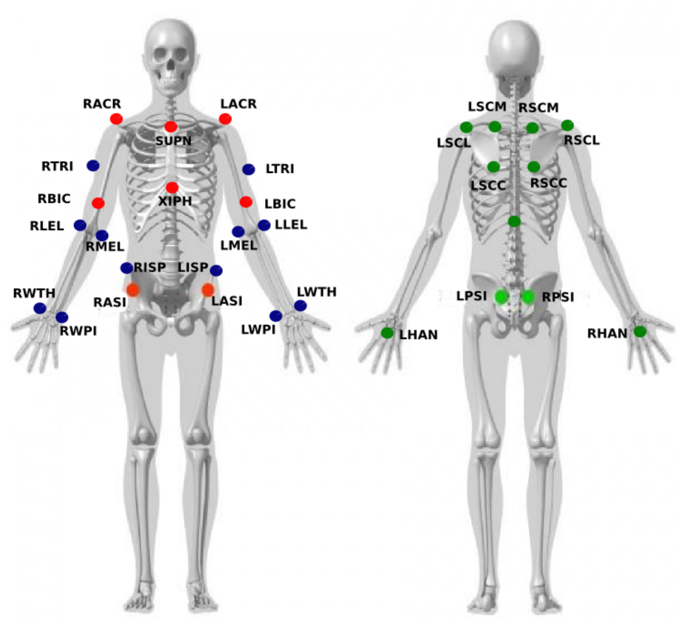


Figure 1 Markerplacement figure, redrawn from https://www.c-motion.com/v3dwiki/index.php?title=Marker$_{set_{G}uidelines}$

The study included a familiarization period before starting the test. The purpose of the familiarization period was to introduce the test subjects to the study and give them a feeling of the equipment they had to use for the test in the lab. To familiarize them with the equipment and testing procedure by pulling the straps besides the force plate. To familiarize the subjects with the weights used, a 1-5 kilograms dumb bell was held and lifted for a few warmup reps. After the familiarization and a breif warmup the subjects performed a number of Maximum Voluntary Isometric Contractions (MVC's) by pulling on the straps while standing on the force plate, and baseline measures of Maximum voluntary Contraction Force were collected.

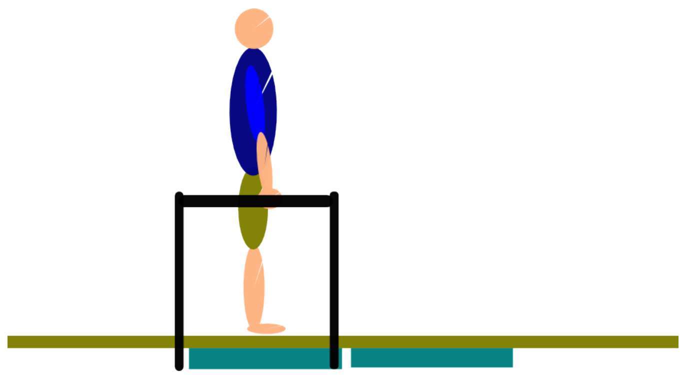


Figure 2 MVC setup drawing, In order to acquire MVC measures subjects were standing on the force platform with their arms along the side of the body, and were instructed to pull up into the handle with their maximum strength shoulder elevation, keeping the knees and trunk straight throughout. This step was performed prior to and immediately following the fatigue protocol.

Following the MVIC protocol the subjects were asked to stand still, holding their hands by the side with the thumbs pointing outwards for 20 seconds while a static calibration trail was recorded. Then baseline kinematic measures was collected, using the Qualisys motion tracking system while the subjects performed a number of maximal scapular plane arm elevation against resistance. For these trials females held a 1.4 kg weight and males held a 2.3 kg weight in their hand. Subjects were instructed to stand upright on a force plate with their feet flat on the floor and raise their arm in the scapular plane which was defined as 40°($\pm$10) °anterior to the frontal plane and also in the frontal plane. Subjects were told to raise and lower their hand over their head with their thumb pointing up. Each trial of arm elevation was performed to a count of 8 s; 4 s to raise their arm and 4 s to lower them. Verbal feedback was provided during the testing to ensure the subjects maintained the same plane of elevation and thumbs up position. These baseline measures represented the pre fatigue condition. Next, the subjects performed a fatigue protocol. In order to fatigue the shoulder girdle muscles, subjects was asked to perform two tasks. During task one subjects was asked to raise and lower their arms, with their elbow in full extension, subjects performed 20 repetitions of arm elevation in the plane of the scapula, against resistance. A dumbell provided the resistance and the amount of weight that subjects lifted for the entire fatigue protocol was targeted at 20 percent of the force that was recorded during the MVIC. For the second task the subjects were asked to raise and lower their arm through a frontal pattern against resistance. The frontal pattern began with the hand of the tested arm resting at the hip. With their elbow in full extension, subjects raised their hand forward up and over the head, and then lowered their arm back down to the starting position and repeated this twenty times. Upon completion of the second activity, subjects immediately returned to the first activity and rotated through the two activities until one of two criteria was met: The subjects reported that they were unable to continue to perform the required tasks, or the subjects failed to correctly perform two tasks in a row. Failure was defined as follows: an inability to move through the required motion more than two times, and/or altering their posture (more than two times) by leaning the trunk, the investigator provided them with verbal feedback to remind them that they are to maintain an upright posture. Upon completing the fatigue protocol, subjects repeated the procedures for obtaining MVIC measures of fatigue, and kinematic measures during arm elevation. Approximately 2 min elapsed from when subjects reached fatigue to when they repeated the trials of arm elevation.

3.4 Setup and software

A Qualisys Motion Capture system certified according to ISO 9001:2015 and compliant with Medical Device Directive 93/42/EEC was used to capture 3D data in realtime in this study. The computer running the Qualisys Track Mannager (QTM) software, was setup by importing the relevant models, calibrating the connected motion capture cameras and force plates.

The reporting of this study was done using Emacs Org mode,

a computing environment for authoring mixed natural and computer language documents. General methods for using Emacs org-mode in scientific publishing have been described by [Schulte *et al.* , 2012]. Statistical calculations was done using R a programming language and software environment for statistical computing and graphics.

4 Data analysis

The kinematic data for scapular orientation and position were described using three scapular and three humeral rotations as dependent variables that were plotted against humeral elevation as the independent variable. Following the collection of kinematic data, a linear interpolation function was used to obtain data at 10°increments.

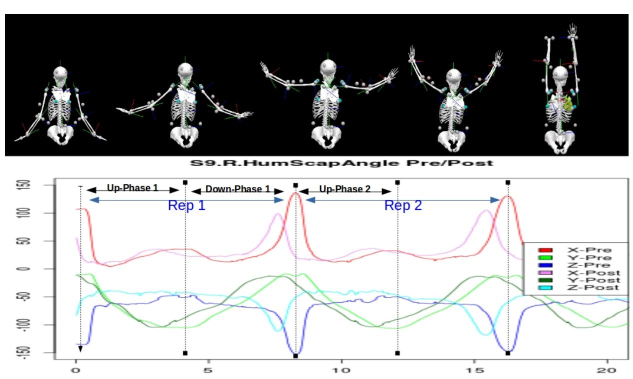


Figure 3 Each trail consists of a number of repetitions of shoulder elevation in the scapular plane. Still frames of one elevation phase and cutout plots of two reps.

The figure shows still frames of one up-phase, the first 4 seconds on the graphical representation below the still frames. The subjects were asked to complete one rep of shoulder elevation on the count of 4 seconds. However using the linear interpolation function we are going to reduce the data by averaging the reps pre and post based on humeral elevation in 10°increments.

4.1 Statistical analysis

A analysis of variance (ANOVA) with three repeated factors, condition, side and humeral elevation was performed on each dependent variable. The dependent variables of interest in this study were scapular external/internal rotation, posterior/anterior tilting, and upwards/downwards rotation. A significance level of 0.05 was was used for the ANOVA for each of the dependent variables. Post hoc Tukey honest significant difference tests were used for follow up analysis.

$$aov(JointAngle \sim Humeral.Elevation + Condition * Side$$

We are interested in how JointAngle changes as a function of the Humeral elevation and condition (Pre/Post). (Thus the JointAngle ˜Humeral.Elevation+ Condition) and the asterisk of (*Side) specifies that we want to look at the interaction between the two IVs as well. This specifies we want to check for differences left to right and left to right by condition aswell .

5 Results

5.1 Subject characteristics

SID	Age	Height	Weight	Gender
1	27	175	72	M
2	33	162	57	F
3	31	186	91	M
4	27	184	64	M
5	24	181	75	M
6	23	180	85	M
7	22	179	80	M
8	23	187	85	M
9	26	175	72	M
Mean	26.22	178.78	75.67	
Sd	3.77	7.61	10.84	

5.2 Mvc

There was a significant drop in force between conditions indicating local muscle fatigue.

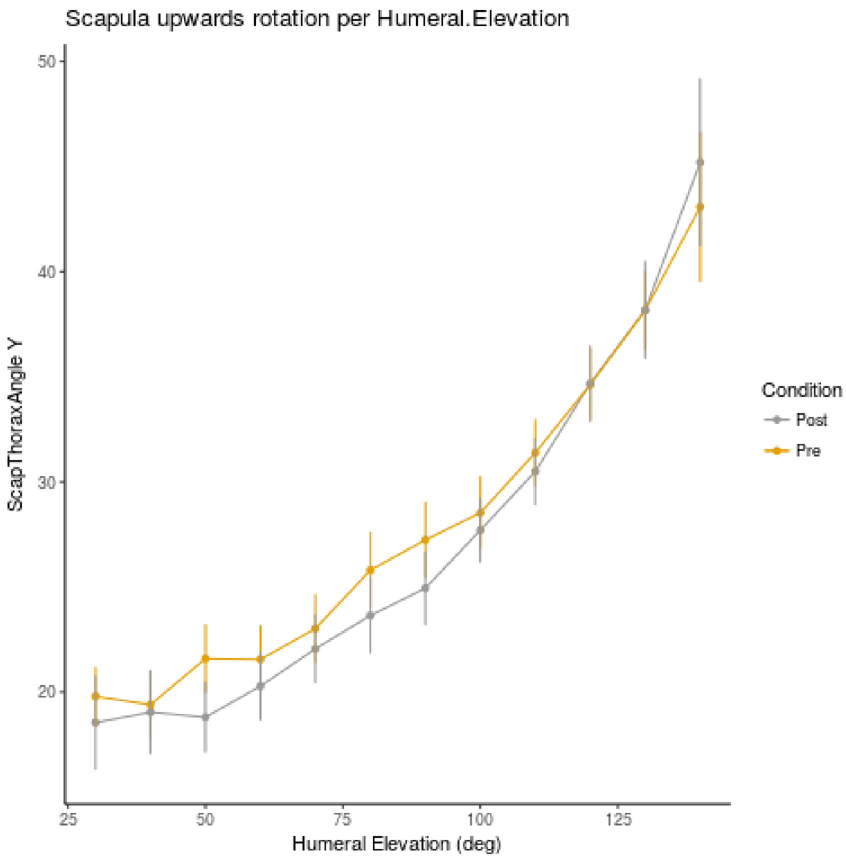
SID	Mean.mvc.pre	Mean.mvc.post	Change
1	16.86878	15.64313	-1.22565
2	8.451326	7.337854	-1.113472
3	24.96045	20.02021	-4.94024
4	18.04711	13.35976	-4.687353
5	20.58173	16.58086	-4.000871
6	27.0423	23.99754	-3.044753
7	31.82551	24.1403	-7.685208
8	31.94811	29.31615	-2.631965
9	17.57484	18.56151	0.9866686
Mean	21.9224	18.77303	-3.149205
SD	7.1974	6.552951	2.552022

```
Paired t-test


data:  Mean.mvc.post and Mean.mvc.pre

t = -3.702, df = 8, p-value = 0.006025

alternative hypothesis: true difference in means is not equal to 0

95 percent confidence interval:

 -5.110863 -1.187546

sample estimates:

mean of the differences

              -3.149205
```

5.3 Kinematics

Of the nine subjects taking part in this study we were able to obtain kinematic data for both conditions for only six subjects, three subjects had to be excluded from the analysis, one subject was excluded since a number of markers fell of due to sweating in the post fatigue measurement, rendering it incomplete. The other subjects were excluded due to incomplete tracking of markers, or unforeseen interference from reflective pieces of clothing. .

5.3.1 ***Scapular Upwards rotation (STY)***

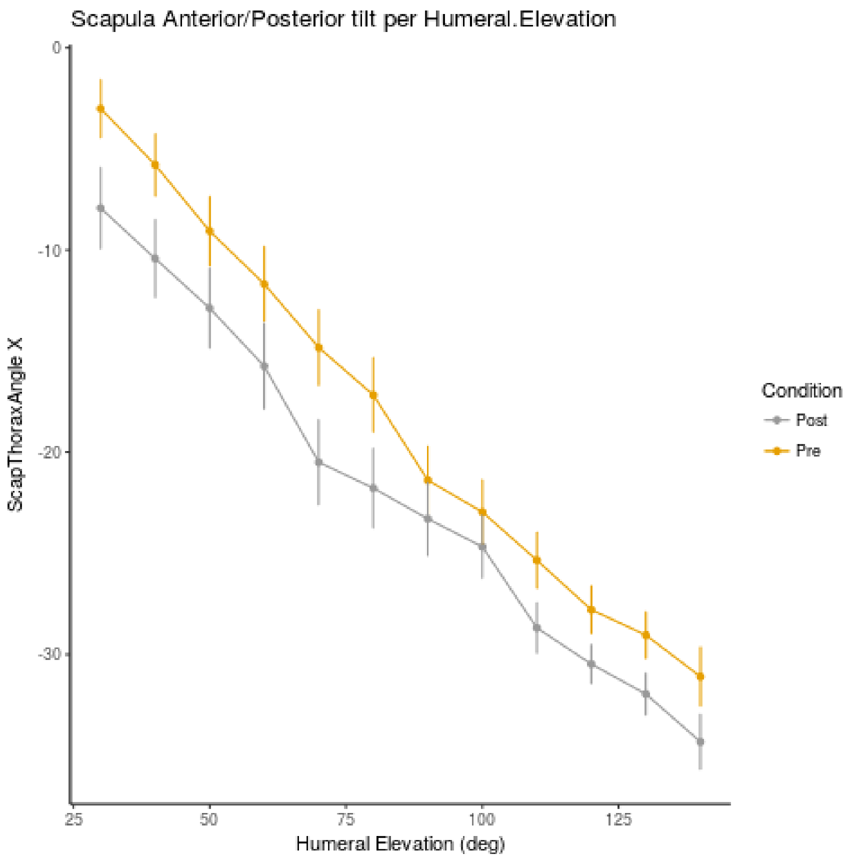


The mean change for scapular upwards rotation (STY) was (-0.9562°) with a stan- dard deviation ranging from 1.460°to 3.83°, there where no main effects of condition or interaction effects between condition and side, but there did seem to be a signifi- cant difference between the left and right sides (df = 1, F = 12.62, p.adj = 0.0168), post hoc tukey hsd test revealed a difference of 3.095°with a CI of 0.562 to 5.628°. With the right shoulder being significantly more upwards rotated, in the early phases of humeral elevation, than the left under both conditions.

Change scores with sd

STY	sdSTY
Min. :-2.7854	Min. :1.460
1st Qu.:-1.8602	1st Qu.:1.619
Median :-0.9280	Median :1.750
Mean :-0.9562	Mean :1.919
3rd Qu.:-0.2918	3rd Qu.:1.805
Max. : 2.1221	Max. :3.830

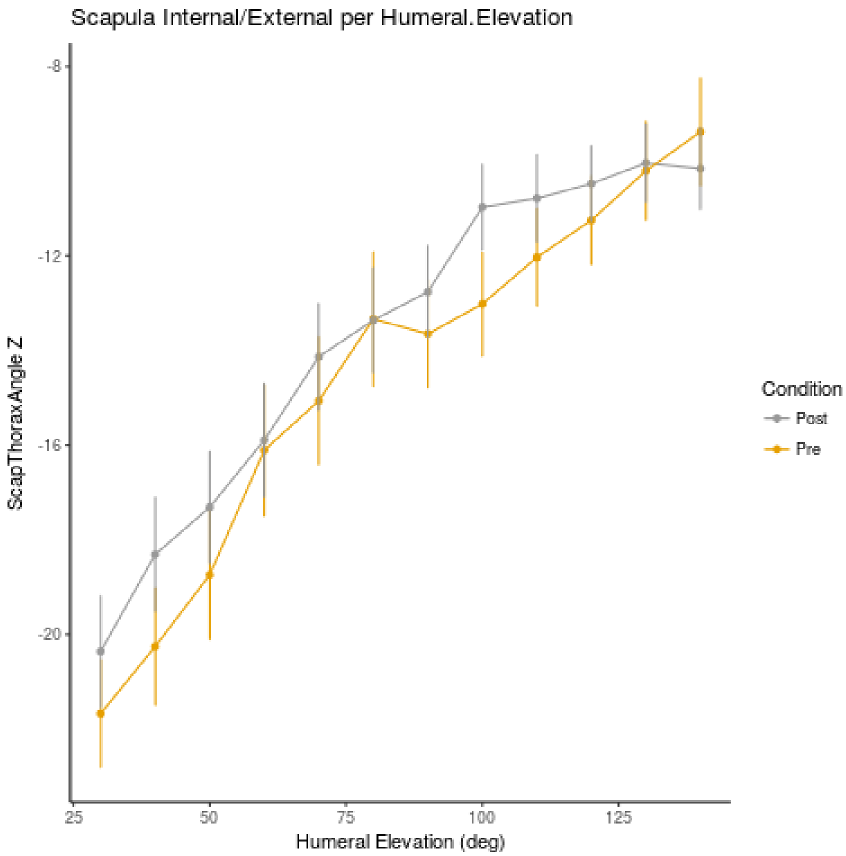
5.3.2 Scapular Anterior- posterior tilting change (STX)



The mean change for scapular anterior tilting (STX) was -4.1263°with a standard error of measurement for each point ranging from 1.083°to 2.311°. A main effect of Condition was observed ($df = 1, F = 34.962, p.adj = 0.0007629$) of 4.126°Confidence interval 1.739 - 6.513°. With the scapula being significantly more anteriorly tilted after fatigue. The post hoc test revealed that although a change was seen in both sides it was the left side pre-post scores that were significantly different, with the scapula being 4.62°more anteriorly tilted after fatigue (p.adj=0.037) confidence interval of 0.196 to 9.059. **Change scores with sd**

STX	sdSTX
Min. :-7.7338	Min. :1.083
1st Qu.:-5.0960	1st Qu.:1.510
Median :-3.9280	Median :1.753
Mean :-4.1263	Mean :1.728
3rd Qu.:-3.1507	3rd Qu.:1.991
Max. :-0.6182	Max. :2.311

5.3.3 Scapular internal rotation change STZ

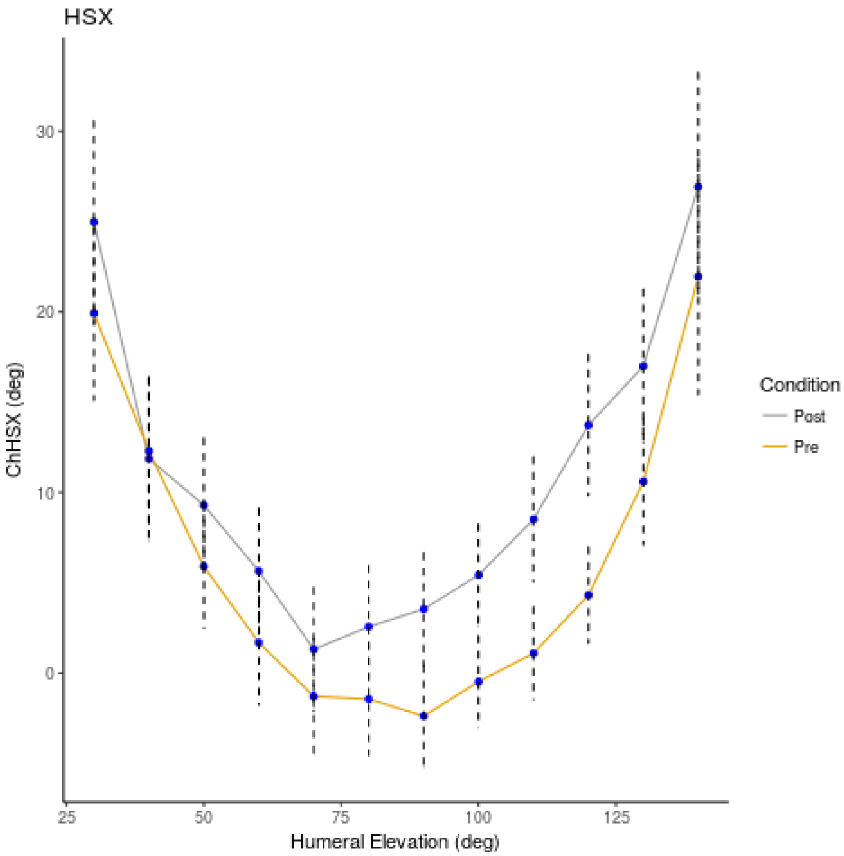


The mean change (Post-Pre) for scapular internal rotation STZ was 0.8804°with a standard error of measurement ranging from 0.8733°to 1.2975°. There where no main effects of condition or interaction effects $p > 0.05$. A significant difference was observed between the left and right sides ($df = 1, F = 8.915, p.adj = 0.005$) of -2.947°Confidence interval -0.896°- -4.999°, with the right side scapula being more internally rotated under both conditions.

Change scores with sd

STZ	sdSTZ
Min. :-0.7774	Min. :0.8733
1st Qu.: 0.2013	1st Qu.:1.0057
Median : 0.8804	Median :1.1129
Mean : 0.8783	Mean :1.1137
3rd Qu.: 1.3402	3rd Qu.:1.2396
Max. : 2.8095	Max. :1.2975

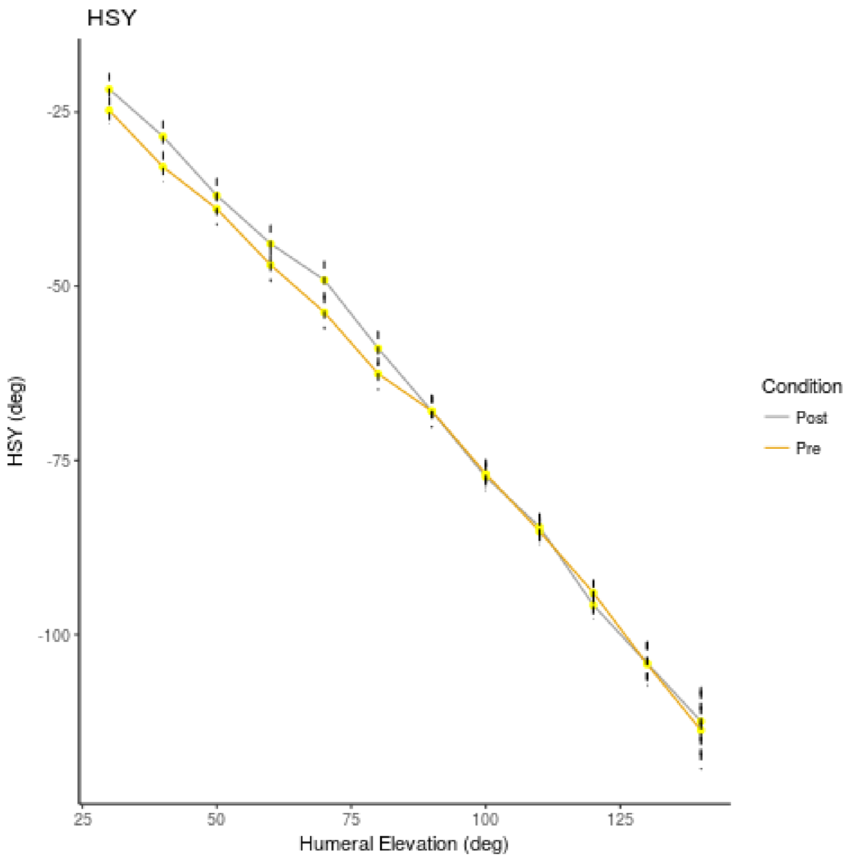
5.3.4 Humeral flexion/extension rotation Change HSX



The, mean change in humeral flexion/extension rotation angle STX was 3.762°with a standard error of measurement ranging from 2.687°to 6.438°. A main effect of condition was observed ($df = 1, F = 8.392, p.adj = 0.014$) of -3.762°CI -0.758–6.766, with an increase in humeral flexion angle and a earlier onset of flexion with fatigue, and also a significant difference left to right ($df = 1, F = 13.969, p.adj = 0.0016$) of 4.853°Lower CI 1.849 and Upper CI 7.85, with the right shoulder being more in flexion than the left. **Change scores with sd**

Stat	HSX	sd(HSX)
Min.	-2.988	2.687
1st Qu.	2.477	3.295
Median	3.982	3.595
Mean	3.762	3.820
3rd Qu.	5.553	3.962
Max.	9.411	6.438

5.3.5 *Humeral abduction/adduction angle change HSY*

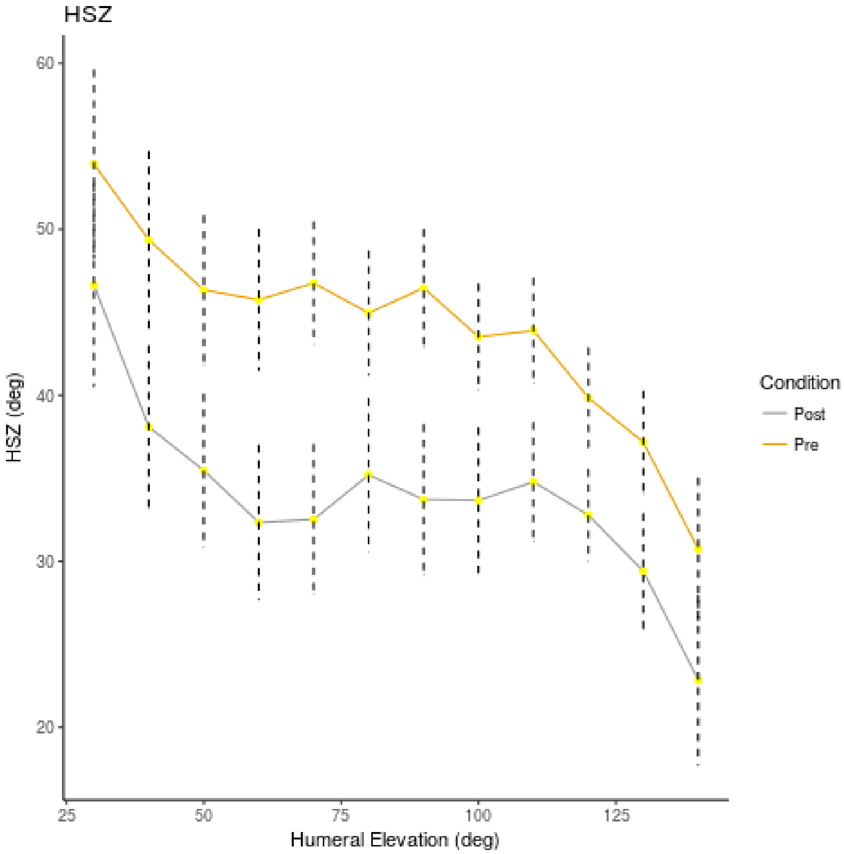


The mean change in humeral abduction angle was 2.8174°with a standard deviation measuring from 1.667°to 5.242°. A main effect of condition was observed ($df = 1, F15.726, p.adj < 0.001$) Pre-Post of -2.187 Confidence Interval -1.428 to -4.205°, in the early phases of humeral elevation, with a slight increase in abduction for both shoulders.

Change scores with sd

HSY	sdHSY
Min. :-1.7735	Min. :1.667
1st Qu.: 0.6902	1st Qu.:2.080
Median : 3.0472	Median :2.360
Mean : 2.8174	Mean :2.505
3rd Qu.: 4.4325	3rd Qu.:2.544
Max. : 6.8687	Max. :5.242

5.3.6 Humeral internal/external (axial) rotation change



The mean humeral axial Z rotation change (Post-Pre) was -0.9536 with a standard error of measurement ranging from 2.895°to 5.893°. There where no main effects of condition given the difference in sign conventions for left and right axial rotation, but taking that into account we do see a significant effect of condition by side with the humerus being significantly more internally rotated with fatigue. With a 10.1°difference Confidence Inteval 5.38 to 14.82°($p.adj < 0.05$) Pre-Post on the left side and a 8.2°difference on the right confidence interval 3.5 to 13°($p.adj < 0.05$).

Change scores with sd

HSZ	sdHSZ
Min. :-14.2268	Min. :2.895
1st Qu.: -9.7795	1st Qu.:3.595
Median : -0.7661	Median :4.065
Mean : -0.9536	Mean :4.182
3rd Qu.: 7.0030	3rd Qu.:4.588
Max. : 12.7707	Max. :5.893

6 Discussion

There was a significant drop in force between conditions indicating local muscle fatigue, we obtanied kinematic recordings for both conditions for only six of the nine subjects but the results of this study indicate that overall muscular fatigue of the shoulder affects scapulothoracic and glenohumeral kinematics. There was a significant effect of fatigue for Anterior/posterior tilt of the scapula after the fatiguing exercise, with a mean increase of 4.13°and a maximal increase of 7.73°anterior tilt however small, this represented a change in rotation of almost 45\consistent with other studies showing small changes in scapular kinematics with fatigue [Tsai *et al.* , 2003, Ebaugh *et al.* , 2006, McQuade *et al.* , 1998a, McQuade *et al.* , 1995]. Recent studies have shown that 4-5°differences in scapular kinematics are associated with shoulder impingement [Ludewig & Cook, 2000] [Lukasiewicz *et al.* , 1999] and decreased subacromial clearance [Michener *et al.* , 2003, Tsai *et al.* , 2003]. Recent studies have shown patients with impingement syndrome have significantly more anterior tilting when compared with asymptomatic subjects [Lukasiewicz *et al.* , 1999] [Ludewig & Cook, 2000]. This increase in anterior tilting is of the same magnitude as found in our and other similar studies [Tsai *et al.* , 2003] [Kvist & Bang, 2015].Tsai et al suggested that the larger the muscle imbalance between internal and external shoulder rotators due to muscle fatigue, the greater the alteration in scapular posterior tilting [Tsai *et al.* , 2003]. It has been suggested that small changes in anterior/posterior titling may be functionally analogous to anatomic changes in acromial morphology, resulting in alterations of soft tissue compression in the subacromial space [Ludewig & Cook, 2000] [Lukasiewicz *et al.* , 1999]. Kuechle et al have shown that during elevation in the scapular plane, the infraspinatus and teres minor moment arms are largest during the initial part of the motion[Kuechle *et al.* , 1997]. Additionally [Sharkey *et al.* , 1994] have also found that these two muscles are most effective in arm elevation during the first 90°of humeral elevation in the scapular plane. A disruption in the balance between internal and external rotation torques may result in compensatory activity from scapulothoracic muscles to help maintain scapular stability [Tsai *et al.* , 2003]. It is unknown whether the observed changes in scapular orientation are a primary result of direct force alterations of the infraspinatus and teres minor muscles or are secondary compensatory changes in the activity of other muscles [Tsai *et al.* , 2003] [Ebaugh *et al.* , 2006].

There is conflicting evidence regarding scapular upwards rotation where [Ebaugh *et al.* , 2006] and [McQuade *et al.* , 1998a] reported increased amounts of scapular upwards rotation with fatige, however [Tsai *et al.* , 2003] and [McQuade *et al.* , 1995] reported decreased amounts of scapular upwards rotation and we did not see any significant change in scapular upwards rotation. The conflicting evidence on scapular upwards rotation motion among studies makes it difficult to hypothesize the effect of altered position on subacromial volume. The inconsistency might result from differences in upper extremity tested (dominant versus non-dominant), fatigue protocol, and warrants closer investigation [Joshi *et al.* , 2011].

One potential explanation for this difference could lie in the fatiguing protocol,since there is a correlation between the amount of fatigue of the external rotators (based on torque production) and changes in scapular kinematics, the effects on scapular kinematics have been shown to increase with increasing levels of fatigue [Tsai *et al.* , 2003, McQuade *et al.* , 1998b]. It is possible that our subjects were only slightly fatigued and therefore had time to recover between finishing the fatigue protocol and kinematic testing, this could also explain why we see the biggest effect on the non-dominant left side, being naturally weaker it is possible that the non-dominant side would be more affected by fatigue than the dominant arm. In a previous study by the same authors examining symptomatic overhead athletes from sports involving overhead activity with a symmetrical bilateral load profile (handstand support), the athletes that developed shoulder pain, reported pain in the non-dominant left shoulder [Kvist & Bang, 2015]. To our knowledge most studies involving overhead athletes and shoulder pain have been focused on a asymmetrical unilateral load profile, and have looked primarely at the dominant arm, our results suggest that involving both sides and studying the effects of a symmetrical bilateral load profile during the fatiguing protocol can provide interesting insight into the possible links between fatigue, kinematic changes and shoulder pain. [Ebaugh *et al.* , 2006] used a measurement protocol involving the subjects touching a plastic rod to ensure the post fatigue measurement took place in the same plane of shoulder elevation, and found significant changes in upwards rotation of the scapula [Ebaugh *et al.* , 2006], it is possible that, with the ability to study movements in a more free-form state using the Qualisys Motion Capture system, the effects we are seeing represent a more natural compensatory pattern where instead of a increase in scapular upwards rotation, we see changes in scapulothoracic and glenohumeral kinematics, with an increase in scapular anterior tilt, humeral internal rotation, flexion and abduction in the early phases of shoulder elevation. Either as an effect of fatigue related changes in balanced force generation of certain shoulder muscles or fatigue related changes in proprioception, or both [Ebaugh *et al.* , 2006], [McQuade *et al.* , 1998a], [Lephart & Jari, 2002], [Kocher *et al.* , 1993].

[Yoshizaki *et al.* , 2009] showed dissimilar shoulder muscle activation and [Lee *et al.* , 2013] showed dissimilar posterior tilting kinematics between dominant and non-dominant shoulders, and this might explain, in part, the differences observed. Several limitations of our study must be acknowledged. Although significant differences were found, the magnitude of these changes were small and the importance of these findings is unknown. Although it is possible that unbalanced rotator cuff forces caused by fatigue may have influenced humeral internal rotation, subjects were asked to keep their thumbs up during the entire protocol, which resulted in their maintaining roughly the same amount of internal rotation after the fatigue protocol. Another limitation is that the subjects were healthy and between the age of 22 and 33 years. It is not known whether the observed effects would also be seen in older subjects or in patients with shoulder pathologies. It is possible that the sensors slipped during the fatiguing protocol due to skin motion or sweat. One way we could have checked this was by adding a control measurement well after the fatigue had worn off, at least an hour afterwards. This study is also limited by the lack of electromyographical data about muscle activity and local muscle fatigue. Limited comparisons can be made with relevant studies because of differences in methods and fatigue protocol. Therefore, our explanations of the findings observed can be regarded only as hypotheses based on the studies in which researchers investigated fatigue induced kinematic changes about the shoulder.

7 Conclusion

This study showed that small but potentially clinically significant changes in scapular kinematics were found after a shoulder fatigue protocol. An increase in scapular anterior tilt, humeral internal rotation, flexion and abduction in the early phases of shoulder elevation was found after fatigue. The results of this study suggest that shoulder fatigue directly affects the way in which the scapula moves on the thorax and in relation to the humerus during elevation of the arm in the scapular plane. Interestingly the results of this study suggest that the scapulothoracic and glenohumeral kinematics of the non-dominant arm is affected more by fatigue. Future research in muscle activation and scapular kinematics after the shoulder is fatigued in a more functional manner is warranted.

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Appendix A: Appendix

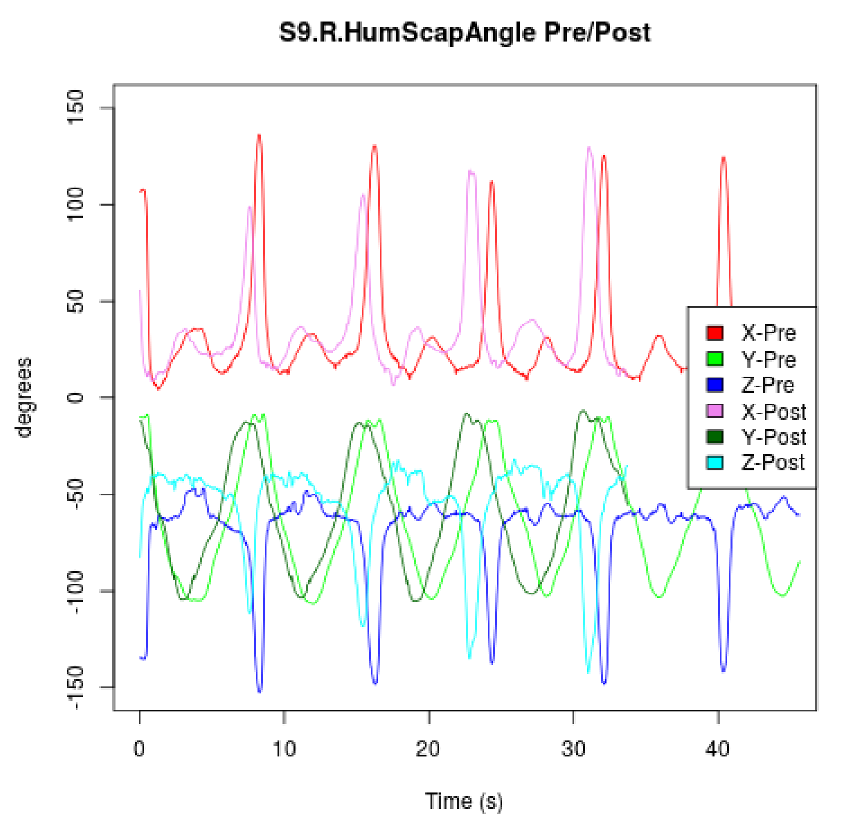
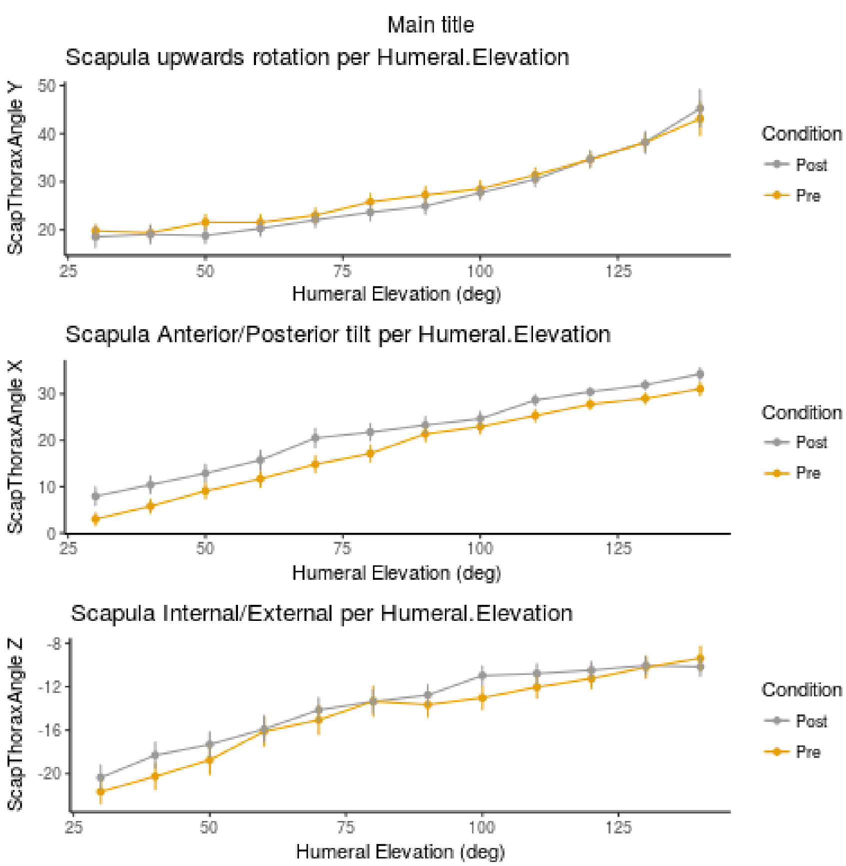


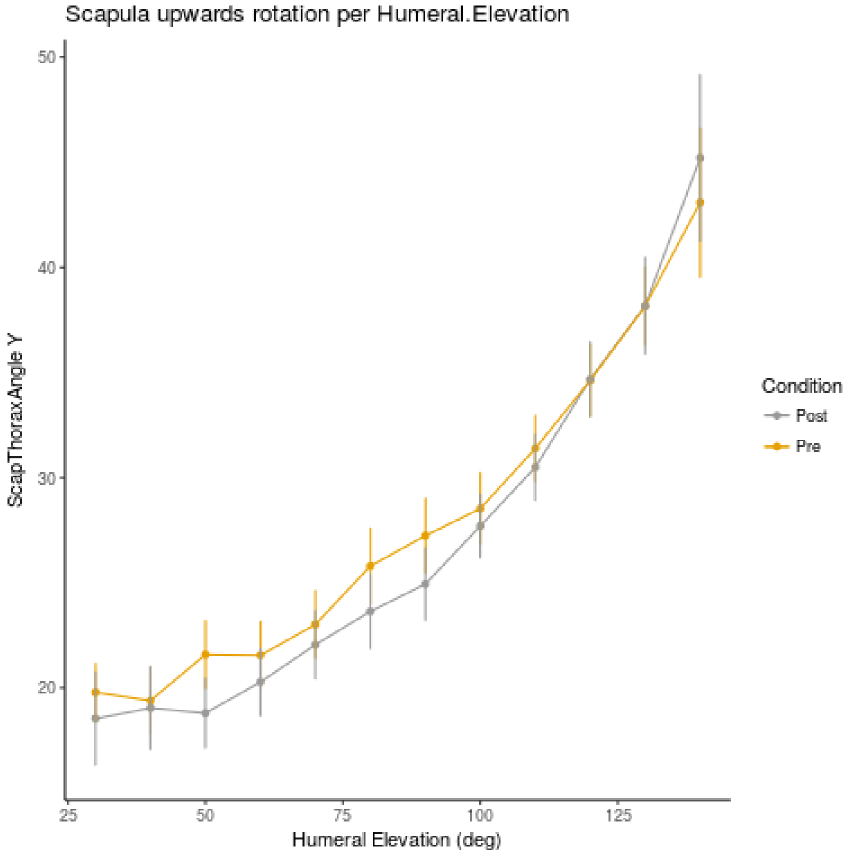
Figure 4 All the calculated joint rotation angles for one subject plotted against time.

Appendix B: Plots and output of statistical calculations.

B.1 ST



B.2 STY



B.2.1 Anova STY

```
Single term deletions

Model:
STY ~ Humeral.Elevation + Condition * Side
  Df Sum of Sq    RSS    AIC
<none>                         198246 1978.0
Humeral.Elevation 11   15963.9 214210 1979.3
Condition          1    7112.3 205358 1986.6
Side               1    2432.7 200678 1979.7
Condition:Side     1    5881.4 204127 1984.8
   Df Sum Sq Mean Sq F value   Pr(>F)
Humeral.Elevation  11  15964    1451   2.086 0.021331 *
Condition           1   7976    7976  11.466 0.000808 ***
Side                1   2725    2725   3.917 0.048761 *
Condition:Side      1   5881    5881   8.455 0.003926 **
Residuals         285 198246     696
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

B.2.2 Es STY

```
Effect Size Calculation for Meta Analysis
```

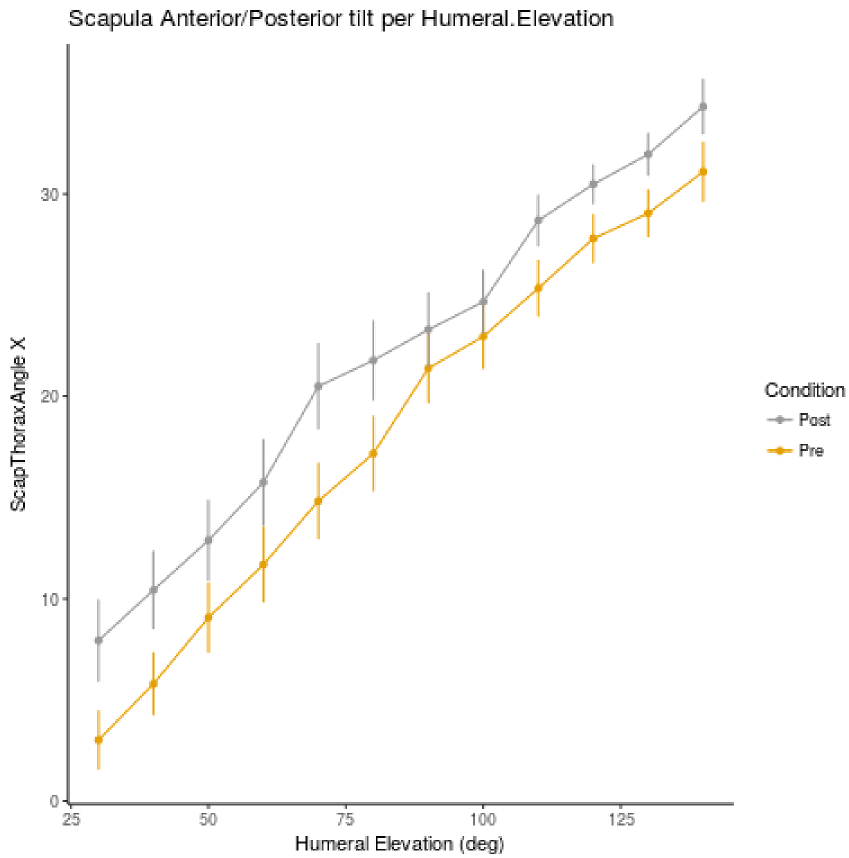
```
     Conversion: F-value (one-way-Anova) to effect size d
    Effect Size:   3.5045
 Standard Error:   1.2036
       Variance:   1.4487
       Lower CI:   1.1455
       Upper CI:   5.8636
         Weight:   0.6903
```

B.2.3 Post Hoc STY

```
  Tukey multiple comparisons of means
    95% family-wise confidence level

Fit: aov(formula = STY ~ Condition * Side)

$Condition
     diff      lwr      upr     p adj
Pre-Post 10.32072 4.202602 16.43885 0.0010134

$Side
 diff       lwr        upr    p adj
R-L -6.027746 -12.14587 0.09037713 0.053459

$`Condition:Side`
     diff        lwr       upr     p adj
Pre:L-Post:L   18.6350257   7.472319 29.797732 0.0001286
Post:R-Post:L   3.1672269  -8.416861 14.751315 0.8945113
Pre:R-Post:L    4.0518693  -7.532219 15.635957 0.8028670
Post:R-Pre:L  -15.4677989 -26.630505 -4.305092 0.0022585
Pre:R-Pre:L   -14.5831564 -25.745863 -3.420450 0.0046162
Pre:R-Post:R    0.8846424 -10.699446 12.468730 0.9972745
```

B.3 STX

B.3.1 Anova STX




```
Single term deletions

Model:
STX ~ Humeral.Elevation + Condition * Side
  Df Sum of Sq   RSS    AIC
<none>                      24216 1347.3
Humeral.Elevation 11   18129.4 42345 1493.0
Condition          1     233.7 24450 1348.2
Side               1       7.1 24223 1345.4
Condition:Side     1     257.0 24473 1348.5
   Df Sum Sq Mean Sq F value Pr(>F)
Humeral.Elevation  11  18129  1648.1  19.397 <2e-16 ***
Condition           1    213   212.8   2.505 0.1146
Side                1     11    10.6   0.125 0.7236
Condition:Side      1    257   257.0   3.025 0.0831 .
Residuals         285  24216    85.0
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

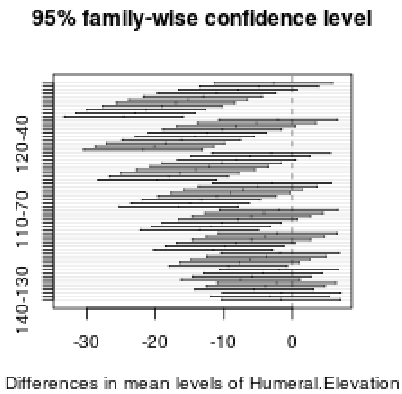
B.3.2 Es STX

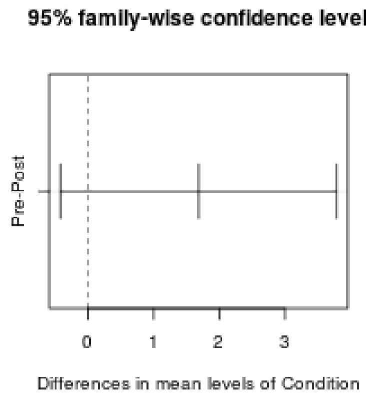
```
Effect Size Calculation for Meta Analysis
```

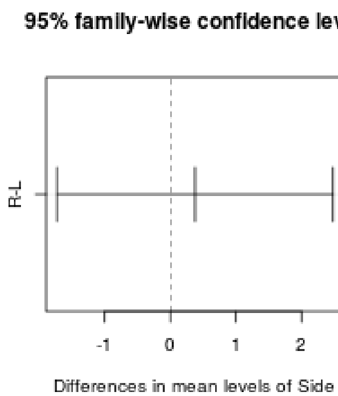
```
     Conversion: F-value (one-way-Anova) to effect size d
    Effect Size:   0.6870
 Standard Error:   0.7779
       Variance:   0.6051
       Lower CI:  -0.8377
       Upper CI:   2.2117
         Weight:   1.6525
```

B.3.3 Post Hoc STX

```
  Tukey multiple comparisons of means
    95% family-wise confidence level

Fit: aov(formula = STX ~ Condition * Side)

$Condition
             diff       lwr      upr     p adj
Pre-Post 1.685891 -1.034309 4.406092 0.2235463

$Side
         diff       lwr      upr     p adj
R-L 0.3768018 -2.343399 3.097002 0.7853442

$`Condition:Side`
                     diff       lwr      upr     p adj
Pre:L-Post:L  -0.08627384 -5.049365 4.876817 0.9999674
Post:R-Post:L -1.54675577 -6.697199 3.603687 0.8653149
Pre:R-Post:L   2.07776517 -3.072678 7.228208 0.7247004
Post:R-Pre:L  -1.46048194 -6.423573 3.502609 0.8721878
Pre:R-Pre:L    2.16403900 -2.799052 7.127130 0.6734249
Pre:R-Post:R   3.62452094 -1.525922 8.774964 0.2667759
```

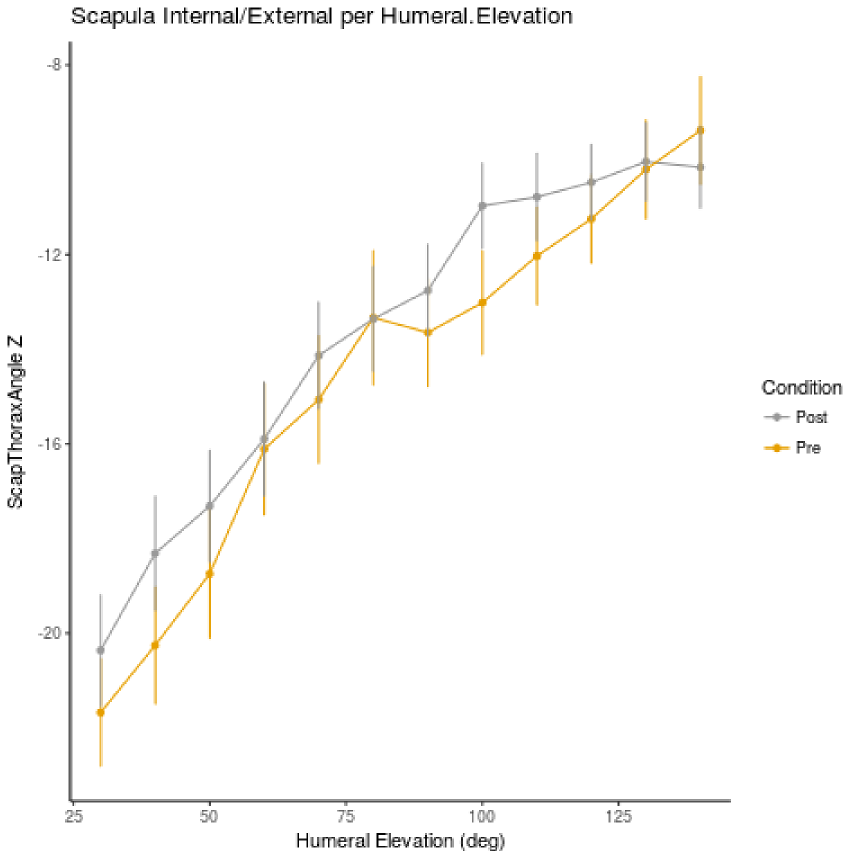

95% family-wise confidence level
140-130
110-70
120-40
-30
-20
-10
0
Differences in mean levels of Humeral.Elevation


95% family-wise confidence level
Pre-Post
0
1
2
3
Differences in mean levels of Condition


95% family-wise confidence level
R-L
-1
0
1
2
Differences in mean levels of Side

B.4 STZ

B.4.1 Anova STZ




```
Single term deletions

Model:
STZ ~ Humeral.Elevation * Condition + Side
    Df Sum of Sq    RSS     AIC
<none>                                 36182 1487.8
Humeral.Elevation            11    2509.10 38691 1485.9
Condition                     1     238.46 36420 1487.7
Side                          1    2354.22 38536 1504.7
Humeral.Elevation:Condition 11     108.60 36291 1466.7
     Df Sum Sq Mean Sq F value    Pr(>F)
Humeral.Elevation            11    2475    225.0    1.710    0.0709 .
Condition                     1     300    300.0    2.280    0.1322
Side                          1    2354   2354.2   17.893 3.19e-05 ***
Humeral.Elevation:Condition  11     109      9.9    0.075    1.0000
Residuals                   275   36182    131.6
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

B.4.2 Es STZ

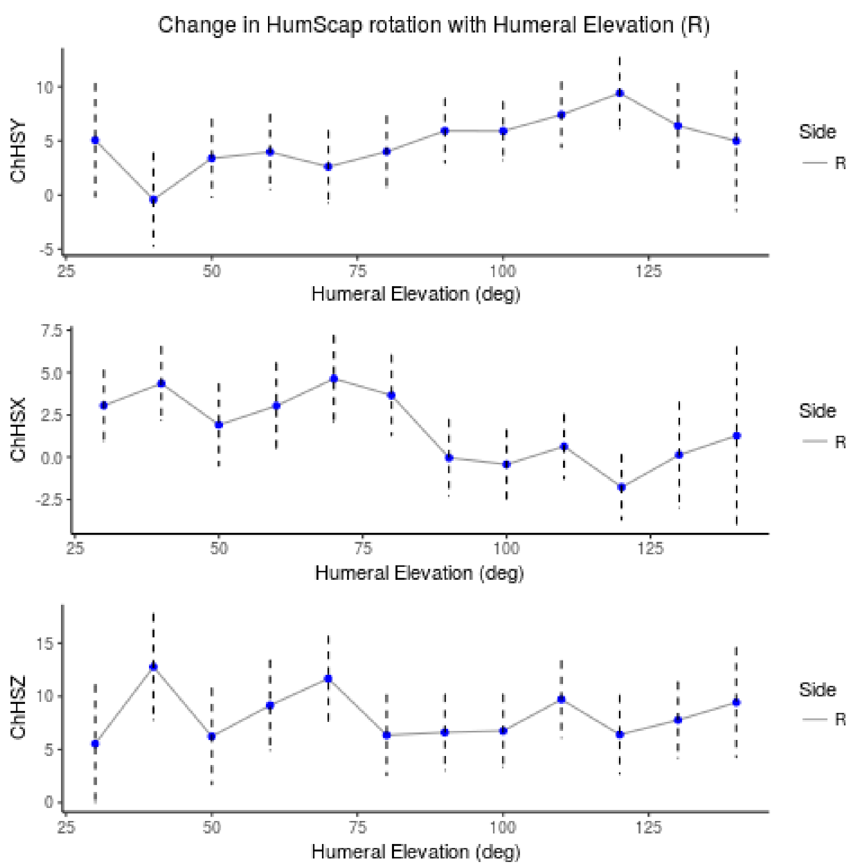
Effect Size Calculation for Meta Analysis

```
     Conversion: F-value (one-way-Anova) to effect size d
    Effect Size:   1.8941
 Standard Error:   0.9098
       Variance:   0.8277
       Lower CI:   0.1109
       Upper CI:   3.6772
         Weight:   1.2082
```

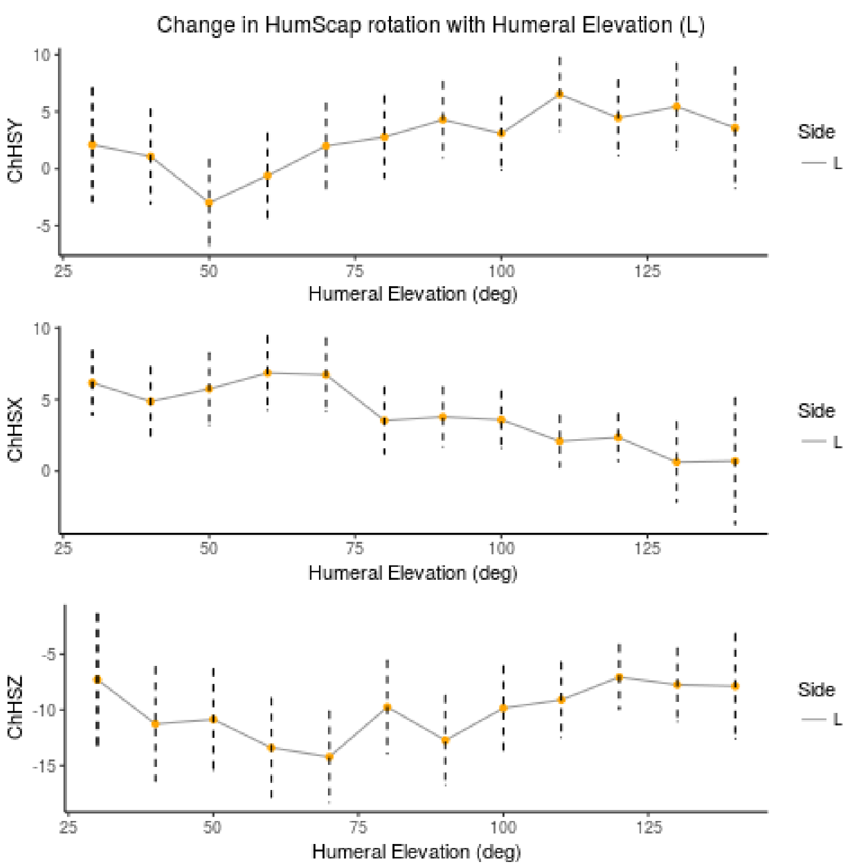
B.4.3 Post Hoc STZ

```
  Tukey multiple comparisons of means
    95% family-wise confidence level

Fit: aov(formula = STZ ~ Condition * Side)

$Condition
             diff        lwr      upr     p adj
Pre-Post 2.001678 -0.5848241 4.588181 0.1288185

$Side
         diff       lwr       upr    p adj
R-L -5.602985 -8.189487 -3.016482 2.71e-05

$`Condition:Side`
                    diff         lwr       upr     p adj
Pre:L-Post:L   4.2286243  -0.4905303  8.947779 0.0968925
Post:R-Post:L -2.9806158  -7.8779140  1.916682 0.3959499
Pre:R-Post:L  -3.8254259  -8.7227241  1.071872 0.1835833
Post:R-Pre:L  -7.2092401 -11.9283947 -2.490086 0.0005706
Pre:R-Pre:L   -8.0540502 -12.7732048 -3.334896 0.0000853
Pre:R-Post:R  -0.8448101  -5.7421083  4.052488 0.9704115
```

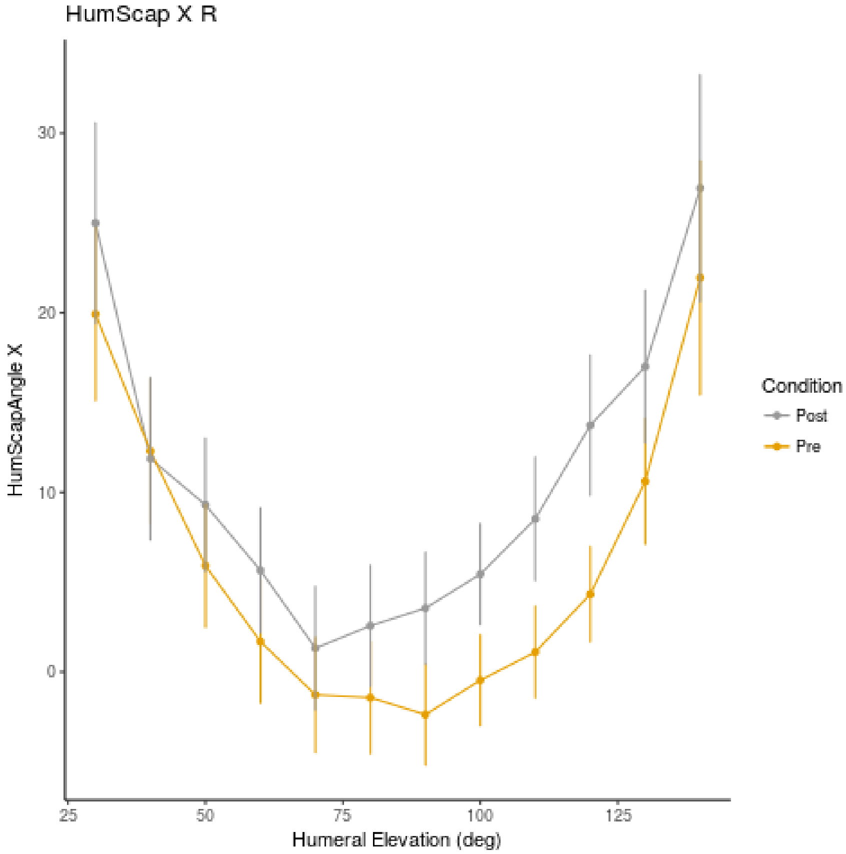
B.5 HS Change R



B.6 HS Change L



B.7 HSX



B.7.1 Anova

```
Single term deletions

Model:
HSX ~ Humeral.Elevation * Condition + Side
    Df Sum of Sq     RSS     AIC
<none>                                    261126 2080.7
Humeral.Elevation            11    17677.2 278803 2078.3
Condition                     1    15688.9 276815 2096.2
Side                          1    18142.7 279269 2098.8
Humeral.Elevation:Condition 11      218.9 261345 2058.9
     Df Sum Sq Mean Sq F value    Pr(>F)
Humeral.Elevation             11  17738     1613   1.698   0.0735 .
Condition                      1  17039    17039  17.944 3.11e-05 ***
Side                           1  18143    18143  19.107 1.75e-05 ***
Humeral.Elevation:Condition  11    219       20   0.021   1.0000
Residuals                    275 261126      950
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

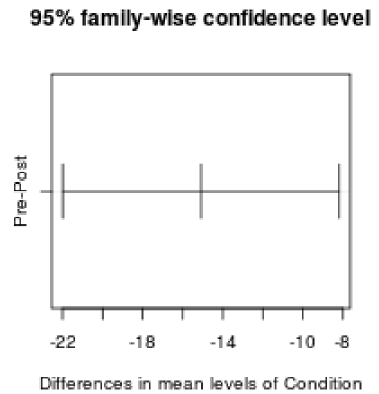
B.7.2 Es HSX

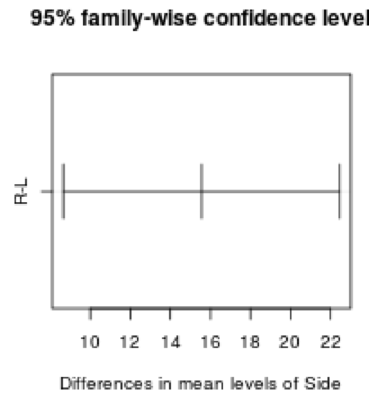
```
Effect Size Calculation for Meta Analysis
```

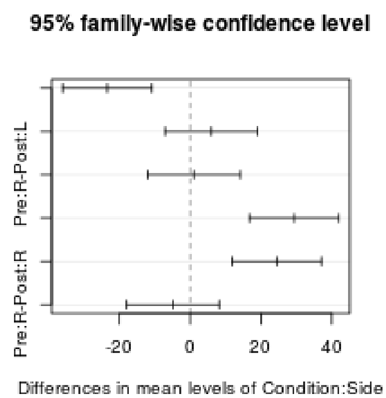
```
     Conversion: F-value (one-way-Anova) to effect size d

    Effect Size:   4.4299

 Standard Error:   1.4047

       Variance:   1.9731

       Lower CI:   1.6768

       Upper CI:   7.1830

         Weight:   0.5068
```

B.7.3 Post Hoc HSX

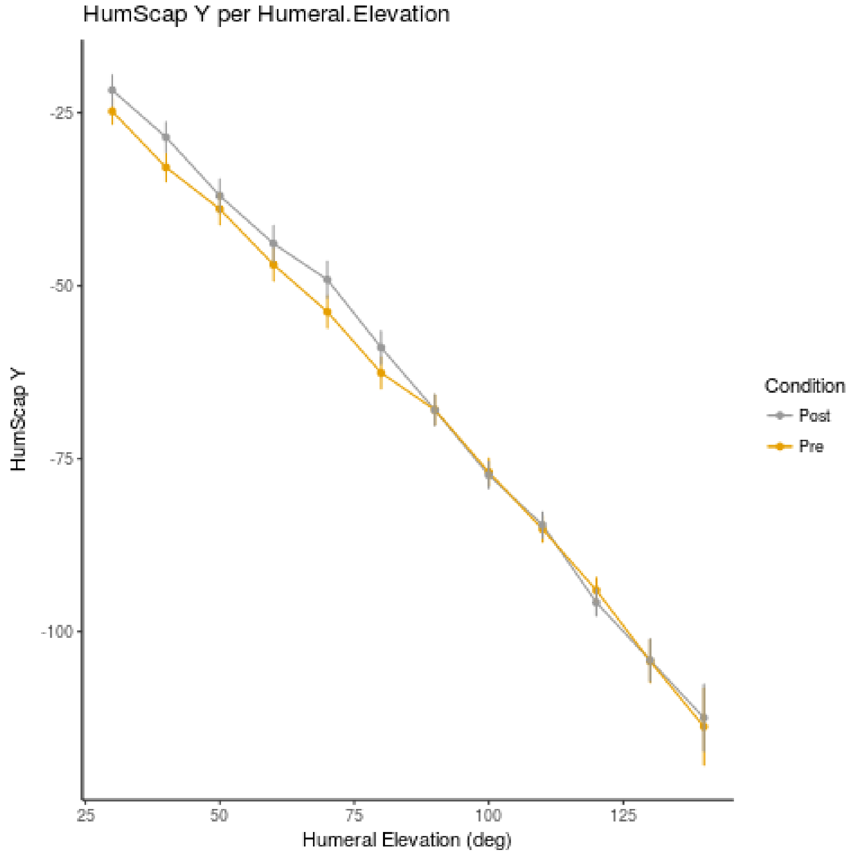
```
  Tukey multiple comparisons of means
    95% family-wise confidence level

Fit: aov(formula = HSX ~ Condition * Side)

$Condition
              diff       lwr       upr    p adj
Pre-Post -15.08467 -21.98753 -8.181815 2.32e-05

$Side
        diff      lwr      upr   p adj
R-L 15.55416 8.651306 22.45702 1.3e-05

$`Condition:Side`
                    diff        lwr        upr     p adj
Pre:L-Post:L  -23.399394 -35.993875 -10.804914 0.0000149
Post:R-Post:L   5.977682  -7.092228  19.047592 0.6389075
Pre:R-Post:L    1.091658 -11.978252  14.161568 0.9964444
Post:R-Pre:L   29.377076  16.782595  41.971556 0.0000000
Pre:R-Pre:L    24.491052  11.896572  37.085533 0.0000052
Pre:R-Post:R   -4.886024 -17.955934   8.183886 0.7689472
```


95% family-wise confidence level
Pre-Post
-22
-18
-14
-10
-8
Differences in mean levels of Condition


95% family-wise confidence level
R-L
10
12
14
16
18
20
22
Differences in mean levels of Side


95% family-wise confidence level
Pre:R-Post:L
Pre:R-Post:R
-20
0
20
40
Differences in mean levels of Condition:Side

B.8 HSY



B.8.1 Anova HSY

```
Single term deletions

Model:
HSY ~ Humeral.Elevation + Condition * Side
  Df Sum of Sq     RSS     AIC
<none>                          56018 1598.9
Humeral.Elevation 11     228744 284762 2064.7
Condition          1       4229  60247 1618.7
Side               1       2267  58286 1608.8
Condition:Side     1       2528  58547 1610.1
   Df Sum Sq Mean Sq F value    Pr(>F)
Humeral.Elevation  11 228744   20795  105.80  < 2e-16 ***
Condition           1   4746    4746   24.14 1.51e-06 ***
Side                1   2451    2451   12.47 0.000482 ***
Condition:Side      1   2528    2528   12.86 0.000394 ***
Residuals         285  56018     197
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

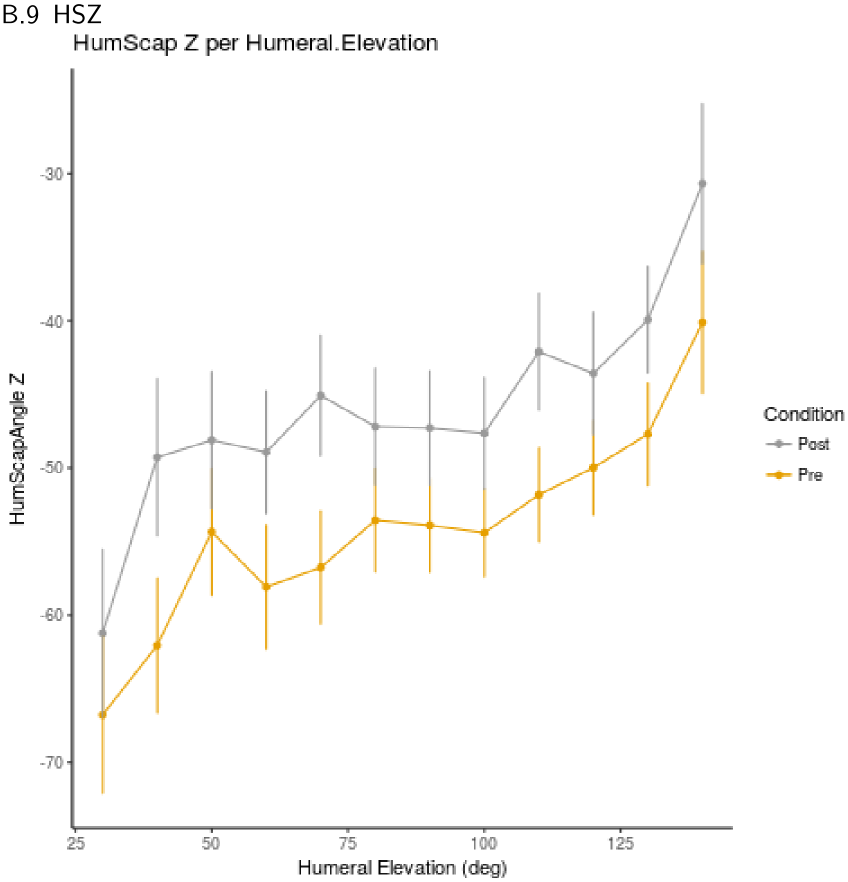
B.8.2 Es HSY

```
Effect Size Calculation for Meta Analysis
```

```
     Conversion: F-value (one-way-Anova) to effect size d
    Effect Size:   5.1379
 Standard Error:   1.5675
       Variance:   2.4570
       Lower CI:   2.0657
       Upper CI:   8.2101
         Weight:   0.4070
```

B.8.3 Post Hoc

B.9 HSZ



B.9.1 Anova HSZ

Output of statistical calculations in R:

```
Single term deletions

Model:
HSZ ~ Humeral.Elevation + Condition * Side
  Df Sum of Sq    RSS    AIC
<none>                        40697 1503.0
Humeral.Elevation 11       253   40950 1482.9
Condition          1        26   40723 1501.2
Side               1    586967  627665 2321.8
```

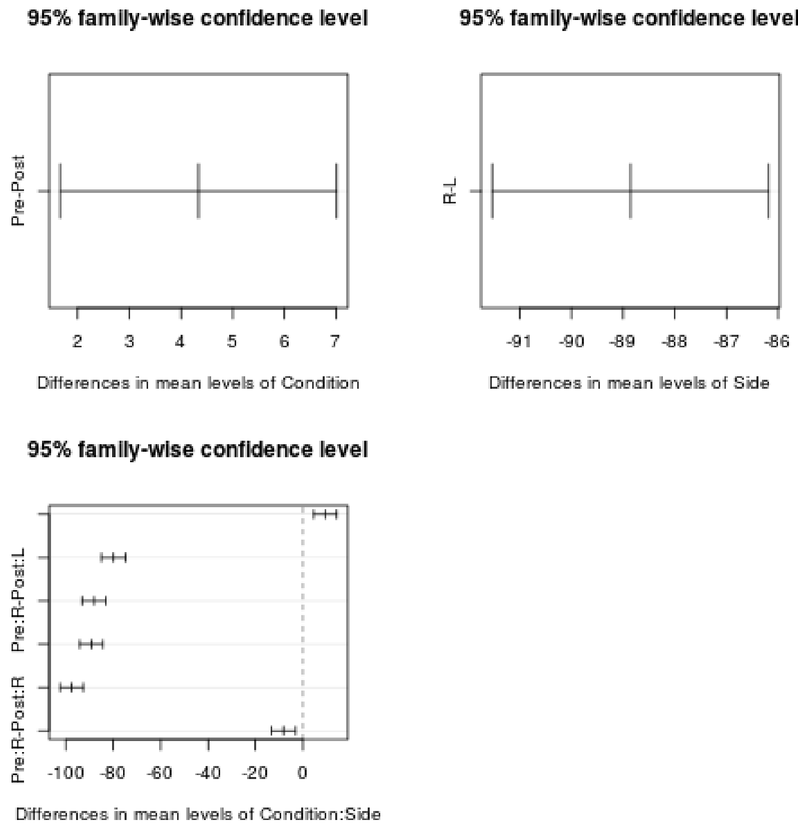
```
Condition:Side     1      5765  46462 1540.8
   Df Sum Sq Mean Sq  F value   Pr(>F)
Humeral.Elevation  11    253      23    0.161  0.99910
Condition           1   1409    1409    9.869  0.00186 **
Side                1 592096  592096 4146.405  < 2e-16 ***
Condition:Side      1   5765    5765   40.372 8.29e-10 ***
Residuals         285  40697     143
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

B.9.2 Es HSZ

```
Effect Size Calculation for Meta Analysis

     Conversion: F-value (one-way-Anova) to effect size d
    Effect Size:   2.3118
 Standard Error:   0.9763
       Variance:   0.9532
       Lower CI:   0.3983
       Upper CI:   4.2254
         Weight:   1.0491
```

B.9.3 Post Hoc

```
  Tukey multiple comparisons of means
    95% family-wise confidence level

Fit: aov(formula = HSZ ~ Condition * Side)

$Condition
             diff      lwr      upr     p adj
Pre-Post 4.338204 1.663193 7.013215 0.0015669

$Side
         diff       lwr       upr p adj
R-L -88.85703 -91.53204 -86.18202     0

$`Condition:Side`
                    diff         lwr        upr     p adj
Pre:L-Post:L    9.377061    4.496419  14.257702 0.0000069
Post:R-Post:L -79.876288  -84.941169 -74.811407 0.0000000
Pre:R-Post:L  -88.073108  -93.137989 -83.008227 0.0000000
Post:R-Pre:L  -89.253349  -94.133990 -84.372707 0.0000000
Pre:R-Pre:L   -97.450169 -102.330810 -92.569527 0.0000000
Pre:R-Post:R   -8.196820  -13.261701  -3.131939 0.0002228
```


95% family-wise confidence level
Pre-Post
2 3 4 5 6 7
Differences in mean levels of Condition
95% family-wise confidence level
R-L
-91 -90 -89 -88 -87 -86
Differences in mean levels of Side
95% family-wise confidence level
Pre:R-Post:L
Pre:R-Post:R
-100 -80 -60 -40 -20 0
Differences in mean levels of Condition:Side