Kinematic Analysis of the Glenohumeral Joint: A Comparison of Post-Operative Rotator Cuff Repair Patients and Controls

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KINEMATIC ANALYSIS OF THE GLENOHUMERAL JOINT: A COMPARISON OF POST-OPERATIVE ROTATOR CUFF REPAIR PATIENTS AND CONTROLS

by

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ABSTRACT

KINEMATIC ANALYSIS OF THE GLENOHUMERAL JOINT: A COMPARISON OF POST-OPERATIVE ROTATOR CUFF REPAIR PATIENTS AND CONTROLS

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Rotator cuff (RC) repair is a standard surgical intervention used to alleviate pain and loss of function in the shoulder due to torn RC tendons, involving re-attachment of the tendon to the humerus. Quantitative evaluation of kinematics following RC repair is possible with video motion analysis techniques, yet is rarely performed.

With the purpose of quantifying the effects of RC repair, a Vicon 524 (Oxford, UK) motion analysis system was used to investigate three-dimensional (3D) kinematics of the glenohumeral (GH) joint and thorax following supraspinatus repair. A validated, 18 marker, inverse dynamics model based on ISB standards was applied to analyze GH joint kinematics in a population of persons who underwent recent RC repair and persons with ideal shoulder health. The kinematic data characterized GH joint motion during ADLs following single tendon repair of the supraspinatus.

Motion capture was performed on ten (10) healthy subjects and ten (10) subjects at 9 to 12 weeks post arthroscopic RC tendon repair (supraspinatus). The tasks included ten ADLs characteristic of motions normally performed at home and work and three rehabilitation motions performed both actively and passively. Kinematics of the GH joint and thorax, as well as temporal characteristics of the trials were analyzed between groups. Hotelling's T^2 test and Welch's t-test were used to examine significant differences in tri-planar (3D) kinematics between the groups ($\alpha = 0.05$).

ADLs with significantly different kinematics suggest that specific combined motions (e.g. performing extension while adducting as done when reaching to perineum) may be limited after rotator cuff repairs (especially after repairs of the supraspinatus), while single-plane mobility is returned to a healthy range suitable for most ADLs. Significantly different thorax kinematics support the use of thorax motion to compensate for limited GH joint mobility, however even with compensatory motion RC repair subjects completed tasks with similar temporal quality as those without shoulder pathology.

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To my father, Jimmy, here's the first step towards making true the many promises I made to you.

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I. Introduction

Operative repair of the rotator cuff is frequently used to decrease pain and increase range of motion of the shoulder's glenohumeral joint (GH joint) in persons with rotator cuff pathology. However, GH joint kinematics of this population has been limited to manually measurable motions. Three-dimensional (3D) motion analysis of the upper extremities (UE) has only recently been applied to examine clinical pathologies. Furthermore, 3D motion analysis studies of subjects with shoulder repair during dynamic motions have yet to be published, the results of which could provide insight into the GH joint range of motion (ROM) utilized after surgery.

A. Glenohumeral Joint Anatomy and Kinesiology

The GH joint, commonly referred to as the shoulder joint, consists of the humerus and scapula. The four muscles of the rotator cuff (supraspinatus, infraspinatus, subscapularis, and teres minor) as well as their tendons rotate and stabilize the humerus at the GH joint (Figure 1). In terms of kinesiology, the GH joint has a ball and socket configuration, with the head of the humerus acting as the ball of the joint, and the glenoid fossa of the scapula acting as the socket. The shoulder itself is composed of multiple anatomical joints including the GH joint, the acromioclavicular joint, and the sternoclavicular joint; however, articulation of the humerus and thorax mainly occurs at the GH joint.

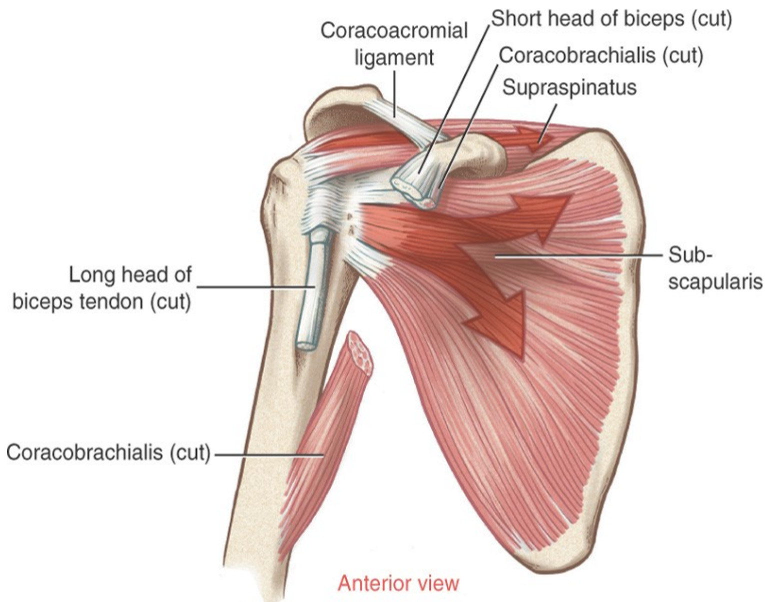


Figure 1. Anterior view of the rotator cuff (Neumann, 2010)

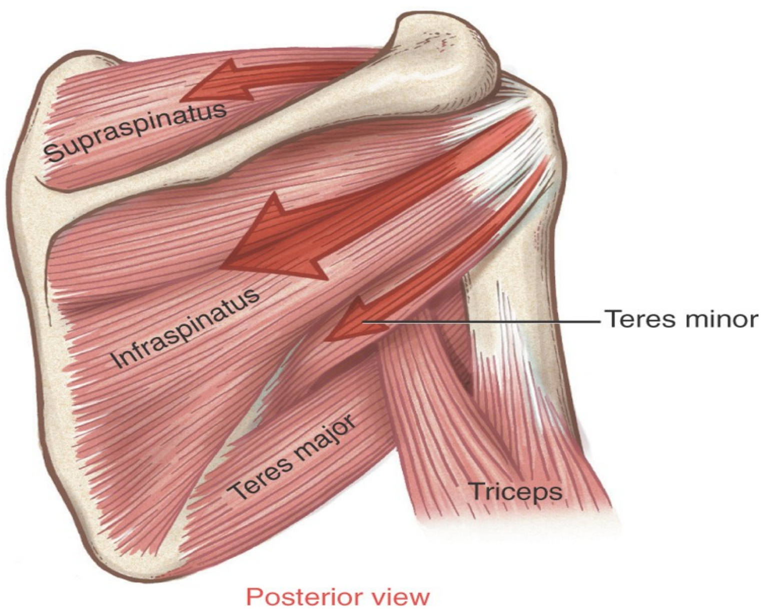


Figure 2. Posterior view of the rotator cuff (Neumann, 2010)

Movement at the GH joint is caused by the scapulohumeral muscles, which originate on the scapula and attach to the humerus. Two other muscles that attach to the humerus, the latissimus dorsi and the pectoralis major, originate respectively from the thoracic/lumbar spinae and the sternum. Together the muscles inserting into the humerus are responsible for abduction/adduction, flexion/extension, and internal/external rotation at the GH joint (Table 1).

Table 1. Muscles which insert into the humerus grouped by their action on the humerus about the GH joint

Flexion	Extension	Internal Rotation	External Rotation	Abduction	Adduction
Biceps Brachii	*Latissimus Dorsi*	*Latissimus Dorsi*	*Teres Minor*	*Supraspinatus*	*Pectoralis Minor*
Pectoralis Major	*Teres Major*	*Teres Major*	*Infraspinatus*	*Deltoid*	*Pectoralis Major*
Coracobrachialis	*Triceps*	*Subscapularis*	*Deltoid*		*Latissimus Dorsi*
Deltoid	*Deltoid*	*Deltoid*			*Teres Major*

From goniometer based studies, typical mean ROM at the shoulder across ages 2-69 years old for men and women without shoulder pathology include 67.5°-72.5° internal rotation, 84.1°-91.1° external rotation,180.1°-187.6° abduction, and 64.6°-67.3°extension (J. Roy et al., 2009; C. J. Barnes, Van Steyn, & Fischer, 2001). 164.0°-177.8° of passive ROM in shoulder flexion was reported by a similar study (Soucie et al., 2011). ROM in these studies was measured with the subject in a static position at the maximum limit of a single-plane motion.

B. Indications For Surgical Intervention

As with any load bearing joint in the human body, the GH joint is affected by aging, overuse, and is subject a number of pathologies. Additionally, the relatively large range of motion coupled with the small articular surface area of the glenoid fossa (relative to the articular surface area of the humeral head) leaves the responsibility of shoulder stability mainly up to the muscles of the rotator cuff. Symptoms of rotator cuff and GH joint pathology include stiffness, weakness, and tearing of associated musculature and connective tissue (Lentz, Barabas, Day, Bishop, & George, 2009; Yung, Asavasopon, & Godges, 2010).

According to the American Academy of Orthopaedic Surgeons (AAOS), rotator cuff tear prevalence may exceed 50% in individuals older than the age of 65. Also from AAOS, 200,000 Americans require shoulder surgery related to rotator cuff repair each year, and an additional 400,000 Americans have surgery related to rotator cuff tendonitis for partial tears (K. Yamaguchi, 2011)

Rotator cuff tears can result in decreased shoulder ROM, pain due to impingement, and weakness in various planes of motion (Yamamoto, Takagishi, Kobayashi, Shitara, & Osawa, 2011). A common intervention to alleviate these symptoms is surgical rotator cuff repair. Rotator cuff tears are reported in athletes participating in sports with overhead activity (e.g. tennis and rugby) (Goldberg, Chan, Best, & Bruce, 2003; Sonnery-Cottet, Noel, & Walch, 2002) and those who do manual labor (Nove-Josserand et al., 2011). Acuity of tear, weakness, size of tear, muscle atrophy, fatty infiltration, and duration of symptoms are assessed when determining treatment (Wolf, Dunn, & Wright, 2007). Examples of surgical intervention include tendon to bone fixation with one metal suture anchor, side-to-side repair with permanent sutures, and debridement. Depending on severity of tear, less invasive procedures such as corticosteroid injections, exercise therapy, and continuous passive motion of the shoulder can also be used to return function and alleviate pain of the shoulder (Huisstede, Koes, Gebremariam, Keijsers, & Verhaar, 2011).

Combined with rehabilitation, the goal of RC repair is to return function to the shoulder lost due to rotator cuff tear. This includes the ability to perform activities of daily living (ADLs) without pain, and returning muscle strength and ROM at the shoulder to healthy levels (Kibler, McMullen, & Uhl, 2012; van et al., 2012).

Correction of many symptoms related to rotator cuff tears have been reported. Shoulder stiffness and suprascapular neuropathy due to RC tears pre-intervention have been reversed by RC repair (Costouros, Porramatikul, Lie, & Warner, 2007; Tauro, 2006). Additionally, ROM has been reported to increase in shoulder flexion, external rotation, and internal rotation compared to pre-surgical values (Franceschi et al., 2008).

Beyond alleviation of symptoms, both high satisfaction and increased quality of life are reported by patients that have received RC repair surgery. In a study of satisfaction, over 130 of 311 subjects reported maximum satisfaction with surgical outcome (O'Holleran, Kocher, Horan, Briggs, & Hawkins, 2005). Another study assessing of quality of life using UCLA and SF-36 scores reported an overall increased quality of life comparing pre and post-surgical results in subjects with RC repair (Osti, Papalia, Del Buono, Denaro, & Maffulli, 2010).

C. Motion Analysis Assessment of Glenohumeral Joint Kinematics

While satisfactory patient-reported outcomes of rotator cuff repair coincide with the common use of surgical intervention as treatment of torn rotator cuff muscles (M. J. Bey et al., 2011), a trend for more quantitative means of assessing surgical repair of the rotator cuff has led to the use of quantitative motion analysis to examine dynamic range of motion.

Currently, manual ROM measurement of the GH joint in extension/flexion (sagittal plane), abduction/adduction (coronal plane), and internal/external rotation (transverse plane) is used to determine shoulder functionality in shoulder pathology research. These are determined by measuring the starting and ending angular position of the GH joint during a prescribed motion (extension/flexion, abduction/adduction, or internal/external rotation).

ROM measurements have been used extensively to determine the success of rotator cuff repairs. For instance, the ROM values of previous studies have been shown to increase from pre-operative values. A study by Franceschi et al. found that mean ROM increased by 27° in forward flexion, 13° in external rotation, and 24° in internal rotation after rotator cuff repair (Franceschi et al., 2008). Similar values were found in studies determining the effectiveness of repairs of rotator cuff tears paired with superior labral anterior-posterior (SLAP) lesions (Franceschi et al., 2008;Voos et al., 2007) and with rotator cuff tears paired with rheumatoid arthritis (Riek, Ludewig, & Nawoczenski, 2008).

However, these measures do not fully capture the actual kinematics used during activities of daily living (ADLs). ADLs are tri-axial and defined by multiple axes of motion, as opposed to the prescribed single-plane motions used in traditional ROM measurements. To determine the kinematics of these motions, 3D motion tracking systems and a suitable biomechanical model are required. 3D motion analysis as we know it today has existed since the late 1980's in the form of tracking passive markers on anatomical landmarks with cameras. Currently, joint angles are automatically derived by software and hardware packages such as Vicon (Vicon Motion Systems Ltd, Oxford, UK). However, before the use of computing to automate joint angles, simple techniques using only reflective strips, strobe lights, photos, and manual measurements were used to determine 2D gait kinematics. Even these simple methods were able to reveal joint motion patterns of gait, still unobtainable by use of goniometric measurements (Sutherland, 2002).

Optical-based motion analysis systems, such as the Vicon (Vicon Motion Systems Ltd, Oxford, UK) system used in this study, are the most commonly used systems. Their popularity is due to providing a large capture volume compared to other types of motion capture systems, such as magnetic systems which track variations in magnetic flux using sensors on the body and a nearby magnetic field transmitter. Optical systems also have less instances of positional drift of markers, as seen in inertial systems which use gyroscopes placed on the body to provide kinematics. Optical systems are less constraining than mechanical motion capture systems which are essentially exoskeletons that use electrogoniometers to track joint motions.

Even among optical systems there are different ways of capturing 3D motion, including using passive, reflective markers (reflecting near-infrared light from the cameras), using LEDs as markers, and even marker-less systems which identify body segments via specialized algorithms. Clinically, passive-marker based systems are prevalently used due to the ease of placing the markers on anatomical landmarks to create anatomical frames and coordinate systems associated with bony segments (Kontaxis, Cutti, Johnson, & Veeger, 2009).

D. Biomechanical Modeling

A common strategy of analyzing 3D motion combines a motion capture system with a biomechanical model. The conventional gait model (CGM) for instance is used to define lower limb kinetics and kinematics during ambulation. The model is a standard in many motion capture packages including those provided by motion analysis companies such as Qualisys AB (Gothenburg, Sweden) and Vicon Motion Systems Ltd. (Oxford, UK). Essentially, markers are placed on a subject creating a segmental framework defining the body. In the CGM, these segments include the foot, shank, and thigh of each limb, as well as pelvis. Using multiple cameras, the trajectories of each marker (and therefore, each segment) can be tracked in 3D in real time. Views from at least two cameras are needed to locate each marker in space. By themselves, each camera is able to define a single marker in a 2D plane, without information on depth. By combining the views of two or more cameras through stereophotogrammetry the marker can be used as a common point in the 2D view of each camera. The depth of the marker can then be determined through inverse projection and triangulation.

The segments are defined within a model by including anthropomorphic measurements (i.e. model parameters) and specifically placed markers (usually on bony landmarks), with the convention of using at least three markers to define a segment. The segmental markers define the coordinate systems of each segment, defining not only the location of the segment in space, but its orientation with respect to the floor of the laboratory (which also has a defined coordinate system). Joint angular kinematics between each segment are then further defined by a sequence of Euler angles (Kadaba, Ramakrishnan, & Wootten, 1990). This type of 3D motion analysis has successfully been used to diagnose and prescribe treatment for lower extremity challenges (such as those related to cerebral palsy) through analysis of gait kinematics and kinetics at the hip, knee, and ankle joints (Chang, Seidl, Muthusamy, Meininger, & Carollo, 2006; Slavens, Sturm, Bajournaite, & Harris, 2009). Similar principles are used in UE motion analysis models (Slavens et al., 2009).

UE motion analysis has been performed on subjects with various UE pathologies, but has not yet focused on assessing rotator cuff repair. For example, motion analysis has been used to assess shoulder function in persons with impingement syndrome (McClure, Michener, & Karduna, 2006). 3D motion analysis has also been used to define shoulder kinematics during ADLs in subjects with paraplegia and tetraplegia (Gronley et al., 2000; Riek et al., 2008), as well as during reaching tasks in subjects with UE hemiparesis due to stroke (Patterson, Bishop, McGuirk, Sethi, & Richards, 2011; Hingtgen, McGuire, Wang, & Harris, 2006). With respect to UE control and paralysis, obstetrical brachial plexus palsy and cerebral palsy's effects on UE kinematics have been analyzed with 3D motion analysis (Fitoussi et al., 2009; Slavens et al., 2009; Strifling et al., 2008). Additionally, the UE model implemented in this study has successfully been used to determine UE kinematics in Loftstrand crutch users (Slavens et al., 2009; Slavens, Sturm, & Harris, 2010).

3D motion analysis of the upper extremity (UE) has also successfully been performed on subjects without UE pathology. For instance, a 2009 study examined kinematics of the humerus, scapula, and thorax for five different activities of daily living (ADLs) in subjects without shoulder pathology (Rundquist, Obrecht, & Woodruff, 2009). 3D motion analysis models have also been used to examine the kinematics and kinetics of athletics, including baseball pitching (Fleisig, Bolt, Fortenbaugh, Wilk, & Andrews, 2011) and during the “snatch” motion used by weight lifters (Chen et al., 2013). UE models have additionally been used to capture UE kinematics during ADLs in a normal pediatric population (Petuskey, Bagley, Abdala, James, & Rab, 2007).

E. Purpose of Study

The current study used 3D video motion analysis technology (Vicon) along with a validated UE model to compare both healthy subjects and subjects with rotator cuff pathology (i.e. patients who have received successful supraspinatus repair surgery). This work is more definitive than prior studies which lack dynamic kinematic characterization.

The purpose of the study was to examine 3D kinematics of the GH joint and thorax following rotator cuff surgery as compared to a group of healthy shoulder subjects. GH joint activity using a combination of flexion/extension, abduction/adduction, and internal/external rotation are typically used during ADLs. Thorax motion may also be employed for stability. Both GH joint and thorax motion were monitored in this study to compare quantitative differences between a surgically repaired group and a healthy shoulder group.

The hypotheses of this study are:

1) Rotator cuff repair subjects will have different kinematics values (minimum angle, maximum angle, and ROM) specifically in abduction (coronal plane) due to supraspinatus tendon repair.
2) Kinematics of the RC repair group in the transverse and sagittal planes will be similar to the kinematics of the healthy shoulder group.

II. Methods and Materials

This project analyzed de-identified archival 3D motion data of the GH joint and thorax in post-rotator cuff repair and healthy shoulder populations. This archival data included sagittal, transverse, and coronal plane rotations of the thorax and shoulder, as well as frame numbers defining the time of angular position, all during trials of ADLs and rehabilitation motions. A previously validated model created by Slavens et al. (Slavens et al., 2009) consisting of 11 reflective markers was used to analyze one side of the UE (dominant or surgical). All motion analysis trials were conducted in the Motion Analysis Lab (MAL) which was operated by the Orthopaedic and Rehabilitation Engineering Center (OREC) and the Medical College of Wisconsin, Department of Orthopaedic Surgery, located at Froedtert Memorial Lutheran Hospital. The MAL was set up to perform motion analysis of the upper and lower extremities, as well as collect skeletal muscle electrical activity via electromyography (EMG) to determine muscle activation patterns. A Vicon 524 (Oxford, UK) motion analysis system was used to analyze the motion of the UE. This included 14 infrared Pulnix cameras, Vicon Workstation 5.2.4 software, and a Vicon Data Station which both powered the cameras and supported data communication between the cameras and PC.

A. Kinematic Model

The specific model used consists of four body segments: 1) thorax, 2) upper arm, 3) forearm, and 4) hand (Slavens et al., 2010). Depending on the desired kinematic data, either the left or right side (or both) can be observed during motion capture trials. It is important to note that the model measures motion of the GH joint. The shoulder itself is made up of multiple joints, including the acromioclavicular joint, sternoclavicular joint, scapulothoracic joint, and GH joint. When referring to the shoulder joint, the GH joint is usually the joint being referenced. Wrist and elbow joints are also defined in the model, but kinematics of those joints were not analyzed for this project. Although the original model can observe both right and left UE during the same motion capture trial, the marker set used in this study was placed on a single arm to quantify movements in the arm of surgical repair compared to dominant side. This also helped to simplify data processing. The segments of the model modified for use in this study are defined as rigid bodies by the 11 reflective markers placed on bony anatomical landmarks. The following figure shows marker placement and joint coordinate systems for the UE model placed on the right side of the body.

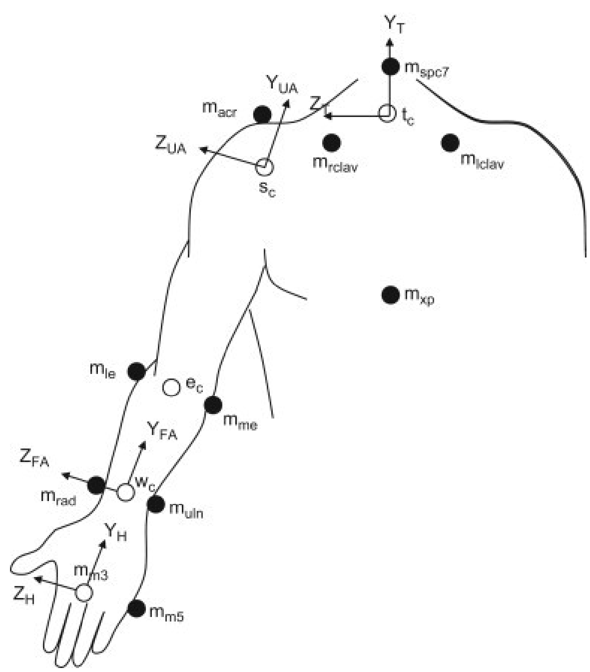


Figure 3. Upper extremity model marker placement, joint centers and segmental coordinate systems for the right side (Slavens et al., 2010).

Referencing marker placement for the right UE body segments are defined as follows:

<u>Hand (H):</u> The hand is defined by markers on 5th metacarpal (m_{rm5}), the radial styloid process (m_{rrad}), and the ulnar styloid process (m_{ruln}).

<u>Forearm (FA):</u> The forearm is defined by the m_{rrad} and m_{ruln} markers and markers on the medial epicondyle (m_{rme}) and lateral epicondyle (m_{rle}) of the humerus.

<u>Upper Arm (UA):</u> The arm segment is defined by the m_{rle} and m_{rme} markers, as well as a marker on the acromion (m_{racr}).

<u>Thorax (T):</u> The thorax is defined by the m_{racr} marker, markers on C7 spinous process (m_{spc7}), markers on the sternal extremity of the right clavicle (m_{rclav}) and left clavicle (m_{lclav}), and a marker on the xiphoid process of the sternum (m_{xiph}).

1. Joint Angles

a. Segments

In the UE model created by Slavens et al the two segments used to define the GH joint are the thorax and the humerus (Slavens, Bhagchandani, Wang, Smith, & Harris, 2011). Each segment has its own origin and coordinate system. The following equations define the model for subjects using their right arm. Subjects using their left arm used the same model, the only difference being the use of left side markers instead of right side markers.

i. Thorax

As defined by Nguyen and Baker (Nguyen & Baker, 2004), the thorax's origin ($\bar{t}_c$) is defined specifically as the center between the three markers, the right clavicle, left clavicle, and C7 markers:

$$\bar{t}_c = \frac{1/2(\bar{m}_{rclav} + \bar{m}_{lclav}) + \bar{m}_{spc7}}{2} \tag{1}$$

Note that the marker locations are defined as having three components (values in x, y and z axes of the laboratory).

To initially define the coordinate system of the thorax, a temporary coordinate system is used in Slavens' UE model. This coordinate system is used to define a virtual point 10 mm to the right of the thorax's origin. This virtual point ($\bar{P}_t$), is then used to defined axes with the +x direction defined poster to anterior, the +y direction inferior to superior, and the +z direction medial to lateral (as suggested by ISB standards):

Temporary Thorax Coordinate System:

$$\bar{Y}_{temp} = \frac{\bar{m}_{spc7} - \bar{m}_{xiph}}{\left|\bar{m}_{spc7} - \bar{m}_{xiph}\right|} \tag{2}$$

$$\bar{X}_{temp} = \left(\frac{1/2(\bar{m}_{rclav} + \bar{m}_{lclav}) - \bar{m}_{xiph}}{\left|1/2(\bar{m}_{rclav} + \bar{m}_{lclav}) - \bar{m}_{xiph}\right|}\right) \boldsymbol{X}\ \bar{Y}_{temp} \tag{3}$$

$$\bar{Z}_{temp} = \bar{X}_{temp}\ \boldsymbol{X}\ \bar{Y}_{temp} \tag{4}$$

Virtual Point

$$\bar{P}_{t} = \bar{t}_{c} + 10\left(\bar{X}_{temp}\right) \tag{5}$$

Thorax Coordinate System

$$\bar{X}_{\boldsymbol{T}} = \frac{\tfrac{1}{2}\left(\bar{m}_{\boldsymbol{rclav}} + \bar{m}_{\boldsymbol{lclav}}\right) - \bar{m}_{\boldsymbol{spc7}}}{\left|\tfrac{1}{2}\left(\bar{m}_{\boldsymbol{rclav}} + \bar{m}_{\boldsymbol{lclav}}\right) - \bar{m}_{\boldsymbol{spc7}}\right|} \tag{6}$$

$$\bar{Y}_{\boldsymbol{T}} = \frac{\bar{P}_{t} - \bar{t}_{c}}{\left|\bar{P}_{t} - \bar{t}_{c}\right|} \boldsymbol{X} \bar{X}_{\boldsymbol{T}} \tag{7}$$

$$\bar{Z}_{\boldsymbol{T}} = \bar{X}_{\boldsymbol{T}} \boldsymbol{X} \bar{Y}_{\boldsymbol{T}} \tag{8}$$

ii. Humerus

The humerus (i.e. forearm) origin is located at the elbow joint center ($\bar{e}_{c}$), defined by the equation:

$$\bar{e}_{\boldsymbol{c}} = \tfrac{1}{2}\left(\bar{m}_{\boldsymbol{rme}} + \bar{m}_{\boldsymbol{rle}}\right) \tag{9}$$

To define the coordinate system of the humerus, the shoulder joint center ($\bar{s}_{c}$), which is also the GH joint center, is used in conjunction with the elbow joint center to define the +y direction. The manually measured shoulder diameter in mm ($\bar{t}_{y}$), places the shoulder joint center a fixed distance inferior to the acromion marker.

$$\bar{s}_c = \bar{m}_{racr} - \left(\frac{MarkerDiameter}{2} - \bar{t}_y\right) \tag{10}$$

The coordinate system of the humerus defines the +x direction from anterior to posterior, +y direction from inferior to superior, and the +z direction from medial to lateral. Note that the marker on the ulnar styloid process (an anatomical land mark not on the humerus) and elbow joint center are used to define the z-axis of the humerus. This is possible because the ulnar styloid process does not move independently of the elbow joint center. Creating the humerus coordinate system in this ways allows GH joint flexion and extension to be calculated independently from GH joint abduction and adduction.

Humerus Coordinate system

$$\bar{Y}_{Humerus} = \frac{\bar{s}_c - \bar{e}_c}{\left|\bar{s}_c - \bar{e}_c\right|} \tag{11}$$

$$\bar{Z}_{Humerus} = \frac{\bar{m}_{ruln} - \bar{e}_c}{\left|\bar{m}_{ruln} - \bar{e}_c\right|} \boldsymbol{X}\ \bar{Y}_{Humerus} \tag{12}$$

$$\bar{X}_{Humerus} = \bar{Y}_{Humerus}\ \boldsymbol{X}\ \bar{Z}_{Humerus} \tag{13}$$

b. Euler Angles

GH joint rotations are described using Euler angles, with the GH joint center used as the origin. Specifically, the rotations of the distal coordinate system (the UE) are described with respect to the proximal coordinate system (the Thorax) using the Z-X-Y sequence convention. This sequence is used to maximize accuracy of measured angles in the sagittal plane, where the most motion will occur during the motion trials. Below is the

ZXY rotation matrix (Shah, Saha, & Dutt, 2013):

$$\boldsymbol{R_{ZXY}} = \begin{bmatrix} \boldsymbol{cos\theta cos\phi - sin\psi sin\theta sin\phi} & \boldsymbol{-cos\psi sin\phi} & \boldsymbol{cos\phi sin\theta + cos\theta sin\psi sin\phi} \\ \boldsymbol{cos\phi sin\psi sin\theta + cos\theta sin\phi} & \boldsymbol{cos\psi sin\phi} & \boldsymbol{-cos\theta cos\phi sin\psi + sin\theta sin\phi} \\ \boldsymbol{-cos\psi sin\theta} & \boldsymbol{sin\psi} & \boldsymbol{cos\psi cos\theta} \end{bmatrix} \quad (14)$$

Using the ZXY rotation, the coordinate system of the humerus can be expressed as:

$$\begin{bmatrix} x_{Humerus} \\ y_{Humerus} \\ z_{Humerus} \end{bmatrix} = R_{ZXY} \begin{bmatrix} x_{Thorax} \\ y_{Thorax} \\ z_{Thorax} \end{bmatrix} \quad (15)$$

The rotations used to express one coordinate system as another (i.e. Euler angles) seen in the R_{ZXY} matrix correspond to rotation in the transverse, sagittal, and coronal planes:

ψ = *Coronal Plane*

θ = *Sagittal Plane*

ϕ = *Transverse Plane*

These Euler angles represent flexion/extension (θ), abduction/adduction (ψ), and internal/external rotation (ϕ)at the GH joint.

Right-handed coordinate systems were constructed following ISB convention with anatomical position being the neutral position, with the x-axis pointing anteriorly (rotation about the x-axis defining abduction/adduction), the y-axis pointing superiorly (rotation about the y-axis defining internal/external rotation), and the z-axis pointing laterally to the right (rotation about the z-axis defining flexion/extension) (G. Wu et al., 2005). The model axes describe joint angles as shown in the following table:

Table 2: Anatomical rotations and corresponding local coordinate system axes

Shoulder	+	-
X	ADDUCTION	ABDUCTION
Y	INTERNAL ROTATION	EXTERNAL ROTATION
Z	FLEXION	EXTENSION
TRUNK	+	-
X	RIGHT LATERAL FLEXION	LEFT LATERAL FLEXION
Y	LEFT AXIAL ROTATION	RIGHT AXIAL ROTATION
Z	TRUNK EXTENSION	TRUNK FLEXION

The GH joint is modeled as a ball and socket joint, with no translation of the rotational center of the humerus; the joint center of the shoulder is located at the center of the humeral head. This location is defined in the model by shoulder circumference, the marker on the acromion (m_{racr} or m_{lacr}) and the thorax coordinate system. Specifically for the GH joint, relative motion between the local coordinate system of the thorax and local coordinate system of the humerus define the GH joint angles.

B. Participant Populations

Ten participants, including five males and five females ages 41-65 years with an average age of 52.4 years old, whom had received arthroscopic single tendon rotator cuff repair volunteered to participate in the IRB-approved protocol. All rotator cuff surgeries were performed on the supraspinatus tendon by the same surgeon. Testing of the rotator cuff repair participants occurred 9-12 weeks after their operation.

Ten non-pathological participants, including five females and five males ages 20-27 years with an average age of 22.8 years old, without a history of shoulder pathology volunteered for the IRB-approved protocol. Prior to participating in motion analysis trials, the healthy shoulder participants were screened via ultrasound of both shoulders to ensure absence of shoulder pathology.

The healthy shoulder group was not age matched to the rotator cuff repair group due to studies showing increased shoulder pathology relating to increased age (C. J. Barnes, Van Steyn, & Fischer, 2001). However, in persons with shoulders unaffected by pathology, the effect of age on ROM has been inconclusive with some studies reporting no significant loss of ROM or loss of ROM only in certain motions (C. J. Barnes et al., 2001; J. S. Roy, Moffet, Hebert, & Lirette, 2009).

C. Motion Assessment with Vicon System

1. Procedure

Motion was recorded during ADLs and rehabilitation movements. The ADLs were tested first in a randomized order. In general, each ADL had the same starting and ending position (either sitting in a chair with hands on the armrest with back against the chair, or standing with hands at sides). The subject performed each task at a self-selected speed, with the subject beginning the task after being notified that the motion analysis system was collecting data, and the data collection ending after the subject had returned to the starting position of the task. The ADLs were performed with the limb which received surgery, or with the dominant limb in the case of the healthy shoulder subjects.

These ADLs are commonly used in office work and daily life, and were adapted from a study investigating activation of muscles of the shoulder girdle during ADLs in patients with C6 tetraplegia by Gronley et al. (Gronley et al., 2000). The ADLs reflected commonly performed motions that involve reaching forward, backward, overhead, and sideways. A minimum of three trials per ADL were collected. The following table (Table 3) describes each ADL:

Table 3. Description of ADLs

Activities of Daily Living Movements		
Tasks	*Description*	*Expected Glenohumeral Joint Actions*
Combing hair	combing hair from anterior to posterior of scalp while seated at a desk	*Flexion* *Internal Rotation* *Abduction*
Drink from a cup	drink water from an 8 oz. cup positioned anterior to test subject while seated at a desk	*Flexion* *Internal Rotation* *Abduction*
Reach to back	reach to perineum starting with hands at sides while standing	*Extension* *External Rotation* *Internal Rotation* *Abduction*
Reach for a light switch	turn on a light switch positioned 76 cm anterior and 13 cm lateral to shoulder joint while standing	*Flexion* *Abduction*
Push open a door	open a door using a lever type handle 37 cm from floor with pushing motion while standing	*Flexion* *External Rotation* *Abduction*
Pull open a door	open a door using a lever type handle 37 cm from floor with pulling motion while standing	*Flexion* *Extension* *External Rotation* *Internal Rotation* *Abduction*
Write	write subject's name using pen and paper while seated	*Flexion* *Internal Rotation* *Abduction*
Use a computer mouse	move a computer mouse anteriorly and laterally on a desk while seated at a desk	*Flexion* *External Rotation* *Internal Rotation* *Abduction*
Type on a keyboard	type subject's name on a keyboard while seated	*Flexion* *Internal Rotation* *Abduction*
Hold a mobile phone to ear	pick up phone from desk and bring phone to ear while seated at a desk	*Flexion* *Internal Rotation* *Abduction*

2. Activities of Daily Living

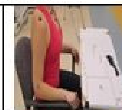
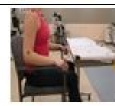
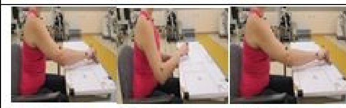
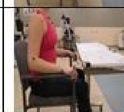
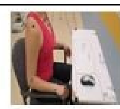
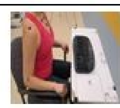
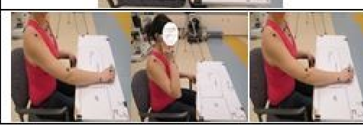
a. ADLs performed while seated:

For the ADLs performed while seated, the subject sat at a desk placed in the center of the capture volume. An ADL was randomly chosen for the subject to perform, and an object corresponding to that ADL was placed on the desk. When the subject was ready, motion capture was initiated and the subject was asked to perform the ADL. After it was performed, motion capture was stopped, the task was repeated and captured at least twice more, and then a new ADL was chosen. For the RC repair subjects, if surgery was performed on the non-dominant side, the subject was excluded from the writing task. Tables 4 and 5 detail the actions of the subject during a single trial.

Table 4. Sitting ADL motion capture procedures

Motion Capture Procedure	
Sitting ADLs	Procedure
Combing hair	*A comb with a reflective marker attached to the end was placed on the desk in front of the subject. From a starting seated position, the subject reached for the comb, picked up the comb, performed a combing motion along their hair, placed the comb back on the desk, and returned to the starting position.*
Drink from a cup	*A cup of water with a reflective marker attached was placed on the desk in front of the subject. From the starting seated position, the subject reached for the cup, picked up the cup, drank from the cup, placed the cup back on the desk, and returned to the starting position.*
Write	*A pen with a reflective marker attached and a piece of paper was placed on the desk in front of the subject. From the starting seated position, the subject reached for the pen, picked up the pen, wrote their name on the piece of paper, placed the pen back on the desk, and returned to the starting position.*
Use a computer mouse	*A computer mouse with a reflective marker attached was placed on the desk in front of the subject. From the starting seated position, the subject reached for the mouse, placed their hand on the mouse, moved the mouse to the far upper corner of the mouse pad (far left or far right corner depending on limb being analyzed) and then back to the mouse's starting position, and returned to the starting position.*
Type on a keyboard	*A computer keyboard was placed on the desk in front of the subject. From the starting seated position, the subject reached for the keyboard, typed their name, and returned to the starting position.*
Hold a mobile phone to ear	*A phone with a reflective marker attached was placed on the desk in front of the subject. From the starting seated position, the subject reached for the phone, picked up the phone, brought the phone to their ear (mimicking answering a phone), placed the phone back on the desk, and then returned to the starting seated position.*

Table 5. Sitting ADL motion profiles

Tasks	*Start*	*Task*	*End*
Combing hair			
Drink from a cup			
Write			
Use a computer mouse			
Type on a keyboard			
Hold mobile phone to ear			

b. ADLs Performed while Standing

The procedure for standing ADLs was similar to the seated ADLs, except the starting position of these ADLs required the subject to stand with their arms at their sides with palms facing medially (toward the center of the body). A wooden frame including a door and a light switch was used during the "Push door Open", "Pull Door Open", and "Reach for a light switch" ADLs. The frame was removed when performing the "Reach to back" ADL. Tables 6 and 7 detail the actions of the subject during a single trial.

Table 6. Standing ADL motion capture procedure

Motion Capture Procedure	
Standing ADLs	Procedure
Reach to back	*From a standing starting position, the subject reached for the perineum, mainly their coccyx. Then the subject returned in the standing starting position. This ADL reflects motions need for personal hygiene*
Reach for a light switch	*From a standing starting position, the subject flipped a light switch placed on the side of a portable door frame at a normal height (about 50 cm from the ground). Then the subject returned in the standing starting position. The frame was placed in the center of the capture space.*
Push open a door	*From a standing starting position, the subject opened and closed a door via a handle-type doorknob located 37cm from the ground. Then the subject returned in the standing starting position. The door was inside the same portable door frame used for the light switch ADL, and was placed in the center of the capture space.*
Pull open a door	*From the standing starting position, the subject opened a and closed a door via a handle-type doorknob located 37cm from the ground. Then the subject returned in the standing starting position. Then the subject returned in the standing starting position. The door was inside the same portable door frame used for the light switch ADL and was placed in the center of the capture space.*

Table 7. Standing ADL Motion Profile

Tasks	*Start*	*Task*	*End*
Reach to perineum			
Reach for a light switch			
Push open a door			
Pull Open a door			

3. Rehabilitation Motions

In addition to the ADLs, three rehabilitation motions were included in this study: 1) internal rotation at the GH joint 2) external rotation at the GH joint and 3) rowing, which was performed by flexing and extending the arm. These motions reflect exercises performed to address joint stiffness and passive ROM when done passively (i.e. when performed by a therapist or aide with the subject providing no voluntary motion). When done against resistance (e.g. weights or resistance bands) the same motions can be used to strengthen the rotator cuff (Fleisig et al., 2011; Smith, Sperling, & Cofield, 2005). The rehabilitation motions were captured in a similar way to the standing ADLs, with each motion having a specific starting position. To simulate active tasks, subjects performed motions with resistance bands. For passive tasks, the subject's arm was moved through the motion by an aide without voluntary muscle activation from the subject. Each task was recorded three times passively and three times actively.

Table 8. Rehabilitation Task Motion Capture Procedure

Motion Capture Procedure		
Rehabilitation Tasks	*Procedure*	*Expected Glenohumeral Joint Actions*
External Rotation	The subject stood in the center of the capture space with their arms at their sides, elbows flexed at 90°, so that the forearm was parallel to the floor. The subject then externally rotated the arm of the monitored limb in this position to the extent of their reach and then returned to the starting position.	*External Rotation*
Internal Rotation	The subject stood in the center of the capture space with their arms at their sides, elbows flexed at 90°, so that the forearm was parallel to the floor. The subject internally rotated the arm of the monitored limb in this position to the extent of their reach and returned to the starting position.	*Internal Rotation*
Reach to back	The subject started with the arm extended, making the arm parallel to the floor. The subject then began a rowing motion (a combination of flexing the elbow and extension at the GHJ) of the monitored arm in this position to the extent of their ROM, and returned to the starting position.	*Flexion* *Extension*

D. Trial Processing

After collection, each trial was processed for analysis. Processing of the trials included reconstruction of the markers within the capture volume, labeling the markers to the UE model marker set, interpolation and low-pass filtering (via a Woltring filter) of the marker trajectories, and application of the UE model.

The trials were then cropped at the following frames:

Trial Start: The trial start was defined as the frame at which continuous forward motion occurred while the subject was in either the standing or sitting starting position.

Trial End: Trial end was defined as the frame at which the subject returned to either the standing or sitting starting position.

Continuous forward motion was defined as continuous motion toward the task object (e.g. mouse, comb, etc.). For tasks done while sitting the trial end frame was followed by ten frames of minimal motion (determined visually). The end frame for standing tasks was defined as the frame when the arm returned to the side of the subject.

Additional events were marked to define the task:

Task Start: The task start is defined as the frame at which the object of the task starts moving. If the task object does not move during the task (e.g. light switch) or if there is no object involved in the task (e.g. rehabilitation motions and reaching to back), the trial start frame is used as the task start frame.

Task Mid: Each task has a periodic motion, starting and ending in the same position. The task's middle fame (Task Mid) was defined as the frame at which the task object was closest to or furthest away from the body, depending on task. For example, the "use phone" task's mid frame was taken when the phone was placed at the ear, while the middle fame for “pushing open a door” was taken when the door was fully opened and the arm was at maximum distance from the body. The writing and typing tasks had no specific middle frames.

<u>Task End</u>: Task end is defined as the frame at which the object of the task stops moving. If the task object does not move during the task (e.g. light switch) or if there is no object involved in the task (e.g. rehabilitation motions and reaching to back), the trial end frame is used as the task end frame,

After cropping and defining trial events, gaps in the trials less than 10 frames were filled via interpolation. A Woltring filter (AKA generalized cross validation) was used as a low-pass filter for each trial. The Woltring filter is a generalized, cross-validatory spline smoothing and differentiation routine equivalent to a double Butterworth filter. The Woltring filter is capable of accommodating data with non-uniform sample rates and with gaps due to marker dropout. For this reason, a cut-off frequency is not specified in the Woltring filter, but rather mean squared error (MSE) was used as to determine cut-off frequency. MSE was set at 20 (Woltring, 1986; Walker, 1998).

The model was then applied to the trials, providing Euler angles defining the kinematics of the GH joint and thorax. Kinematic measures and temporal characteristics were gathered for the individual trials in a sortable database by use of MATLAB code using the MATLAB Toolbox for C3Dserver from C3D.org.

E. Data Analysis

1. Kinematics

After reviewing the raw motion data of the captured trials, it was hypothesized that differences in kinematics would occur at the glenohumeral joint and at the thorax. Minimum angle, maximum angle, and ROM were measured for each plane (sagittal, transverse, and coronal) and joint (GH joint and thorax) for each task. ROM was measured as the difference between the minimum and maximum rotational positions within each trial.

a. Glenohumeral Joint

All post-surgery participants had arthroscopic repair of their supraspinatus tendon, which is a part of the rotator cuff. As previously stated, the rotator cuff is responsible for both stabilizing the humerus and scapula at the GH joint and for articulation between the arm and thorax along with other muscles inserting into the humerus.

b. Thorax

Exaggerated anterior-posterior thorax sway was visually observed during the protocol in post-rotator cuff repair participants, especially during the tasks performed while seated. Due to this observation, thorax kinematics were measured.

2. Temporal Characteristics

All tasks were recorded at 120 Hz throughout the duration of specified tasks (see methods for task description). This allowed kinematic analysis beyond angular position, including comparison of timing related values (duration, instances of patterns such as peaks and valleys in angular position), and plotting of angular position vs. time.

Since there is no set clinical standard for temporal measures during tasks of the UEs, task duration was chosen as the main temporal measurement. Differences in duration between subject groups may reflect differences in quality of motion. Overall duration of each trial was split into time intervals:

Start-to-Object: Duration from Trial Start to Task Start.

Task Duration: Duration from Task Start to Task End.

Object-to-End: Duration from Task End to Trial End.

3. Statistical Analysis

To test the hypotheses of this study, a combination of multivariate (Hotelling's T^2 test) and post-hoc (Welch's t-test) statistical test were used to determine significant differences between the RC repair group and the HS group in minimum angle, maximum angle, and ROM across the three planes of motion (coronal, transverse, and sagittal). While Welch's t-test could be performed for each variable in each plane, multivariate testing was used to determine differences across all three planes for each kinematic variable, reducing the likelihood of type 1 error, i.e. false positives.

Specifically, significant differences between the two groups in coronal plane kinematics (minimum angle, maximum angle, and ROM) for any of the ADLs or rehabilitation motions indicate that abduction was affected by the rotator cuff repair. Significant differences between the groups in transverse and sagittal plane kinematic values indicate that rotator cuff repair affected internal/external rotation and flexion/extension at the shoulder.

Repeatability (Intraclass Correlation Coefficients) was also tested for each kinematic variable in each plane to determine consistency of the variable within each group. The repeatability of each variable reflects how well the variable represents each group. Multivariate testing, post-hoc testing, and repeatability were also tested for temporal characteristics.

a. Intraclass Correlation Coefficient (ICC)

The Intraclass correlation coefficient (ICC) is a descriptive statistic used to assess reproducibility of quantitative measurements, especially when data is structured in groups. In orthopaedics ICC is commonly used to rate the reliability of measurements such as isokinetic strength and anthropomorphic values (Burkhart, Arthurs, & Andrews, 2008; Kakebeeke, Lechner, & Handschin, 2005). As applied to this study the ICC shows the repeatability of each task within each group.

Total variance for a dependent variable *y* (e.g. minimum angle, maximum angle, or ROM in a specific plane for a task) is

$$\boldsymbol{\sigma^2}_{\boldsymbol{y}} = \boldsymbol{\sigma^2}_{\boldsymbol{g}} + \boldsymbol{\sigma^2}_{\boldsymbol{m}} \tag{16}$$

Where $\sigma^2{}_g$ reflects a component of variance attributed to the group (either rotator cuff repairs or ideal shoulders), and $\sigma^2{}_m$ reflects a component of variance attributed to the variations between trials of the same subject (Rodriguez & Elo, 2003; Cleophas & Zwinderman, 2008; DerSimonian & Kacker, 2007).

$$ICC = \frac{\sigma^2{}_g}{\sigma^2{}_m + \sigma^2{}_g} \tag{17}$$

This definition of the ICC will yield only positive numbers. A strong ICC (near 1 on a scale of 0-1) in this study will show that subjects within each group have similar measurements for each task.

Per task, ICC was calculated for each measure of interest (minimum angle, maximum angle, range of motion), plane of motion (coronal, transverse, sagittal), joint (thorax or GH joint), group (RC repair or HS group), and the three temporal characteristics (Start-to-Object, Task Duration, Object-to-End). For each group, values from the individual trials were used to determine ICC (i.e. trials were not averaged per subject).

b. Hotelling's T^2 Test

Hotelling's T^2 test is a multivariate version of the Student's t-test. Hotelling's T^2 test compares multivariate means of two different groups. Hotelling's T^2 test was chosen by design of this study. The small sample size of the two groups (RC repair and HS group) and the assumption that both groups share the same variance-covariance matrix make significant differences found by Hotelling's T^2 to be liberal.(Coombs, Algina, & Oltman, 1996). Use of Hotelling's T^2 also decreased the number of comparisons needed to complete statistical analysis of the data in this study, reducing the occurrence of (type-1 error) false-positives and false negatives (type-2 error). The post hoc two group comparisons were applied only when the test gave a significant p-value. Hotelling's T^2

test determined if there were differences in any of the kinematics and temporal characteristics between the RC repair and HS group for each task. The Hotelling's T^2 test was performed separately for kinematics and duration measures. The Hotelling's T^2 test statistic is

$$\boldsymbol{T}^2 = \frac{\boldsymbol{n_1 n_2}}{\boldsymbol{n_1+n_2}} (\overline{\boldsymbol{x}}_1 - \overline{\boldsymbol{x}}_2)'\boldsymbol{S}^{-1}(\overline{\boldsymbol{x}}_1 - \overline{\boldsymbol{x}}_2) \tag{18}$$

where

$$\boldsymbol{S} = \frac{(\boldsymbol{n_1}-1)\boldsymbol{S_1}+(\boldsymbol{n_2}-1)\boldsymbol{S_2}}{\boldsymbol{n_1}+\boldsymbol{n_2}-2} \tag{19}$$

$\bar{x}_i$, n_i, and S_i are the sample mean vector, sample size and sample covariance matrix for the i^{th} group (i=1,2). The two groups being the RC repair and HS groups.

For GH joint and thorax position data, Hotelling's T^2 tests compared three planes of motion (sagittal, transverse, or coronal) between the rotator cuff repair and healthy shoulder groups. These tests were separately applied for each kinematic variable (minimum angle, max angle, and ROM) and each joint (thorax or GH joint).

For temporal characteristics Hotelling's T^2 tests compared the three duration measures (Start-to-Object, Task Duration, Object-to-End) between the two groups separately for each task. If all three measures were not included in the task (i.e. no object was used to initiate the task), multivariate testing was skipped for the temporal characteristics of that task.

Unlike ICC, averaged values of subject's trials were used as a single measure per person. Therefore, every subject was fully defined by his/her kinematics and temporal characteristics: Eighteen measures from kinematics (3 planes [coronal, transverse, sagittal] x 3 values [min, max, range] x 2 joints [GHJ, Thorax]), and three from temporal characteristics (Start-to-Object, Task Duration, Object-to-End).

c. Welch's t-Test

If the Hotelling's T^2 test found significant differences between groups, the post-hoc Welch's t-tests were used on each individual measurement (GH joint kinematics, thorax kinematics, and temporal characteristics), to determine which measurement or measurements were different between groups. Note that Hotelling's T^2 test assumes equal variance-covariance matrices between the two groups by analogy with the two group t-test in a one dimensional case. Welch's t-test is more conservative than the regular two group t-test, accommodating differences in variances between the groups. This is evident in the equation for the Welch's t statistic:

$$\boldsymbol{t} = \frac{\bar{x}_1 - \bar{x}_2}{\left({S_1}^2/n_1 + {S_2}^2/n_2 \right)^{1/2}} \tag{20}$$

where $\bar{x}_i$, n_i, and S_i are the sample mean vector, sample size and sample covariance for the ith group (i=1,2). Unlike testing with Hotelling's T^2, the mean and variance only account for a specific variable (e.g. only sagittal ROM or only total duration of task) (Algina, Oshima, & Lin, 1994).

For both GH joint and thorax kinematics, Welch's t-test was performed once for each plane if the Hotelling's T^2 test determined a significant difference, further determining which plane or planes of motion showed different values in minimum, maximum, or range of motion.

For the temporal characteristics, Welch's t-test was performed once for each duration measure (Start-to-Object, Task Duration, Object-to-End) of each task. If a specific task did not include all three duration measures, Welch's t-test was performed on the Task Duration variable.

III. Results

A. Complete Trials

Trials incomplete due to marker dropout exceeding 10 frames were excluded from the study. This resulted in an unequal number of comparisons for some tasks (ideally observing ten RC subjects vs. ten HS subjects). The statistics used for this study compensated for these discrepancies. The writing task in particular has much fewer subjects for the RC group compared to the HS group (5 vs. 10). This large difference was due to exclusion of subjects from the writing task who had surgery on the non-dominant shoulder.

Table 9. Number of successful subjects per task

Task	Repair	Healthy
Comb	9	10
Call	10	10
Type	10	10
Drink	10	10
Mouse	9	10
PullDoor	10	10
PushDoor	10	9
Write	5	10
Reach	10	9
Light	10	10
P.Int.Rot	9	9
P.Ext.Rot	9	8
P. Rows	10	10
A.ExtRot	9	10
A.IntRot	8	10
A.Rows	10	10

B. Kinematics

For every successful trial, minimum angle, maximum angle, and ROM were recorded sagittally, coronally, and transversely for the thorax and GH joint. A subject was defined by the average values of their trials. Subject values were further organized into groups and planes of motion (coronal, transverse, and sagittal planes). Comprehensive tables of GH joint and thorax kinematics including mean and standard deviation of minimum angle, maximum angle, and ROM for the RC repair and HS groups are located in the Appendix. The following figures display the mean kinematic values for each group per task.

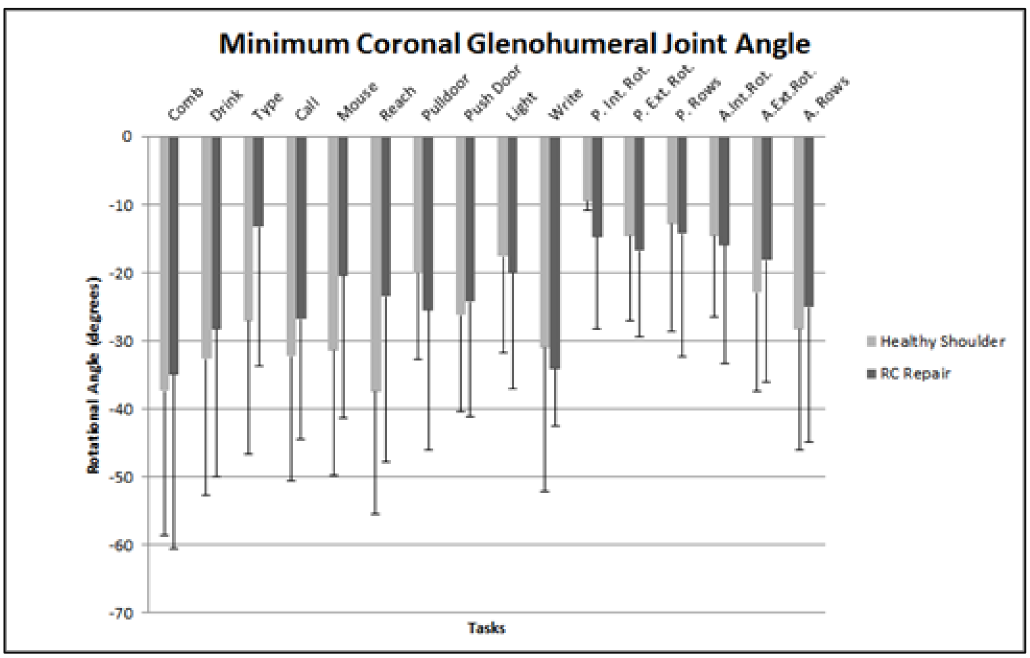


Figure 4. Mean Minimum Coronal Glenohumeral Joint Angle Per Task

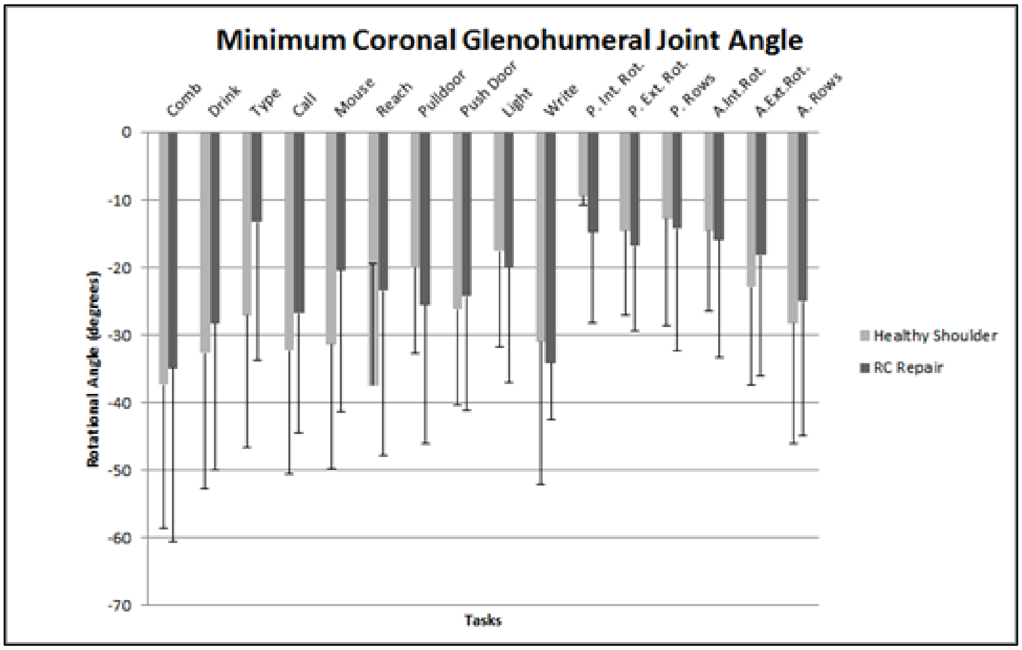


Figure 5. Mean Maximum Coronal Glenohumeral Joint Angle Per Task

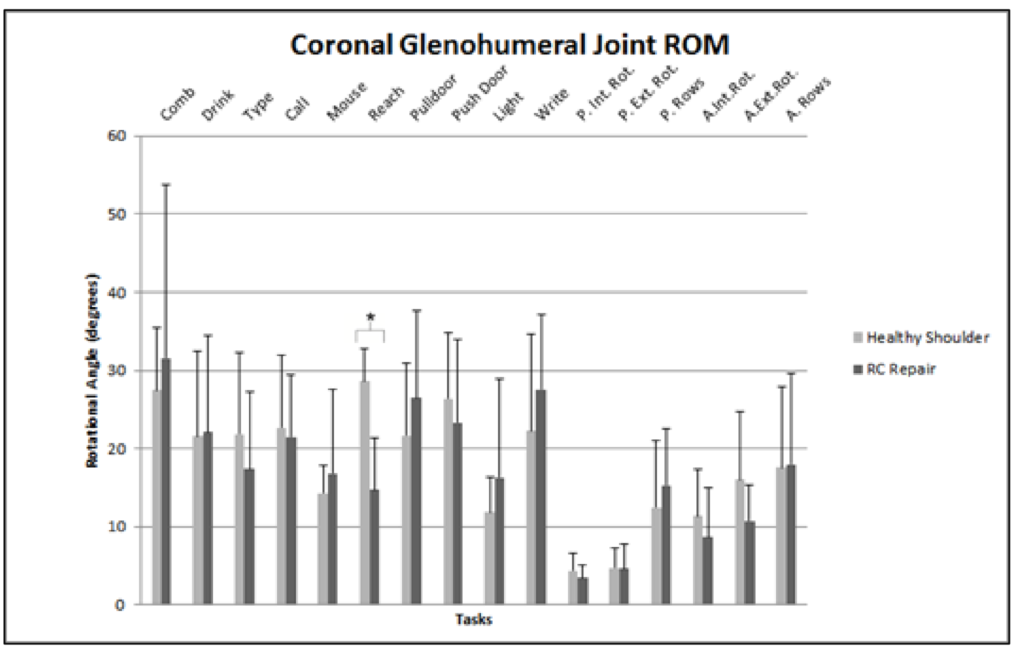


Figure 6. Mean Coronal Glenohumeral Joint Range of Motion Per Task

**** designates significant difference between groups for a single task***

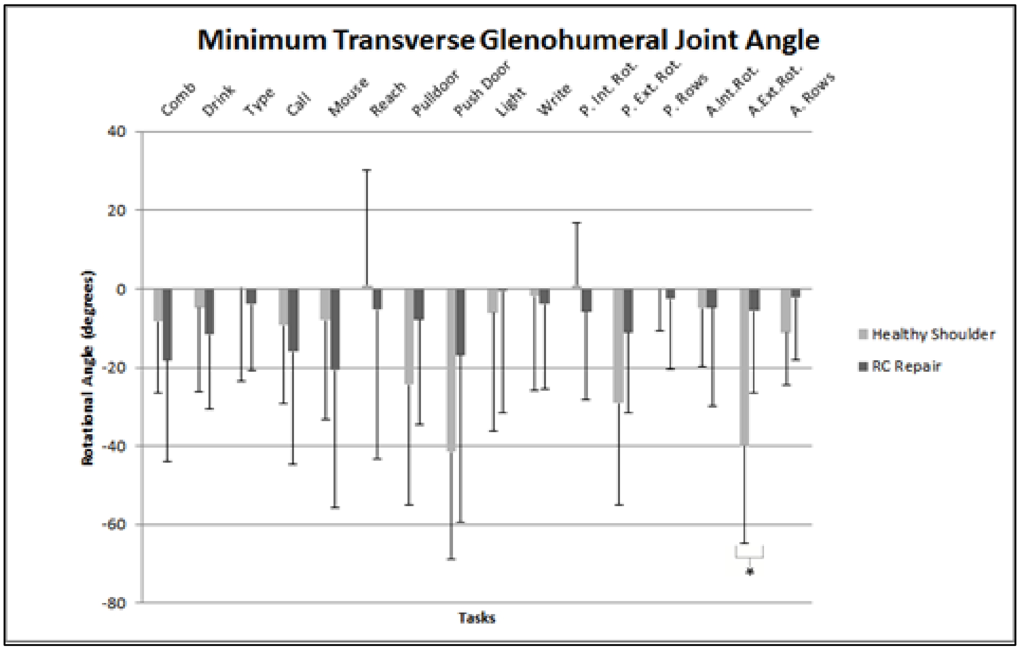


Figure 7. Mean Minimum Transverse Glenohumeral Joint Angle Per Task

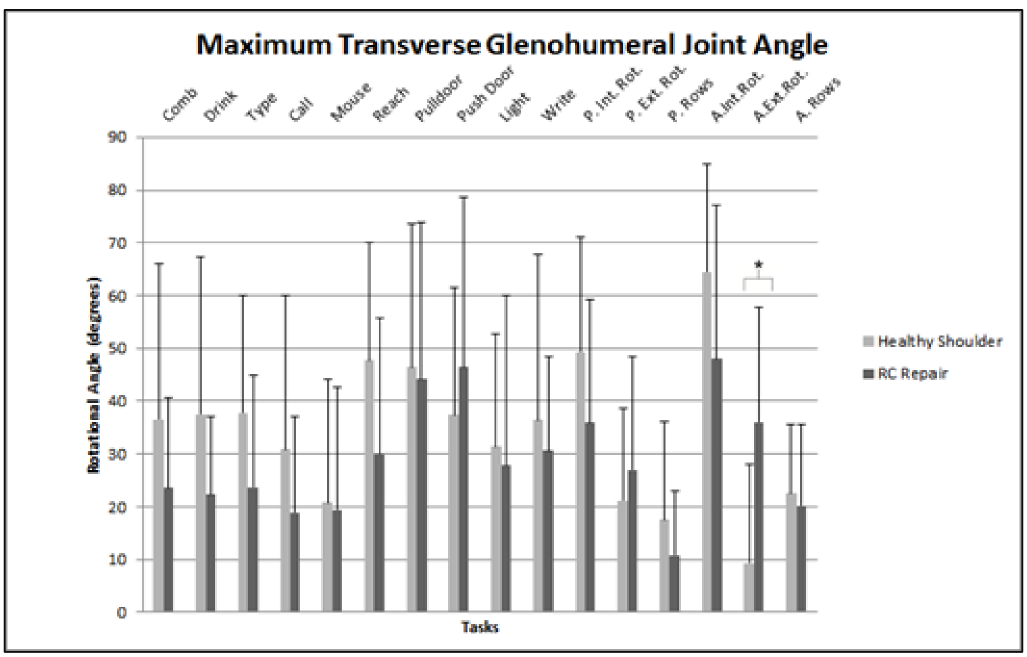


Figure 8. Mean Maximum Transverse Glenohumeral Joint Angle Per Task

**** designates significant difference between groups for a single task***

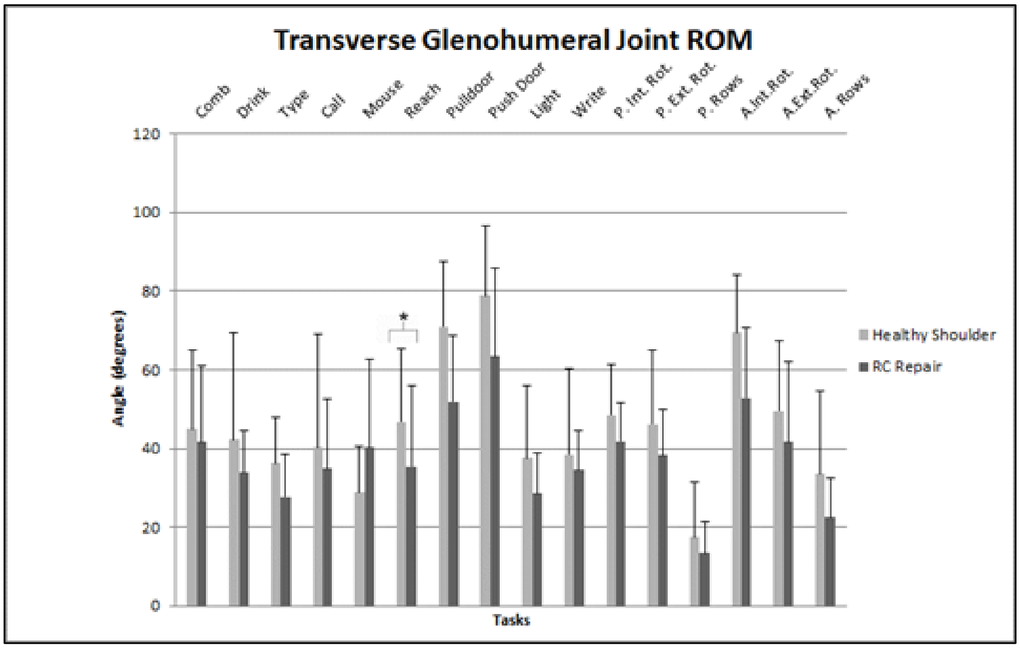


Figure 9. Mean Transverse Glenohumeral Joint Range of Motion Per Task

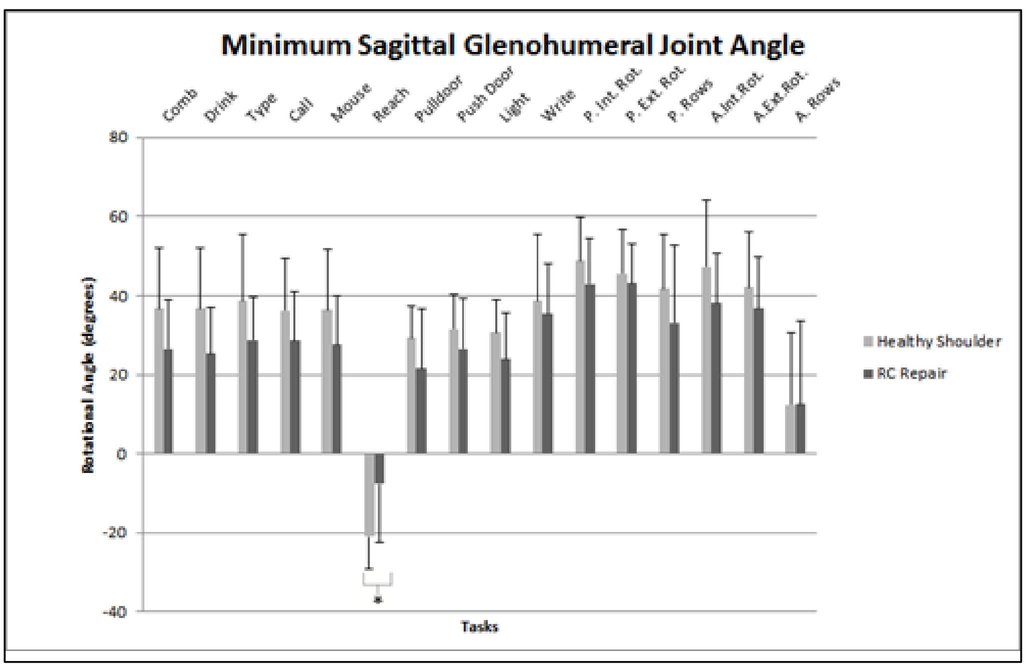


Figure 10. Mean Minimum Sagittal Glenohumeral Joint Angle Per Task

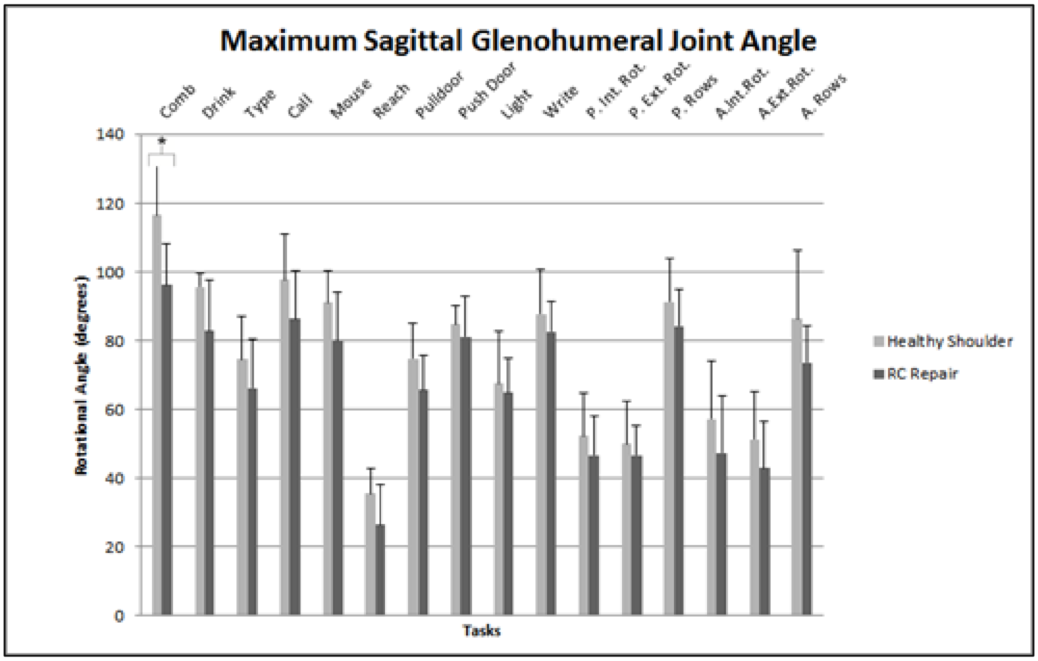


Figure 11. Mean Maximum Sagittal Glenohumeral Joint Angle Per Task

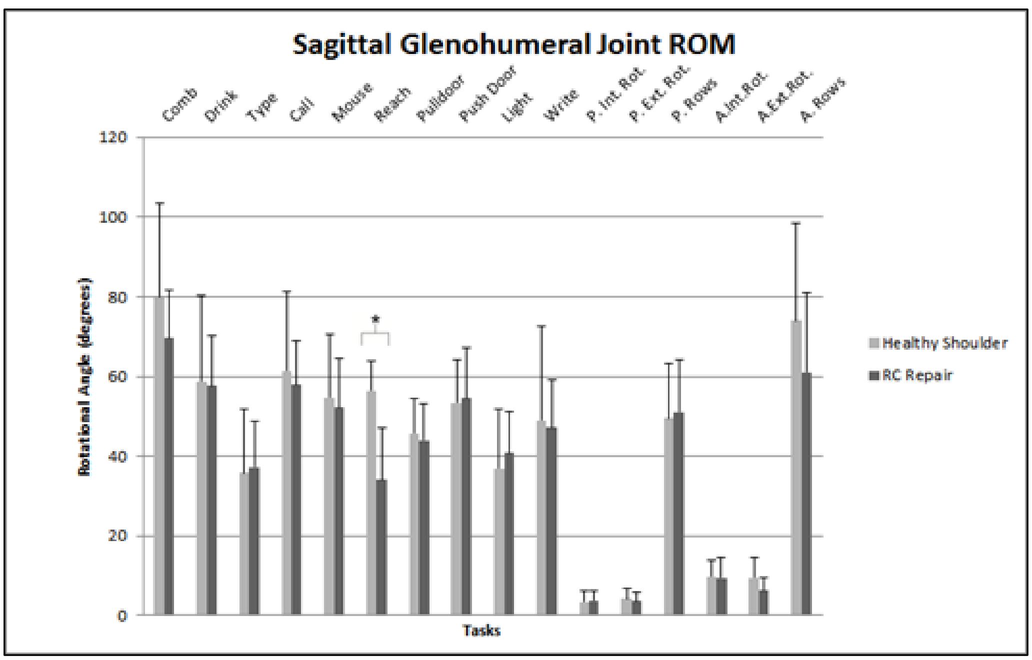


Figure 12. Mean Sagittal Glenohumeral Joint Range of Motion Per Task

Normalized plots of GH joint kinematics further define the ADLs and rehabilitation motions, revealing the combined GH joint actions necessary to complete them.

1. Glenohumeral Joint Kinematics

a. Sitting ADLS

A total of six sitting ADLs were performed: 1) combing hair 2) drinking from a cup 3) typing on a keyboard 4) using a PC mouse 5) writing one's name 6) answering a phone. Each task can be defined by using sagittal (flexion, extension), coronal (abduction, adduction), and transverse (internal rotation, external rotation). Together they define the types of motion performed while sitting at a desk.

i. Coronal Plane Kinematics

For the rotator cuff repair group, the sitting tasks were performed with an overall minimum angle of -34.90 ± 25.63 °, a maximum angle of -3.35 ± 32.24°, and a maximum ROM of 31.55 ± 22.19°. In terms of clinical motion, the rotator cuff repair group required on average 34.90° of abduction, no adduction (slightly adducted at 3.35°), and a total range of motion of 31.55° in the coronal plane (abduction/adduction) to perform the six sitting tasks in total (not individually, which is list in the kinematics tables).

Subjects with healthy shoulders performed the sitting tasks with an overall minimum angle of -37.35 ± 21.23°, maximum angle of -5.26 ± 10.71° and maximum ROM of 27.47 ± 7.95°. This is clinically equivalent to 37.51° of abduction, no adduction (slightly adducted at 5.26), and 27.47° ROM in the coronal plane (abduction/adduction) to perform the six sitting tasks.

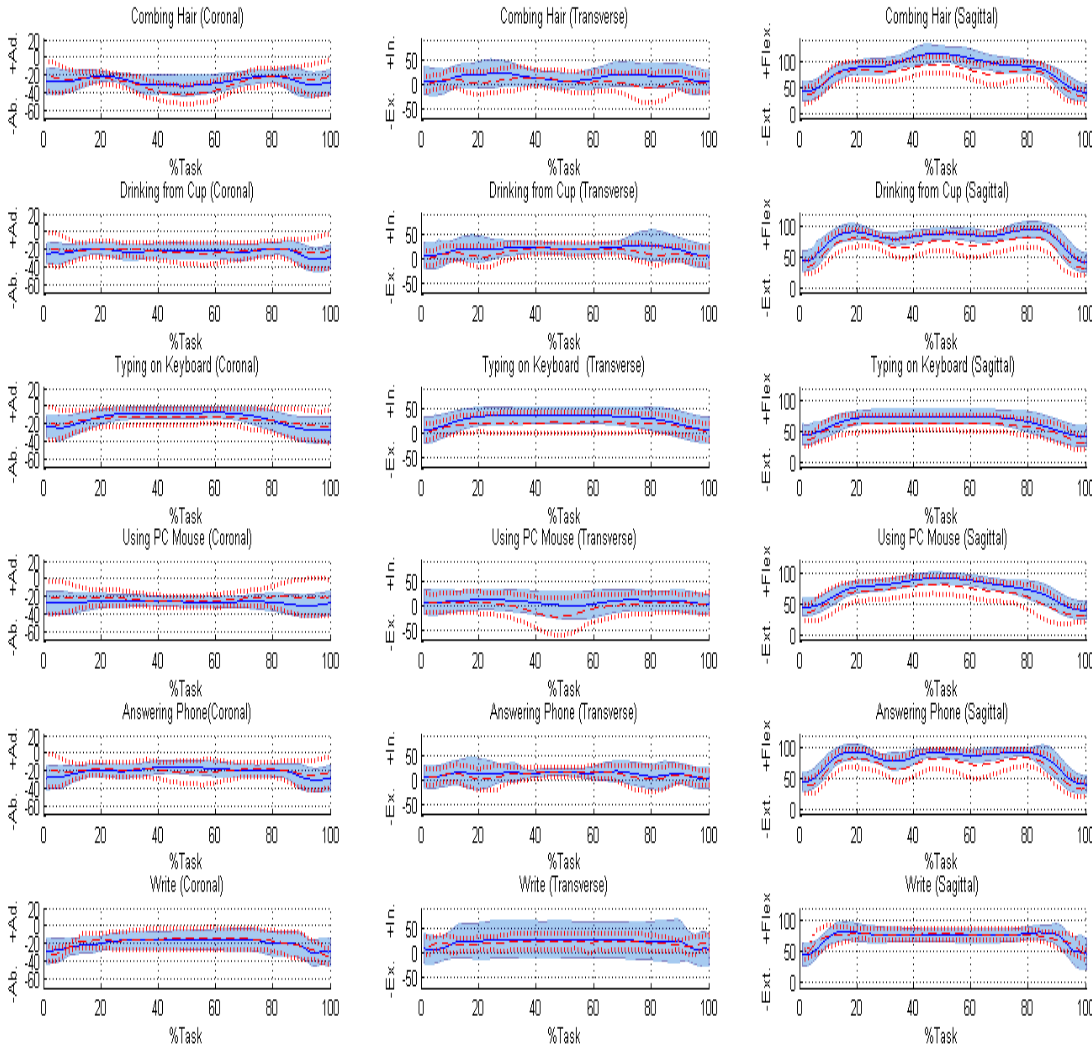


Figure 13. Glenohumeral Joint Kinematics of Sitting ADLs

The six sitting ADLs are defined by angle in the coronal (abduction/adduction), transverse (internal/external rotation), and sagittal (flexion/extension) plane over the duration of the task (designated in the titles above). HS group mean and standard deviation are represented by solid blue line and light blue outline, and the RC repair group mean and standard deviation are represented by the dashed red-line and dotted red outline.

ii. Transverse Plane Kinematics

For the rotator cuff repair group, the sitting tasks were performed with an overall minimum angle of -20.75 ± 35.05°, a maximum angle of 30.57 ± 17.88°, and a maximum ROM of 41.67 ± 19.40°. In terms of clinical motion, the rotator cuff repair group required on average 20.75° of external rotation, 30.57° of internal rotation, and a total range of motion of 41.67° in the transverse plane (internal/external rotation) to perform the six sitting tasks.

Subjects with healthy shoulders performed the sitting tasks with an overall minimum angle of -9.35 ± 19.90°, maximum angle of 37.74 ± 22.24° and maximum ROM of 44.90 ± 20.12°. This is clinically equivalent to 9.35° of external rotation, 37.74° of internal rotation, and 44.90° ROM in the transverse plane (internal/external rotation) to perform the six sitting tasks.

iii. Sagittal Plane Kinematics

For the rotator cuff repair group, the sitting tasks were performed with an overall minimum angle of 25.34 ± 11.59°, a maximum angle of 96.22 ± 12.16°, and a maximum ROM of 69.65 ± 11.95°. In terms of clinical motion, the rotator cuff repair group required no extension (had a minimum of 25.34° flexion), an average 96.22° of flexion, and a total range of motion of 69.65° in the sagittal plane (extension/flexion) to perform the six sitting tasks.

Subjects with healthy shoulders performed the sitting tasks with an overall minimum angle of 36.17 ± 15.37°, maximum angle of 116.60 ± 14.49° and maximum ROM of 79.87 ± 23.75°. This is clinically equivalent to no extension (minimum flexion o 36.17°), 116.60° of flexion, and 79.87° ROM in the sagittal plane (extension/flexion) to perform the six sitting tasks.

b. Standing ADLs

A total of four standing ADLs were performed: 1) reaching to perineum 2) pulling open a door 3) pushing a door and 4) using a wall mounted light switch . Together they define the types of motion performed while standing.

i. Coronal Plane Kinematics

For the rotator cuff repair group, the standing tasks were performed with an overall minimum angle of -25.58 ± 20.37°, a maximum angle of -0.87 ± 18.44°, and a maximum ROM of 26.46 ± 11.19°. In terms of clinical motion, the rotator cuff repair group required on average 25.58° of abduction, no adduction (near neutral at 0.87° abduction), and a total range of motion of 26.46° in the coronal plane (abduction/adduction) to perform the six sitting tasks in total (minimum, maximum, and ROM used for each individual task is list in the kinematics tables).

Subjects with healthy shoulders performed the sitting tasks with an overall minimum angle of -37.51 ± °18.02, maximum angle of 0.13 ± 13.22° and maximum ROM of 28.62 ± 4.21°. This is clinically equivalent to 37.51° of abduction, no adduction (nearly neutral at 0.13° adduction), and 28.62° ROM in the coronal plane (abduction/adduction) to perform the six sitting tasks.

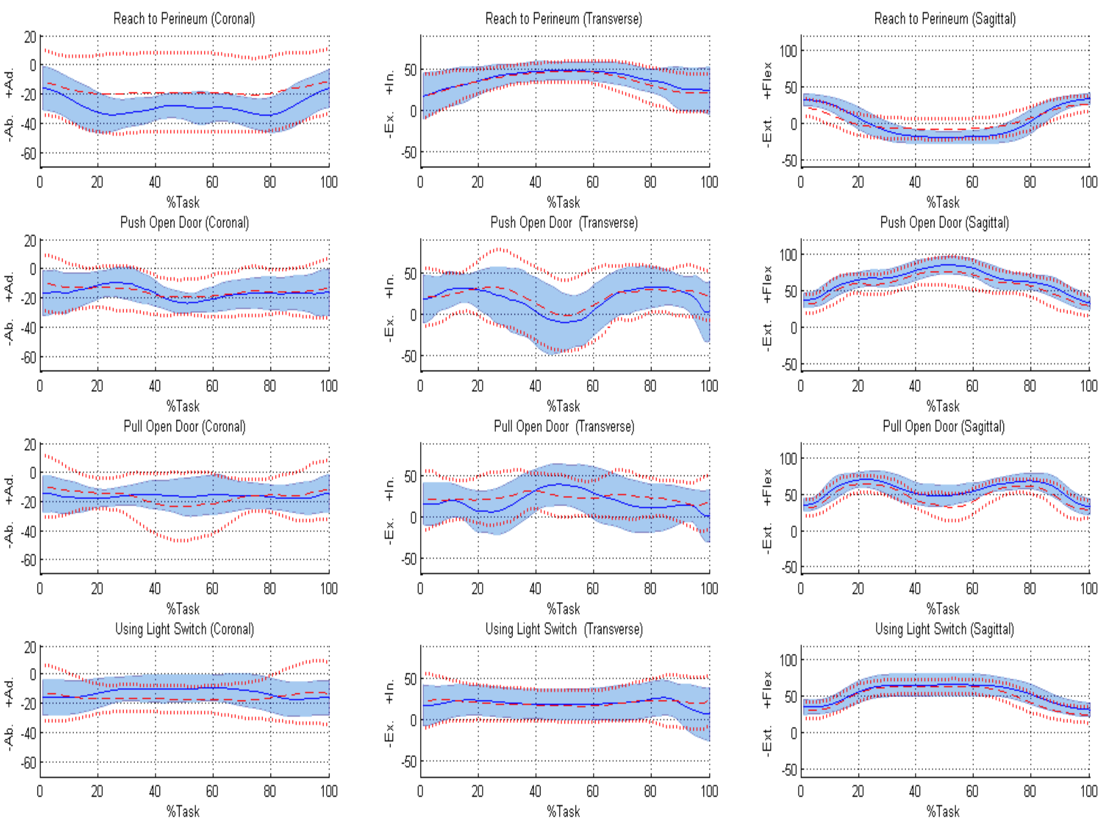


Figure 14. Glenohumeral Joint Kinematics of Standing ADLs

The four standing ADLs are defined by angle in the coronal (abduction/adduction), transverse (internal/external rotation), and sagittal (flexion/extension) plane over the duration of the task (designated in the titles above). HS group mean and standard deviation are represented by solid blue line and light blue outline, and the RC repair group mean and standard deviation are represented by the dashed red-line and dotted red outline.

ii. Transverse Plane Kinematics

For the rotator cuff repair group, the sitting tasks were performed with an overall minimum angle of -16.94 ± 42.43°, a maximum angle of 46.43 ± 32.31°, and a maximum ROM of 63.37 ± 22.58°. In terms of clinical motion, the rotator cuff repair group required on average 16.94° of external rotation, 46.43° of internal rotation, and a total range of motion of 63.37° in the transverse plane (internal/external rotation) to perform the six sitting tasks.

Subjects with healthy shoulders performed the sitting tasks with an overall minimum angle of -41.48 ± 27.30°, maximum angle of 47.68 ± 22.47° and maximum ROM of 78.91± 17.81°. This is clinically equivalent to 41.48° of external rotation, 47.68° of internal rotation, and 78.91° ROM in the transverse plane (internal/external rotation) to perform the six sitting tasks.

iii. Sagittal Plane Kinematics

For the rotator cuff repair group, the sitting tasks were performed with an overall minimum angle of -7.64 ± 14.66°, a maximum angle of 82.59 ± 8.8°, and a maximum ROM of 54.64 ± 12.55°. In terms of clinical motion, the rotator cuff repair group required an average of 7.67° of extension, 82.59° of flexion, and a total range of motion of 54.64° in the sagittal plane (extension/flexion) to perform the six sitting tasks.

Subjects with healthy shoulders performed the sitting tasks with an overall minimum angle of -21.00 ± 8.23°, maximum angle of 84.91 ± 5.46° and maximum ROM of 56.45 ± 7.41°. This is clinically equivalent to 21.00° of extension, 84.91° of flexion, and 56.45° ROM in the sagittal plane (extension/flexion) to perform the six sitting tasks.

c. Rehabilitation Motions

Each rehabilitation motion (internal rotation, external rotation, rowing), is defined in a single plane, although the model allows for analysis of each motion in multiple axes. Internal and external rotation are defined in the transverse plane and rowing defined as extension/flexion in the sagittal plane. Each motion was performed passively and actively, to determine differences in active and passive motion during each task.

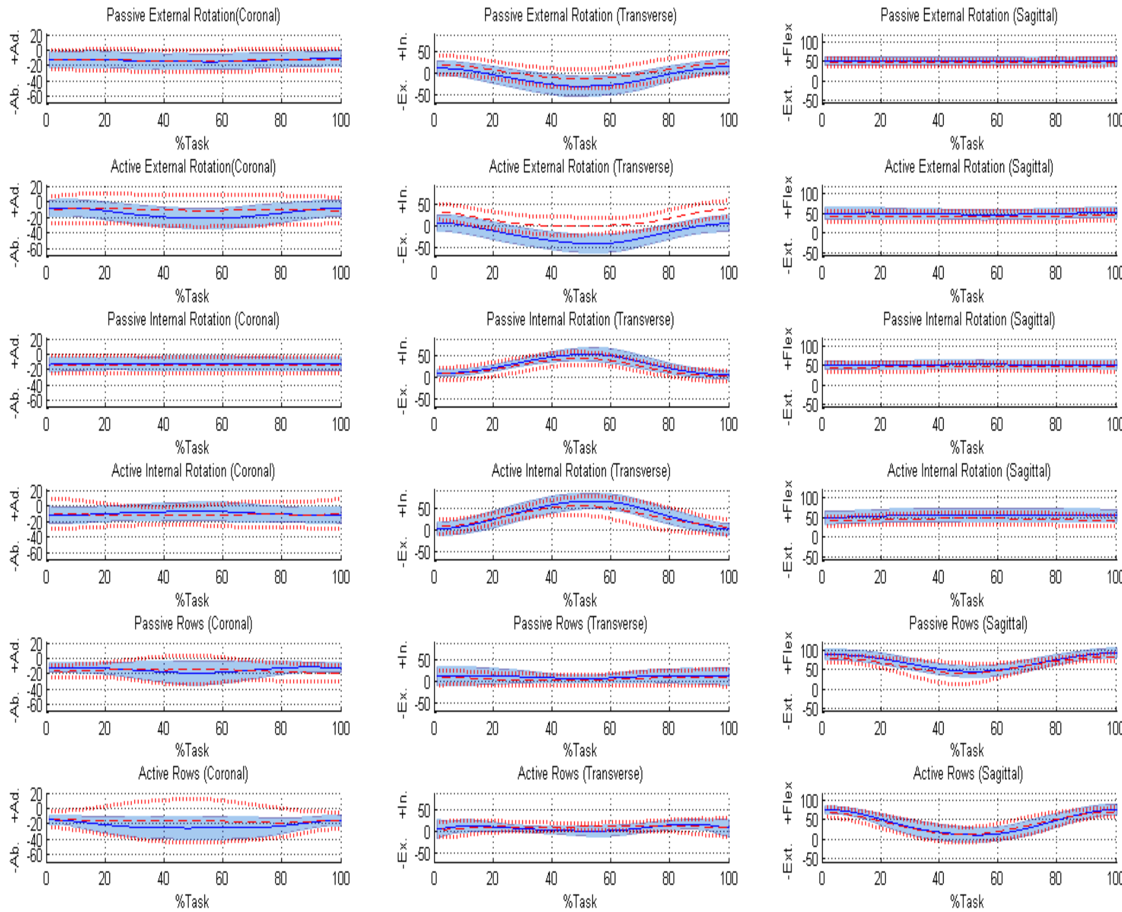


Figure 15. Glenohumeral Joint Kinematics of Rehabilitation Motions

The rehabilitation motions are defined by angle in the coronal (abduction/adduction), transverse (internal/external rotation), and sagittal (flexion/extension) plane over the duration of the task (designated in the titles above). HS group mean and standard deviation are represented by solid blue line and light blue outline, and the RC repair group mean and standard deviation are represented by the dashed red-line and dotted red outline.

Internal rotation for the rotator cuff repair group was performed passively with an average ROM of 41.76 ± 9.87° (minimum angle = -5.84 ± 22.21° and max angle = 35.93 ± 23.26°), with 35.93° internal rotation and an average starting position externally rotated 5.84°. This motion was performed actively with an average ROM of 52.82 ± 18.04° (minimum angle = -4.83 ± 25.18°, max angle = 48.00 ± 29.19°) with 48.00° internal rotation and a starting position 4.83° externally rotated.

The healthy shoulder group performed internal rotation passive with an average ROM of 48.46 ± 12.89° (minimum angle = 0.91 ± 15.85°, maximum angle = 49.38 ± 21.71°) with 49.38° of internal rotation and a starting position near neutral (0.91° internally rotated). Actively they performed the motion with an average ROM of 69.52 ± 14.77° (minimum angle = -5.02 ± 14.63°, maximum angle = 64.50 ± 20.44°) with 64.50° internal rotation and a starting position 5.02° externally rotated

External rotation for the rotator cuff repair group was performed passively with an average ROM of 38.17 ± 11.72° (minimum angle = -11.23 ± 20.18° and max angle = 26.94 ± 21.60°), with 11.23° external rotation and an average starting position internally rotated 26.94°. This motion was performed actively with an average ROM of 41.58 ± 20.41° (minimum angle = -5.54 ± 20.98°, max angle = 36.05 ± 21.74°) with 5.54° external rotation and a starting position 36.05° internally rotated.

The healthy shoulder group performed external rotation passively with an average ROM of 46.08 ± 19.04° (minimum angle = -29.19 ± 25.99°, maximum angle = 21.18 ± 17.49°) with 29.19° of external rotation and a starting position 21.18° internally rotated. Actively they performed the motion with an average ROM of 49.44 ± 17.78° (minimum angle = -40.08 ± 24.71°, maximum angle = 9.36 ± 18.71°) with 40.08° external rotation and a starting position 9.36° internally rotated

Rowing for the rotator cuff repair group was performed passively with an average ROM of 51.08 ± 13.14° (minimum angle = 33.23 ± 19.40° and max angle = 84.31 ± 10.56°), starting at 84.31° flexion and the mid-point of the row at 33.23° flexion. This motion was performed actively with an average ROM of 61.16 ± 19.77° (minimum angle = 12.56 ± 21.04°, max angle = 73.72 ± 10.66°) starting on average at 73.72° flexion and the point of the row at 12.56°flexion.

The ideal healthy shoulder group performed rowing passively with an average ROM of 49.51 ± 13.60° (minimum angle = 41.78 ± 13.51°, maximum angle = 91.28 ± 12.59°) starting at 91.28° flexion and the mid-point of the row at 41.78° flexion. This motion was performed actively with an average ROM of 74.11 ± 24.42° (minimum angle = 12.37 ± 18.14°, max angle = 86.48 ± 19.93°) starting on average at 86.48° flexion and the point of the row at 12.37°flexion.

d. Repeatability (ICC)

ICC values for many measures were >0.8, indicating strong repeatability of measures kinematics (minimum angle, maximum angle, ROM). ICC values ~0.5 represent moderate repeatability. For both groups, only ROM in specific tasks showed below moderate repeatability. Focusing on kinematic measures below with ICC values <0.5, the RCR group performed four tasks 1) reaching to perineum, 2) passive external rotation 3) pulling open a door, 4) Pushing open a door) with below moderate repeatability in ROM.

Specifically, ROM for reaching to perineum and passive external rotation had repeatability values in the coronal plane (~0.00 and 0.22 respectively), and ROM for pulling open a door and pushing open a door had lower repeatability in the transverse plane (0.47 and 0.38 respectively).All other GH joint kinematics across all planes for the RC repair group had ICC values >0.5.

The HS group had below moderate repeatability in coronal plane ROM for passive internal rotation (0.40) and in transverse plane ROM for pushing open a door (0.47). ICC values for all kinematics (minimum angle, maximum angle, and ROM for the GHJ and thorax) are located in the appendix.

e. Significantly Different Tasks

Of the ten ADLs, three had significantly different kinematics between the rotator cuff repair and healthy shoulder groups (combing hair, reaching to perineum, and pulling open a door). Specifically, the comb task had a significantly different maximum GH joint angle ($p=0.0405$), the reach task was significantly different in both minimum angle ($p=0.0487$) and ROM ($p<0.001$), and the task of pulling a door open had significantly different ROM ($p=0.046$) between groups. All other tasks showed no significant difference.

Table 10. Tasks with Significantly Different Glenohumeral Joint Range of Motion

Kinematics		Glenohumeral Joint Range of Motion		
		Healthy	Repairs	P-value (Welch's t-test)
Reach	Coronal	28.62 ± 4.21	14.74 ± 6.64	*0.0004
	Transverse	46.79 ± 18.57	35.34 ± 20.45	0.2067
	Sagittal	56.45 ± 7.41	34.13 ±12.97	*0.0003
PullDoor	Coronal	21.70 ± 9.19	26.46 ± 11.19	0.3127
	Transverse	70.89 ± 16.73	51.92 ± 16.63	*0.0204
	Sagittal	45.62 ± 8.80	44.02 ± 9.22	0.6957

Mean +/- standard deviation in seconds shown for each variable.
****denotes significant difference between groups (a=0.05)***

Table 11. Significantly Different Maximum Glenohumeral Joint Angles

Kinematics		Glenohumeral Joint Maximum Angle		
		Healthy	Repairs	P-value (Welch's t-test)
Comb	Coronal	-9.88 ± 17.76	-3.35 ± 32.24	0.6000
	Transverse	36.59 ± 29.43	23.51 ± 17.03	0.2490
	Sagittal	116.60 ± 14.49	96.22 ± 12.16	*0.0039
A.Ext.Rot	Coronal	-6.92 ± 11.37	-10.79 ± 16.79	0.5696
	Transverse	9.363 ± 18.71	36.05 ± 21.74	*0.0116
	Sagittal	51.43 ± 13.65	42.83 ± 13.75	0.1905

Table 12. Significantly Different Minimum Glenohumeral Joint Angles

Kinematics		Glenohumeral Joint Minimum Angle		
		Healthy	Repairs	P-value (Welch's t-test)
Reach	Coronal	-37.51 ± 18.02	-23.52 ± 24.35	0.1628
	Transverse	0.885 ± 29.22	-5.35 ± 38.02	0.6862
	Sagittal	-21.00 ± 8.23	-7.64 ± 14.66	*0.0248
A.Ext.Rot	Coronal	-22.93 ± 14.41	-18.19 ± 17.85	0.5361
	Transverse	-40.08 ± 24.71	-5.54 ± 20.98	*0.0043
	Sagittal	42.05 ± 14.14	36.66 ± 13.01	0.3664

The rehabilitation motion, active external rotation, was significantly different in minimum angle (p=0.0237) and maximum angle (p=0.0286) between groups. All other rehabilitation motions were not significantly different in GH joint kinematics.

Post-hoc testing revealed which planes of motion were significantly different for the measured GHJ kinematics of the three ADLs and the rehabilitation motion (active external rotation).

For the combing hair task, sagittal plane maximum GH joint angle (i.e. flexion for combing hair) was significantly different between the rotator cuff repair and healthy shoulder groups (p=0.039). For this task the RC repair group used 96.22 ± 12.16° and the HS group used 116.60± 14.49° of flexion on average.

The reach to perineum task was significantly different in minimum GH joint angle (i.e. extension for reaching to perineum) in the sagittal plane (p=0.0247). On average the RC repair group used 7.64 ± 14.66° and the HS group used 21.00 ± 8.23° of extension on average to accomplish this task. ROM in both the coronal and sagittal plane were significantly different as well between groups (both with p-values < 0.001). The RC repair group used 14.74 ± 6.64° coronal ROM and 34.13 ±12.97° sagittal ROM for the reach to perineum task. The HS group used 28.62 ± 4.21° coronal ROM and 56.45 ± 7.41° sagittal ROM to complete this task.

For pulling open a door, transverse GH joint ROM (i.e. external/internal rotation) was significantly different between the rotator cuff repair group and the healthy shoulder group (p=0.020). For this task the RC repair group used 51.92 ± 16.63 ° and the HS group used 70.89 ± 16.73° on average.

Active external rotation was significantly different in both minimum transverse GHJ angle (external rotation) and maximum transverse GHJ angle (internal rotation), with p=0.004 and p=0.012 respectively. The RC repair group used 5.54 ± 20.98° external rotation and 36.05 ± 21.74° internal rotation to accomplish this task, while the HS group used 40.08 ± 24.71° external rotation and 9.363 ± 18.71° internal rotation on average to perform active external rotation**.**

2. Thorax Kinematics

Thorax kinematics were also acquired from the same six sitting and four standing ADLs. The motions of each task were defined by coronal (left and right lateral flexion), transverse (left and right axial flexion), and sagittal (thorax extension and flexion) plane movement.

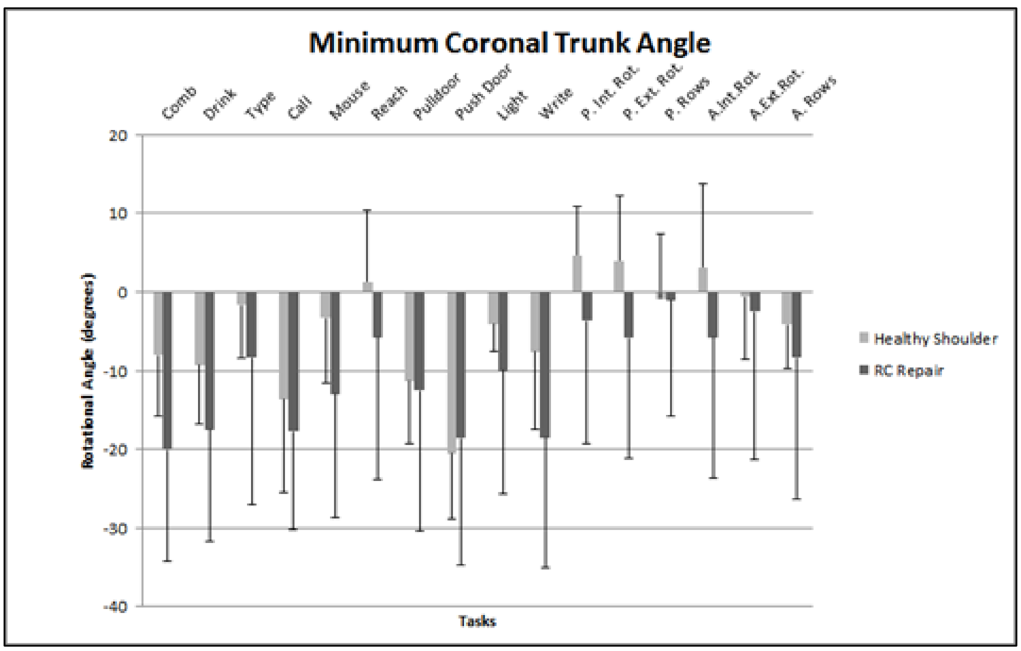


Figure 16. Mean Minimum Coronal Thorax Angle Per Task

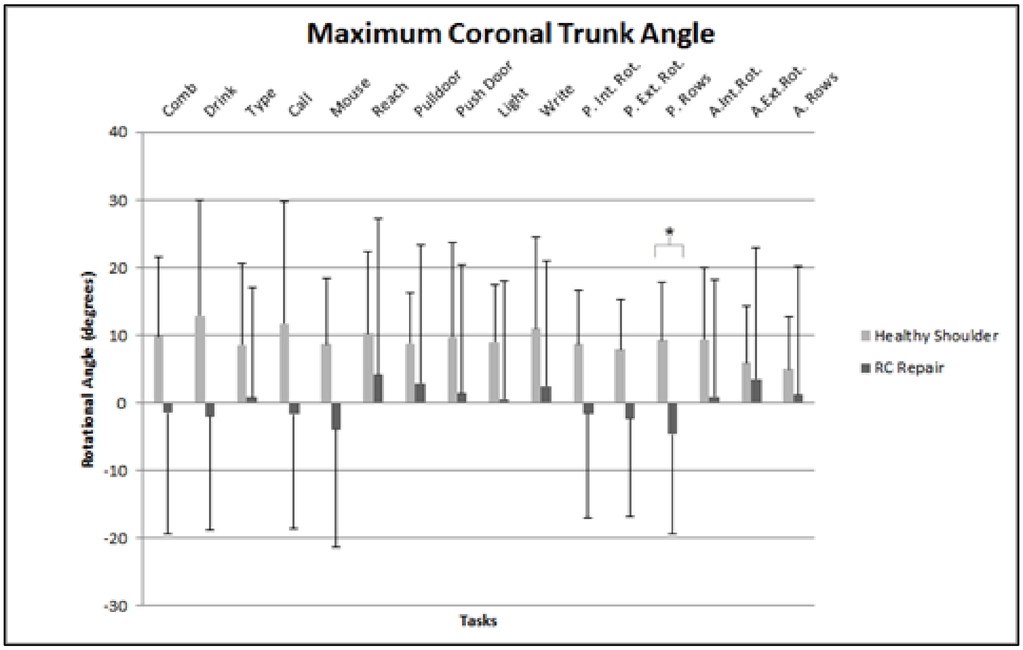


Figure 17. Mean Maximum Coronal Thorax Angle Per Task

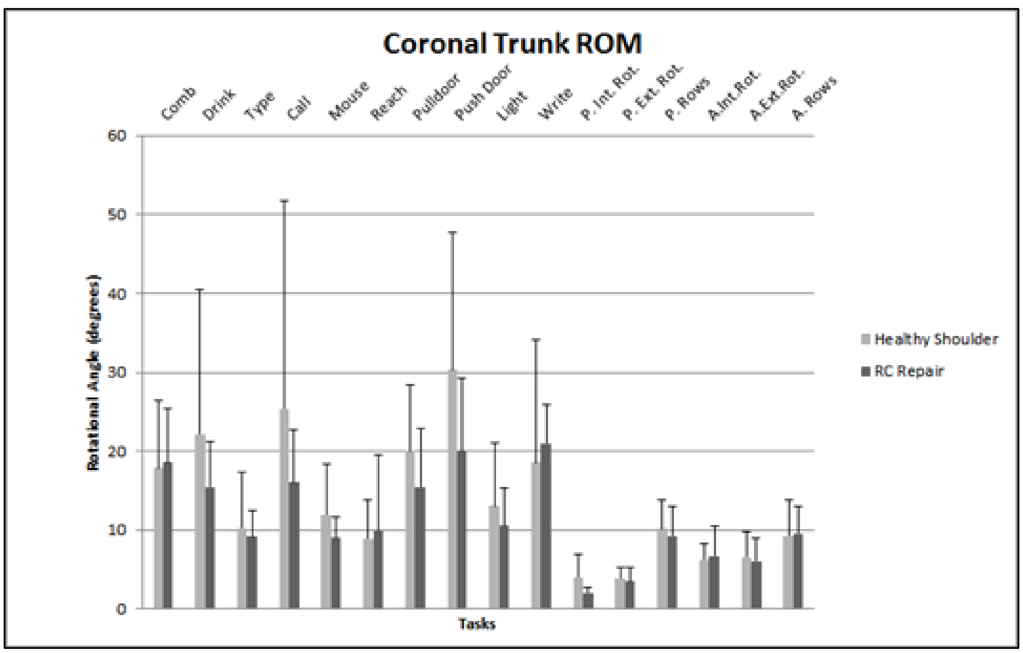


Figure 18. Mean Coronal Thorax Range of Motion Per Task

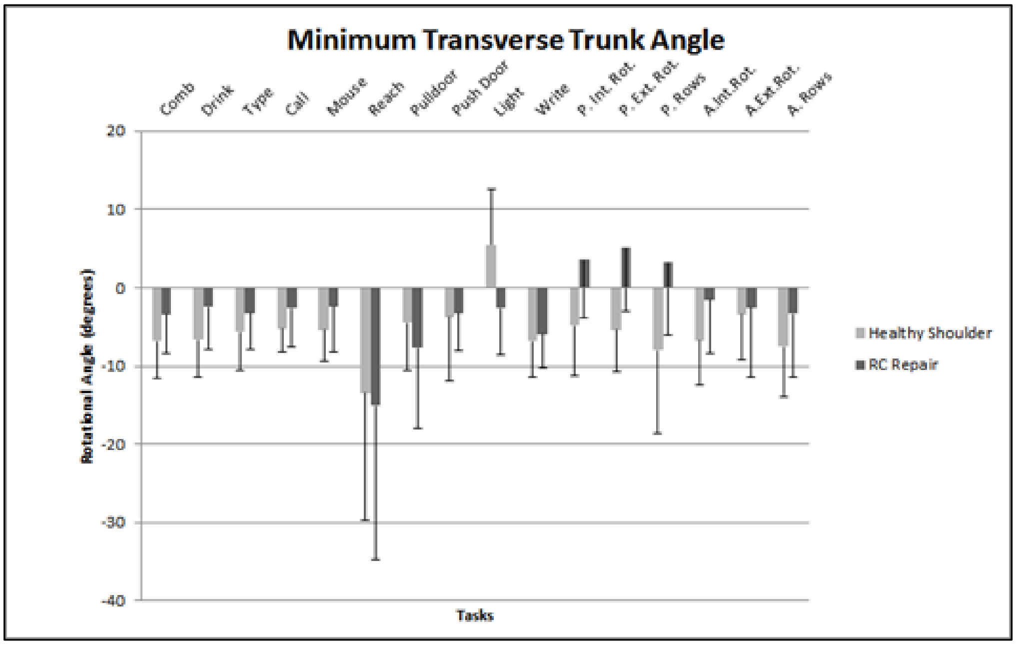


Figure 19. Mean Minimum Transverse Thorax Angle Per Task

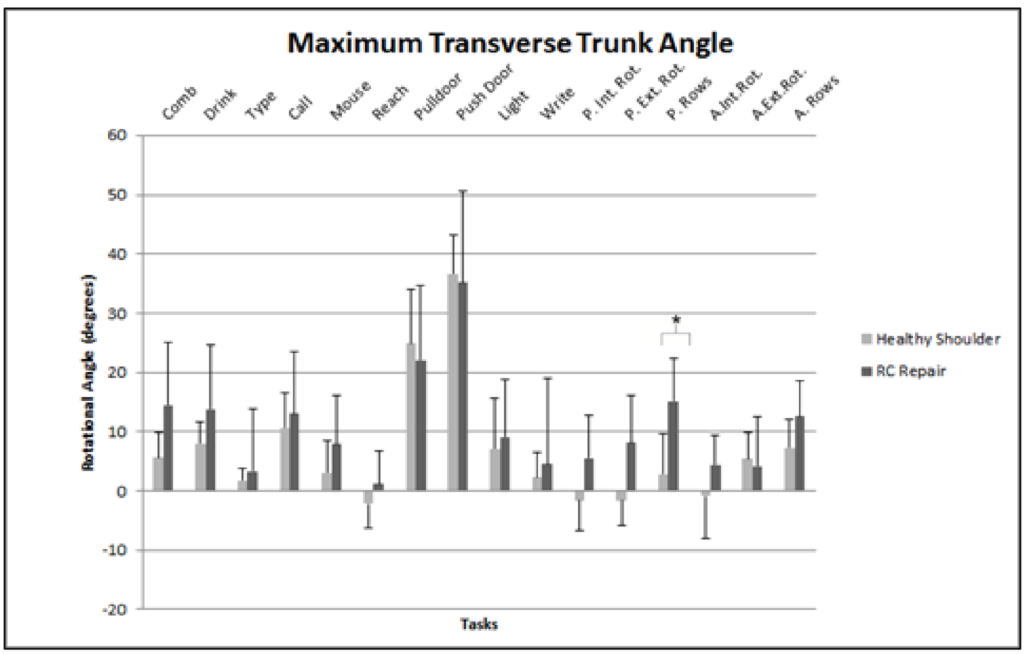


Figure 20. Mean Maximum Transverse Thorax Angle Per Task

**** designates significant difference between groups for a single task***

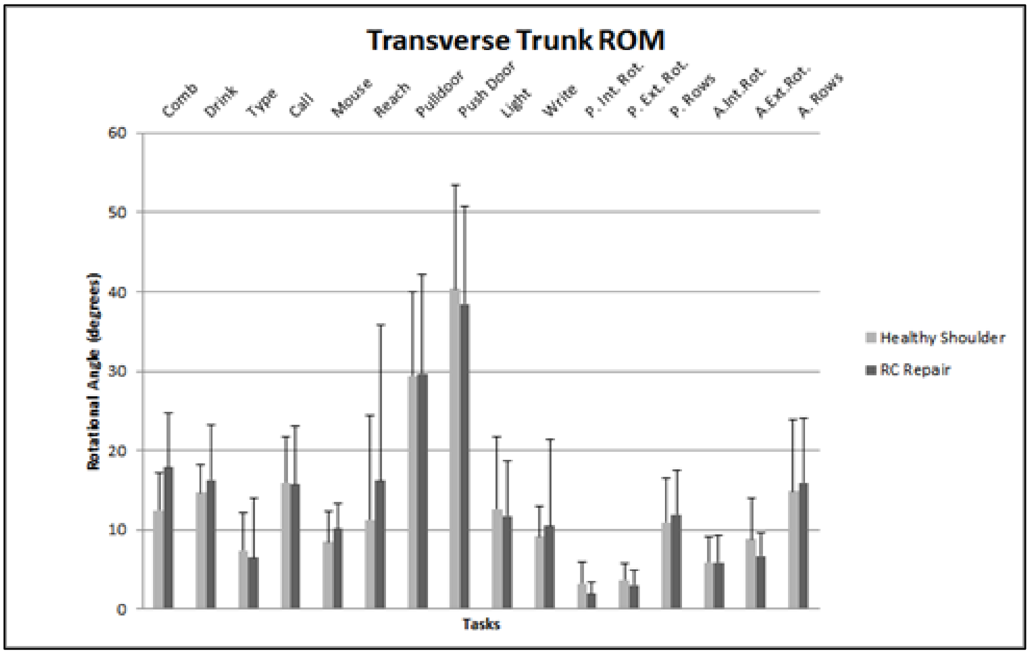


Figure 21. Mean Transverse Thorax Range of Motion Per Task

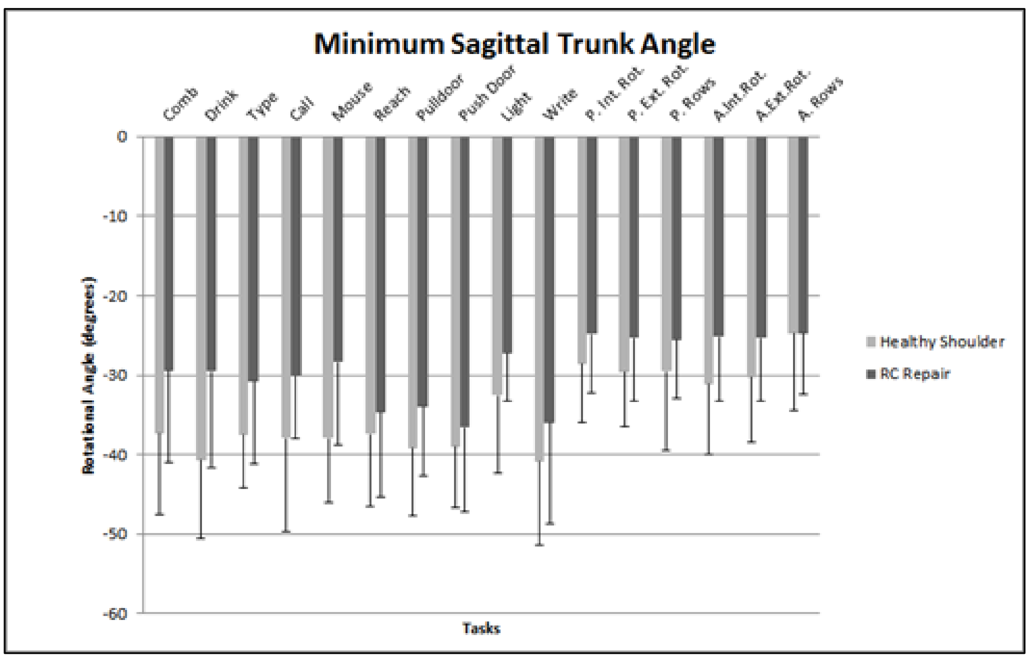


Figure 22. Mean Minimum Sagittal Thorax Angle Per Task

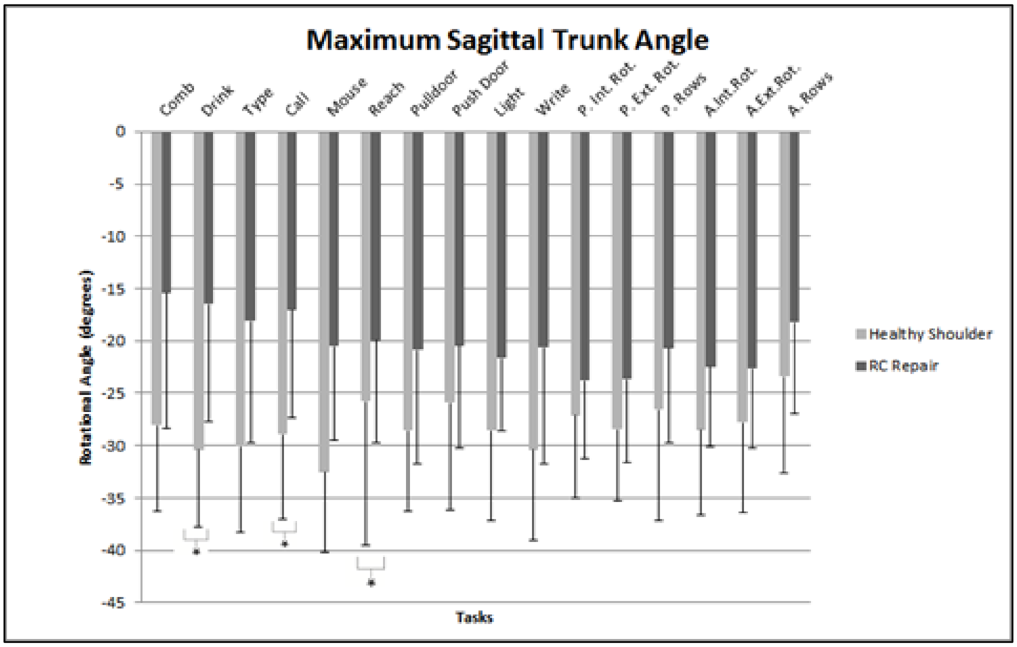


Figure 23. Mean Maximum Sagittal Thorax Angle Per Task

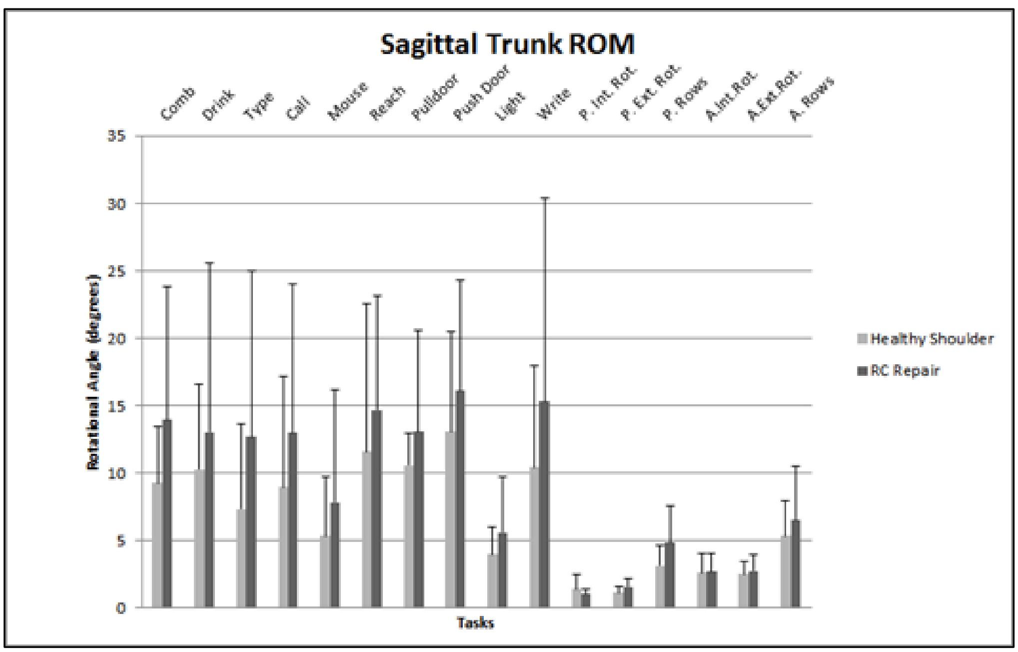


Figure 24. Mean Sagittal Thorax Range of Motion Per Task

a. Sitting ADLs

i. Coronal Plane Kinematics

For the rotator cuff repair group, the sitting tasks were performed with an overall minimum angle of -20.12 ± 14.09 °, a maximum angle of 2.56 ± 18.33°, and a maximum ROM of 21.02 ± 4.84°. In terms of clinical motion, the rotator cuff repair group required on average 20.12° of left lateral flexion, 2.56° of right lateral flexion (near neutral) , and a total range of motion of 21.02° in the coronal plane (left and right lateral thorax flexion) to perform the six sitting tasks.

Subjects with healthy shoulders performed the sitting tasks with an overall minimum angle of -13.61 ± 11.93°, maximum angle of 12.92 ± 17.03° and maximum ROM of 25.38 ± 26.42°. This is clinically equivalent to 13.61° of left lateral flexion, 12.92° of right lateral flexion (slightly adducted at 0.76°), and 25.38° of ROM in left and right lateral thorax flexion to perform the six sitting tasks.

ii. Transverse Plane Kinematics

For the rotator cuff repair group, the sitting tasks were performed with an overall minimum angle of -5.94 ± 4.23°, a maximum angle of 14.54 ± 10.52°, and a maximum ROM of 17.90 ± 6.88°. In terms of clinical motion, the rotator cuff repair group required on average 5.94° of right axial rotation, 14.54° of left axial rotation , and a total range of motion of 17.90° in the transverse plane (left and right axial thorax rotation) to perform the six sitting tasks.

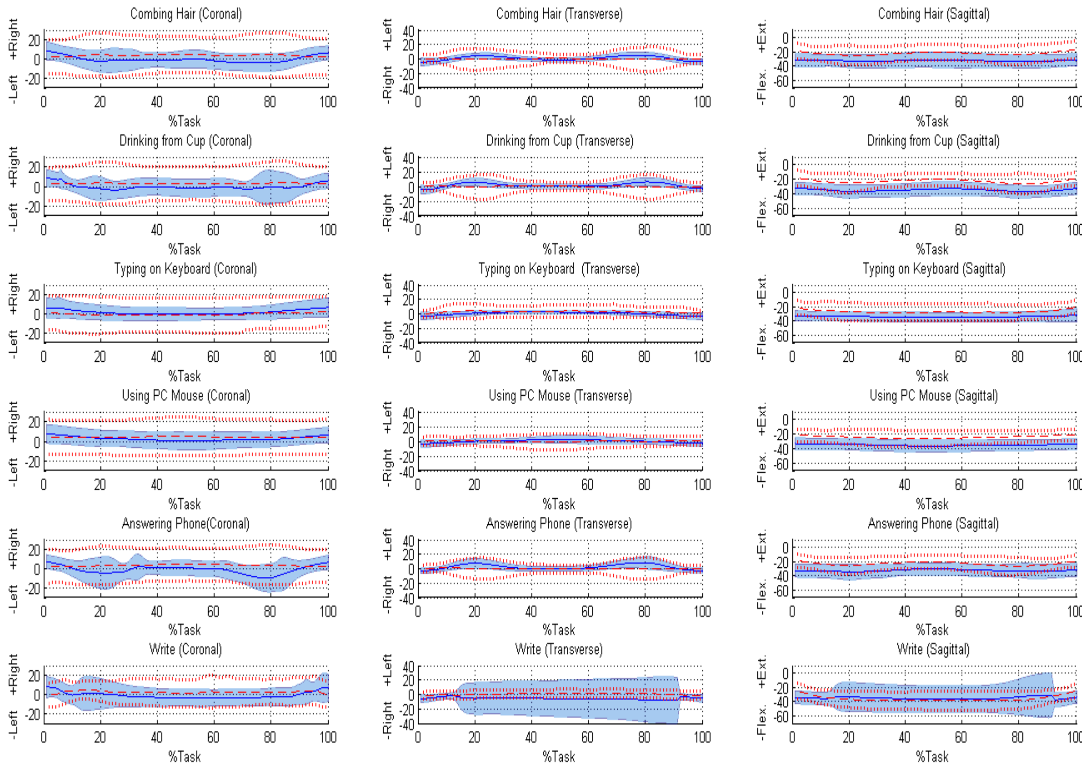


Figure 25. Thorax Kinematics of Sitting ADLs

The six sitting ADLs are defined by angle in the coronal (left/right lateral flexion), transverse (left/right axial rotation), and sagittal (flexion/extension) plane over the duration of the task (designated in the titles above). HS group mean and standard deviation are represented by solid blue line and light blue outline, and the RC repair group mean and standard deviation are represented by the dashed red-line and dotted red outline.

Subjects with healthy shoulders performed the sitting tasks with an overall minimum angle of -6.87 ± 4.75°, maximum angle of 10.78 ± 5.94° and maximum ROM of 15.99 ± 5.68°. This is clinically equivalent to 6.87° of right axial rotation, 10.78° of left axial rotation, and 15.99° of ROM in left and right axial thorax rotation to perform the six sitting tasks.

iii. Sagittal Plane Kinematics

For the rotator cuff repair group, the sitting tasks were performed with an overall minimum angle of -35.95 ± 12.69°, a maximum angle of -15.42 ± 12.97°, and a maximum ROM of 15.35 ± 14.99°. In terms of clinical motion, the rotator cuff repair group required on average 35.95° of thorax flexion (forward tilt), no thorax extension (backward tilt) with a minimum of 15.42° thorax flexion , and a total range of motion of 15.35° in the sagittal plane (thorax flexion and extension) to perform the six sitting tasks.

Subjects with healthy shoulders performed the sitting tasks with an overall minimum angle of -40.84 ± 10.51°, maximum angle of -28.07 ± 8.18° and maximum ROM of 10.44 ± 7.47°. This is clinically equivalent to 40.84° of thorax flexion, no thorax extension (a minimum of 10.78° thorax flexion used for the sitting tasks), and 10.44° of ROM in thorax flexion and extension to perform the six sitting tasks.

b. Standing ADLs

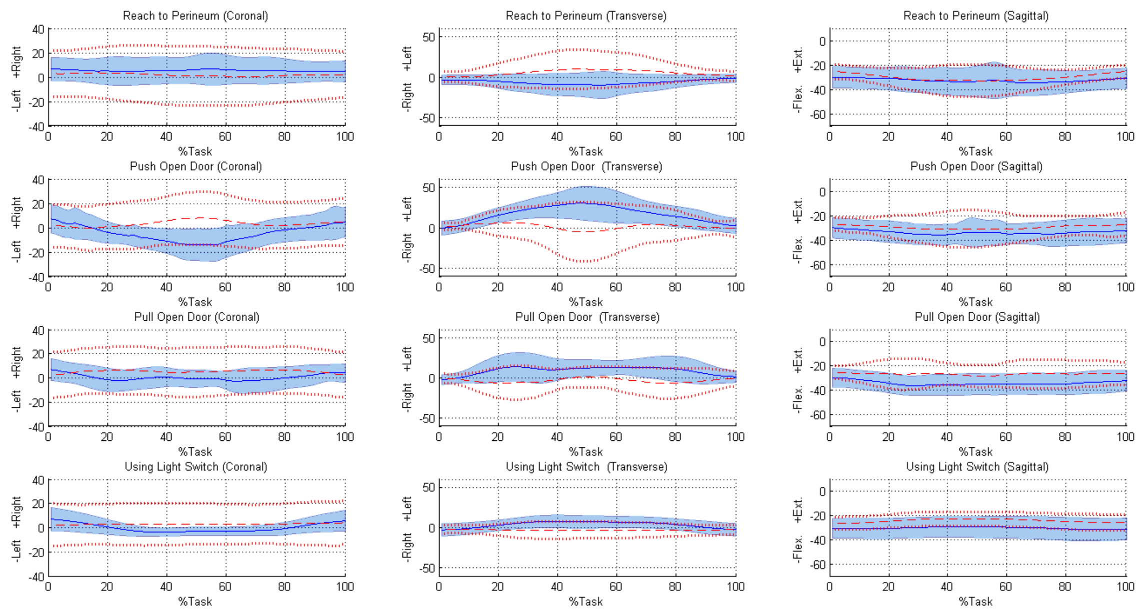


Figure 26. Thorax Kinematics of Standing ADLs

The four standing ADLs are defined by angle in the coronal (left/right lateral flexion), transverse (left/right axial rotation), and sagittal (flexion/extension) plane over the duration of the task (designated in the titles above). HS group mean and standard deviation are represented by solid blue line and light blue outline, and the RC repair group mean and standard deviation are represented by the dashed red-line and dotted red outline.

i. Coronal Plane Kinematics

For the rotator cuff repair group, the standing tasks were performed with an overall minimum angle of -18.62 ± 16.19°, a maximum angle of 4.18 ± 23.14°, and a maximum ROM of 20.04 ± 9.21°. In terms of clinical motion, the rotator cuff repair group required on average 18.62° of left lateral thorax flexion, 4.18° of right lateral thorax flexion , and a total range of motion of 20.04° in the coronal plane (left and right lateral thorax flexion) to perform the four standing tasks.

Subjects with healthy shoulders performed the sitting tasks with an overall minimum angle of -20.51 ± 8.33°, maximum angle of 10.25 ± 12.16° and maximum ROM of 30.29 ± 17.41°. This is clinically equivalent to 20.51° of left lateral thorax flexion, 10.25° of right lateral thorax flexion, and 30.29° of ROM in left and right lateral thorax flexion to perform the four standing tasks.

ii. Transverse Plane Kinematics

For the rotator cuff repair group, the standing tasks were performed with an overall minimum angle of -15.05 ± 19.69°, a maximum angle of 35.20 ± 15.42°, and a maximum ROM of 38.46 ± 12.20°. In terms of clinical motion, the rotator cuff repair group required on average 15.05° of right axial thorax rotation, 35.20° of left axial thorax rotation, and a total range of motion of 38.46° in the transverse plane (left and right axial thorax rotation) to perform the four standing tasks.

Subjects with healthy shoulders performed the sitting tasks with an overall minimum angle of -13.47 ± 16.21°, maximum angle of 36.66 ± 6.55 ° and maximum ROM of 40.42 ± 13.00°. This is clinically equivalent to 13.47° of right axial thorax rotation, 36.66° of left axial thorax rotation, and 40.42° of ROM in left and right axial thorax rotation to perform the four standing tasks.

iii. Sagittal Plane Kinematics

For the rotator cuff repair group, the standing tasks were performed with an overall minimum angle of -36.57 ± 10.67°, a maximum angle of -19.93 ± 9.80°, and a maximum ROM of 16.11 ± 8.18°. In terms of clinical motion, the rotator cuff repair group required on average 36.57° of thorax flexion, no thorax extension (tasks performed at a minimum of 19.93° thorax flexion), and a total range of motion of 16.11° in the sagittal plane (thorax flexion and extension) to perform the four standing tasks.

Subjects with healthy shoulders performed the sitting tasks with an overall minimum angle of -40.84 ± 10.51°, maximum angle of -25.79 ± 13.70° and maximum ROM of 13.09 ± 7.37°. This is clinically equivalent to 40.84° of thorax flexion, no thorax extension (tasks performed with a minimum of 25.79° of thorax flexion), and 13.09° of ROM in thorax flexion and extension to perform the four standing tasks.

c. Rehabilitation Motions

While the three rehabilitation motions were prescribed to specific planes of motion for the GH joint, actions at the thorax were not limited during passive or active trials. Thorax motion did occur during the standing rehabilitation trials, although with less ROM compared to the GH joint.

i. Coronal Plane Kinematics

For the rotator cuff repair group, the rehabilitation motions were performed with an overall minimum angle of -25.09 ± 19.83°, a maximum angle of -2.53 ± 21.07°, and a maximum ROM of 17.97 ± 11.57°. In terms of clinical motion, the rotator cuff repair group required on average 25.09° of left lateral thorax flexion, no right lateral thorax flexion (at least 2.53° of left lateral thorax flexion), and a total range of motion of 17.97° in the coronal plane (left and right lateral thorax flexion) to perform the three rehabilitation motions both passively and actively.

Subjects with healthy shoulders performed the rehabilitation motions with an overall minimum angle of -4.11 ± 5.69°, maximum angle of 9.38 ± 10.59° and maximum ROM of 10.14 ± 3.60°. This is clinically equivalent to 4.11° of left lateral thorax flexion, 9.38° of right lateral thorax flexion, and 10.14° of ROM in left and right lateral thorax flexion to perform the rehabilitation motions.

ii. Transverse Plane Kinematics

For the rotator cuff repair group, the rehabilitation motions were performed with an overall minimum angle of -3.33 ± 8.16°, a maximum angle of 15.16 ± 7.27°, and a maximum ROM of 15.96 ± 8.05°. In terms of clinical motion, the rotator cuff repair group required on average 3.33° of right axial thorax rotation, 15.16° of left axial thorax rotation, and a ROM of 15.96° in the transverse plane (right and left axial thorax rotation) to perform the three rehabilitation motions.

Subjects with healthy shoulders performed the rehabilitation motions with an overall minimum angle of -8.04 ± 10.52°, maximum angle of 7.37 ± 4.64° and maximum ROM of 14.87 ± 8.96°. This is clinically equivalent to 8.04° of right axial thorax rotation, 7.37° of left axial thorax rotation, and 14.87° of ROM in right and left axial thorax rotation to perform the rehabilitation motions.

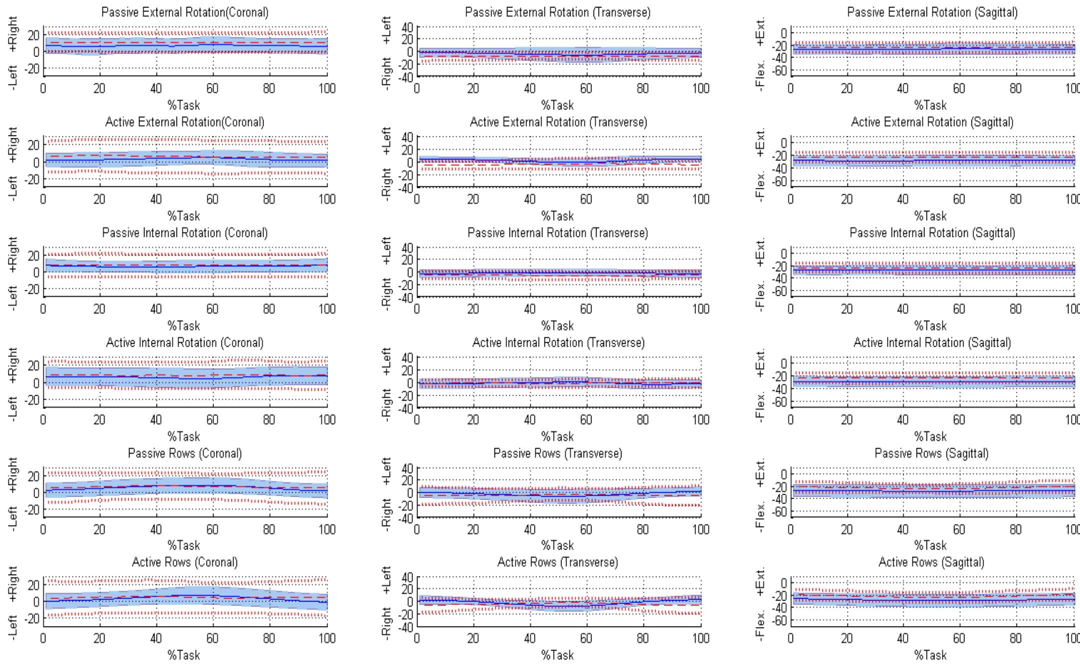


Figure 27. Thorax Kinematics of rehabilitation Motions

The rehabilitation motions are defined by angle in the coronal (left/right lateral flexion), transverse (left/right axial rotation), and sagittal (flexion/extension) plane over the duration of the task (designated in the titles above). HS group mean and standard deviation are represented by solid blue line and light blue outline, and the RC repair group mean and standard deviation are represented by the dashed red-line and dotted red outline.

iii. Sagittal Plane Kinematics

For the rotator cuff repair group, the rehabilitation motions were performed with an overall minimum angle of -25.57 ± 7.27°, a maximum angle of -18.24 ± 8.75°, and a maximum ROM of 6.54 ± 3.94°. In terms of clinical motion, the rotator cuff repair group required on average 25.57° of thorax flexion, no thorax extension (a minimum of 18.24° of thorax flexion), and a ROM of 6.54° in the sagittal plane (thorax flexion and extension) to perform the three rehabilitation motions.

Subjects with healthy shoulders performed the rehabilitation motions with an overall minimum angle of -31.11 ± 8.82°, maximum angle of -23.43 ± 9.15° and maximum ROM of 5.35 ± 2.62°. This is clinically equivalent to 31.11° of thorax flexion, no thorax extension (a minimum of 23.43° of right lateral thorax flexion), and 5.35° of ROM in thorax flexion and extension to perform the rehabilitation motions.

d. Repeatability (ICC)

For the RC repair group, the tasks of typing on a keyboard (0.475), active internal rotation (0.194), and active rowing (0.3094) had ICC values showing below moderate repeatability in coronal ROM for the thorax. In the sagittal plane, pulling open a door (~0.00) and passive external rotation (~0.00) showed low repeatability in ROM. Pushing open a door and passive internal rotation had below moderate ICC values for measures in both the transverse and sagittal planes. Specifically, pushing open a door showed lower ICC values in maximum angle (0.479) in the transverse plane (i.e. left axial thorax rotation) and sagittal plane ROM (0.355). Passive internal rotation had below moderate ICC values for both transverse ROM (0.493) and sagittal ROM (0.453).

The HS group had below moderate repeatability in coronal plane ROM for writing (0.414), passive internal rotation (~0.00), passive external rotation (0.382), active internal rotation (0.252) and active rowing (~0.00). Sagittal ROM showed below moderate repeatability for passive internal rotation (~0.00), passive internal rotation (0.269), and active external rotation (0.386).

e. Significantly different Tasks

Of the ten ADLs, three had significantly different thorax kinematics. Specifically, overall maximum thorax angle (accounting for coronal, transverse, and sagittal plane) was significantly different for drinking from a cup (p=0.031), using a phone (p=0.046) and using a PC mouse (p=0.036). The rehabilitation motion of passive rowing was also significantly different (p=0.015) in maximum thorax angle.

Table 13. Tasks with Significantly Different Maximum Thorax Angle

Kinematics		Trunk		
		Maximum Angle		
		Healthy	Repairs	P-value (Welch's t-test)
Call	Coronal	11.77 ± 18.10	-1.70 ± 16.97	0.1033
	Transverse	10.78 ± 5.94	13.01 ± 10.55	0.5690
	Sagittal	-28.93 ± 8.08	-17.05 ± 10.28	*0.0105
Drink	Coronal	12.92 ± 17.03	-1.97 ± 16.89	0.0652
	Transverse	8.03 ± 3.60	13.80 ± 10.89	0.1398
	Sagittal	-30.41 ± 7.31	-16.48 ± 11.23	*0.0048
Mouse	Coronal	8.66 ± 9.68	-3.90 ± 17.32	0.0782
	Transverse	3.06 ± 5.35	7.83 ± 8.27	0.1633
	Sagittal	-32.52 ± 7.66	-20.49 ± 8.98	*0.0066
P.Rows	Coronal	9.26 ± 8.67	-4.63 ± 14.71	*0.0215
	Transverse	2.87 ± 6.79	15.16 ± 7.27	*0.0010
	Sagittal	-26.55 ± 10.60	-20.69 ± 9.02	0.2001

Mean +/- standard deviation in degrees shown for each variable.
**** denotes significant difference between groups***

Further analysis of thorax motion shows significant differences sagittal plane maximum angle (thorax extension) for using a phone (12.99 ± 11.01° vs. 8.97 ± 8.18° p=0.105), drinking from a cup (13.04 ± 12.55° vs. 10.28 ± 6.33° p=0.005), and using a PC mouse (7.83 ± 8.37° vs. 5.362 ± 4.36° p=0.007) between RC repair and healthy shoulder groups respectively.

The passive rowing rehabilitation motion was significantly different in maximum angle in two planes, coronal plane maximum angle (4.63 ± 14.71° vs. 9.26 ± 8.67°, p=0.022) and transverse plane maximum angle (15.16 ± 7.27° vs. 2.87 ± 6.79°, p=0.001) for the RC repair and healthy shoulder groups. On average, the RC repair group did not perform right lateral thorax flexion during passive row (a minimum of 4.63° left lateral thorax flexion was used) while the healthy shoulder group performed 9.26° of right lateral thorax flexion, and the RC repair group performed 15.16° of left axial thorax rotation while the HS group performed 2.87° of left axial thorax rotation (near neutral).

3. Temporal Characteristics

As described previously, temporal characteristics for each ADL including time from starting position to touching a task's object (Start-to-Object), total time using the object (Task duration), and from finishing using the object to returning to starting position (Object-to-End) were collected for each trial. For tasks without an object (certain ADLs and rehabilitation tasks), time between starting motion to ending motion (from leaving starting position to returning to starting position) was considered duration of the task, with no Start-to-Object or Object-to-End values recorded. These values were gathered in a similar fashion to the kinematic data.

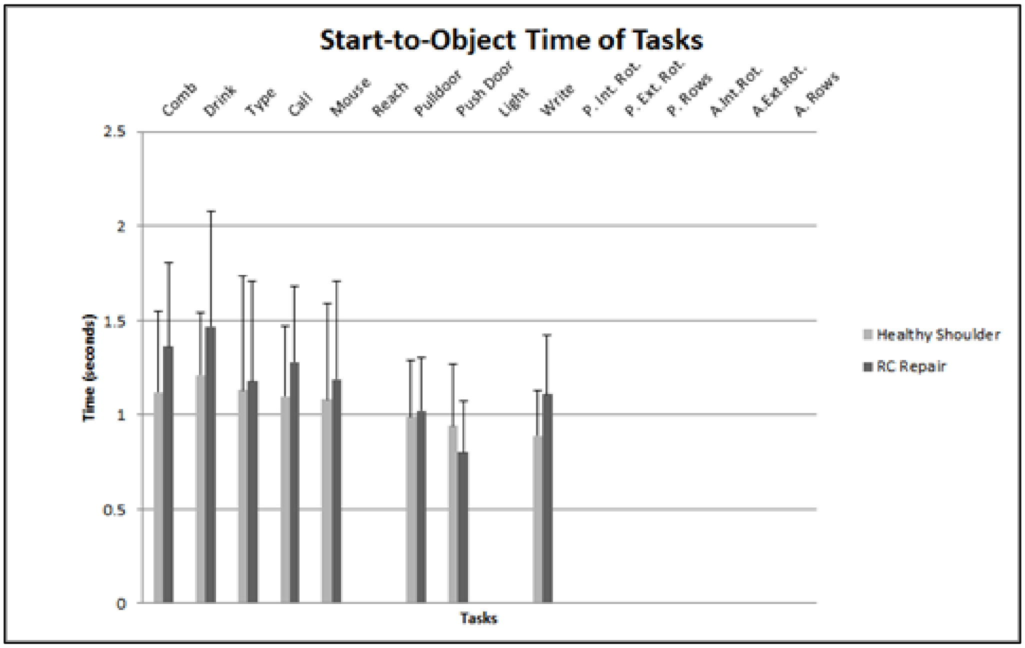


Figure 28. Mean Start-to-Object Time per Task

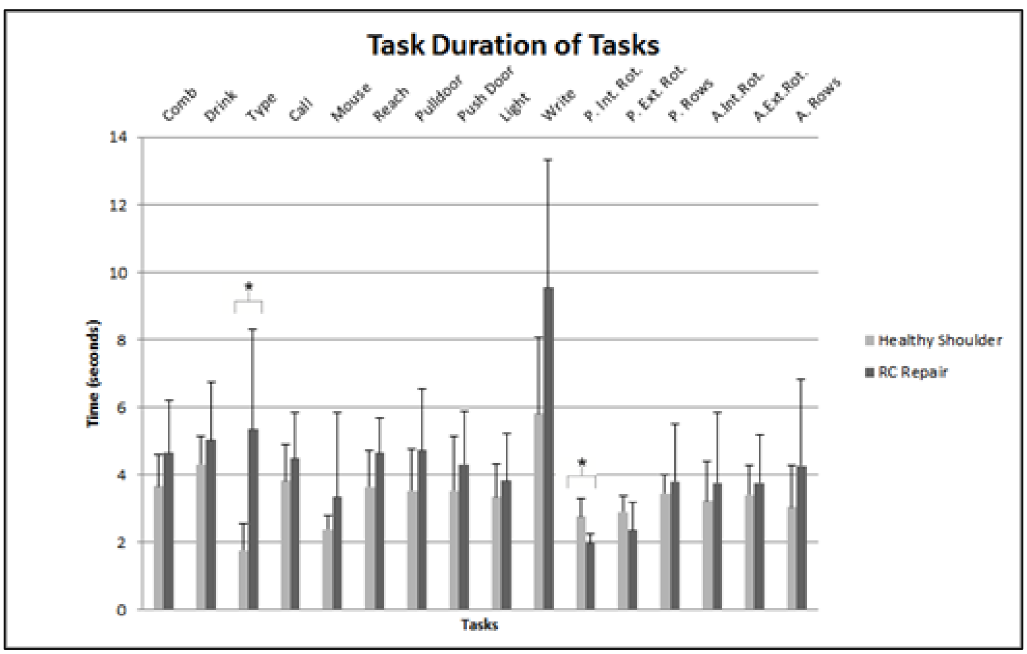


Figure 29. Mean Task Duration Time per Task

**** designates significant difference between groups for a single task***

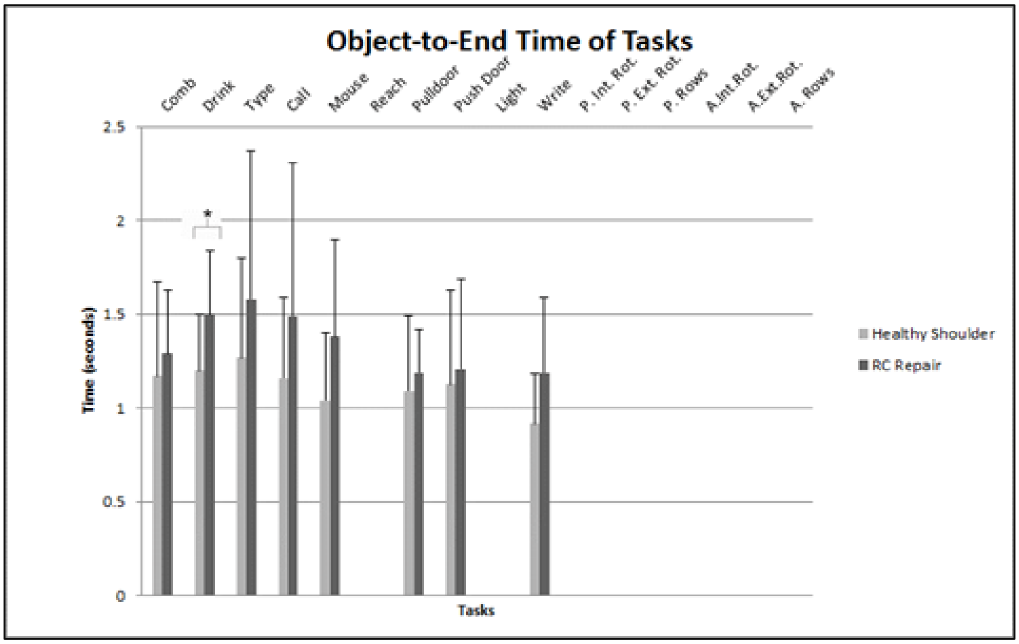


Figure 30. Mean Object-To-End Time per Task

a. Sitting ADLs

The RC repair group performed the sitting ADLs using at most an average of 1.47 ±0.61 seconds to grab the ADL object, 9.54 ± 3.78 seconds at most to perform the task, and 1.58 ± 0.79 seconds to return to the starting position after performing the task. The HS group used at most 1.21 ± 0.33 seconds to grab the ADL object, 5.81 ±2.28 seconds to perform a sitting task, and 1.27 ± 0.53 seconds to return to the starting position.

b. Standing ADLs

Two of the standing ADLs, reach to perineum and using a light switch, did not have Start-to-Object and Object-to-End measures. The RC repair group took at most 4.65 ± 1.04 seconds to perform these tasks and the HS group took 3.65 ±1.08 seconds. The pulling open and pushing open a door ADLs had Start-to-Object, Task Duration, and

Object-to-End measures. The RC repair group performed these tasks using at most 1.02 ± 0.28 seconds to grab the door, 4.73 ± 1.82 seconds to open and close the door, and 1.21 ±0.48 to return to the standing starting position. The HS group took at most 0.99 ± 0.30 seconds to grab the door, 3.65 ±1.08 seconds to open and close the door, and 1.13 ±0.50 seconds to return to the starting position.

c. Rehabilitation Motions

The RC repair group performed the rehabilitation motions using at most 4.28 ± 2.55 seconds, and the HS group used as most 3.45 ±0.56 seconds. Start-to-Object and Object-to-End duration measures were not recorded for the rehabilitation motions.

d. Repeatability

None of the tasks (ADLs or rehabilitation motions) showed below moderate repeatability for temporal characteristics in the RC repair group. Four of the ADLs (drinking from a cup, reaching to the perineum, pulling open a door, and writing) and one passive rehabilitation motion (internal rotation) showed below moderate repeatability (ICC < 0.5) in the HS group. Quantitatively, the HS group had little variance in temporal characteristics both as a group and among individual subjects.

Specifically for the HS group, the drinking ADL had below moderate ICC values for the time to grab the ADL object (0.395) and the time returning to starting position after performing the task (0.345). The reach to perineum task had very low repeatability for duration of the task (~0.00), as did the time returning to starting position for pulling open a door (~0.00). Duration for passive internal rotation was performed with an ICC of 0.494, slightly below moderate repeatability.

e. Significantly different Tasks

Only tasks with all three temporal characteristics (Start-to-Object, Task Duration, and Object-To-End) were included in multivariate analysis. The ADLs reach to perineum and using a light switch and all rehabilitation motions were excluded from multivariate analysis since trials of these tasks only included task duration. Of the included tasks, the ADLs of typing on a keyboard and writing had significantly different temporal characteristics ($p<0.001$ and $p=0.049$ respectively).

Table 14. Tasks with Significantly Different Temporal Characteristics

Temporal Characteristics		Healthy	Repairs	P-value (Welch's t-test)
Drink	DurationTO	1.21 ± 0.33	1.47 ± 0.61	0.0902
	DurationTASK	4.31 ± 0.85	5.04 ± 1.71	0.2449
	DurationBACK	1.20 ± 0.30	1.50 ± 0.34	*0.0465
Type	DurationTO	1.13 ± 0.61	1.18 ± 0.53	0.8450
	DurationTASK	1.76 ± 0.80	5.35 ± 2.98	*0.0040
	DurationBACK	1.27 ± 0.53	1.58 ± 0.79	0.3109
P.Int.Rot	DurationTO	N/A	N/A	N/A
	DurationTASK	2.77 ± 0.52	1.99 ± 0.24	*0.0297
	DurationBACK	N/A	N/A	N/A

Mean +/- standard deviation in seconds shown for each variable. * denotes significant difference between groups

The more conservative Welch's t-test showed no significant differences in specific temporal characteristics between the RC repair group and HS group for the writing ADL, while the typing ADL was significantly different in task duration (9.54 ± 3.78 seconds vs. 5.81 ± 2.28 seconds for RC repair and HS group respectively).

For tasks with only one temporal characteristic, only the passive internal rotation task duration was significantly between the RC repair group and HS group, with an average of 1.99 ± 0.24 seconds for the RC repair group and 2.77 ± 0.52 seconds for the HS group to complete the task.

IV. Discussion

For most of the ADLs and rehabilitation motions, there were no significant differences in kinematics (GH joint and thorax) or temporal characteristics. **These findings support the use of rotator cuff repair to return normal functionality for most ADLs.** Previous studies on GH joint kinematics agree that RC repair can return GH joint kinematics to normal ranges depending on extent pre-operative limitations of ROM. A study by Tauro et al specifically states that if pre-operative total ROM deficit (TROMD) does not total to more than 70° total in abduction, forward flexion, external rotation, and internal rotation, shoulder stiffness will likely resolve post-surgery (Moosmayer et al., 2010; Namdari & Green, 2010; Tauro, 2006). TROMD was not calculated in the RC repair group due to lack of pre- and post- operative values for maximum abduction and forward flexion (Internal and external rotation maximum angles were measured during the rehabilitation motion trials), but lack of significant differences between groups for the majority of the tasks in this study supports return of normal shoulder ROM and overall kinematics during ADLs if ROM deficits were present pre-operatively.

Additionally, any activities that were significantly different were still capable of being performed by the RC repair group as a whole, with altered kinematics in both the GH joint and thorax Consistent trends in altered kinematic patterns for the ADLs provide evidence of compensatory motion in the RC repair groups.

A. Glenohumeral Joint

Three ADLs and one rehabilitation motion had significantly different kinematics between groups: combing hair, reaching to the perineum, pulling open a door, and active internal rotation. Combing hair and reaching to perineum were different from the other ADLs in that the tasks did not occur directly in front of the body, with combing being an overhead motion and reaching to perineum requiring the arm to be behind the back. Other studies including these two ADLs have noted that these motions include large amounts of axial rotation (Magermans, Chadwick, Veeger, & van der Helm, 2005). All three ADLs were performed using external rotation and abduction.

Maximum GH joint flexion (maximum sagittal angle) was significantly different in the combing task, an overhead task with much more required flexion than the other tasks. RC repair subjects performed this task with an average of 96.22° flexion while the HS group used an average of 116.60°. Repair of the supraspinatus tendon was not expected to limit GH joint flexion. Combing also required more abduction to bring the comb over the head when referencing the healthy shoulder subjects. Although not significantly different in abduction, GH joint flexion while abducted was on average decreased in RC repairs while combing. Reduction in abduction was expected from both cadaveric studies of induced rotator cuff tears and pre-operative supraspinatus tear studies (Muraki et al., 2008; Oh, Jun, McGarry, & Lee, 2011; Tauro, 2006)

Reaching to the perineum also showed reduced sagittal plane kinematics in RC repairs in extension (sagittal minimum angle) and ROM in the sagittal plane, using on average only 7.64° of extension and 28.62° sagittal ROM compared to 21.00° extension and 56.45° ROM used by the HS group. Although significantly different in coronal

ROM, this measure had low repeatability (ICC ~0.00) amongst the RC repair group. Since coronal ROM was not significantly different in other ADLs, it can be safely inferred that coronal ROM used during ADLs (mostly abduction) was similar between the RC repair and HS groups. Reaching to the perineum did require much more extension at the GH joint than the other ADLs, and the low ICC of coronal ROM amongst the RC repair group for this task may indicate difficulty in performing combined extension and abduction, with a variety of coronal plane patterns used to perform the task.

Like the other significantly different ADLs, pulling open a door had significantly different kinematic values in a plane that was not controlled by the supraspinatus, specifically in transverse ROM in internal and external rotation (an average of 51.92° ROM used by RC repairs and 70.89° ROM by the HS group). The task also required abduction, like the other significantly different ADLs.

The task of external rotation itself was limited in the RC repairs when done against resistance. The RC repair group was significantly different in both amount of initial internal rotation and amount of external rotation used to perform the task. When averaged, the RC repair group only performed at most 5.54° of external rotation, while the healthy shoulder group performed 40.08°. This significant difference is not seen passively. During active external rotation (as described in this study with 0° abduction, 0° flexion, and 90° flexion at the elbow) the supraspinatus may have been active to stabilize the humerus on the scapula. Other studies support return of active external rotation after RC repair of the supraspinatus, even compared to other interventions for rotator cuff tear, such as debridement. (Moser, Jablonski, Horodyski, & Wright, 2007).

The GH joint kinematics of these tasks highlight that motions other than those controlled by the supraspinatus, like GH joint flexion, may be impacted by repair of the supraspinatus. Goniometer based studies also show reduced external rotation and flexion compared to normal ranges while abduction ROM is restored to in patients with RC repair of the supraspinatus(McCabe, Nicholas, Montgomery, Finneran, & McHugh, 2005). Additionally, while the supraspinatus is involved in abduction, the muscle has secondary actions at the glenohumeral joint as an external rotator (when the arm is abducted) and an internal rotator (when the arm is flexed) (Ackland & Pandy, 2011).

The supraspinatus has a prominent role in stabilization of the glenohumeral joint, keeping the head of the humerus in contact with the scapula's glenoid fossa as well. Altered kinematics at the GH joint have been attributed to changed contact position of the humerus to the glenoid and displacement of ligaments associated with the shoulder due to RC tears and RC repair (M. J. Bey et al., 2011b; C. Wu et al., 2012; K. Yamaguchi et al., 2000). Return of integrity of the supraspinatus with RC repair may allow greater stabilization of the GH joint, resulting in the results of this study. Namely, a return of ROM in abduction useful for ADLs, with weakened stability due to pre-operative weakness resulting in reduced ROM in certain combined planes (ex. abduction and extension while reaching to perineum) not specifically activated by the supraspinatus.

The collective significant results of these tasks support the conclusion that GH joint motion in other planes (i.e. flexion, extension, and external rotation) while abducted (or more generally, when the supraspinatus is actively stabilizing the GH joint) are limited in those with RC repair, especially for the subjects of this study who underwent RC repair of the supraspinatus.

Additionally, inspection of average kinematic patterns of the ADLs in the transverse, coronal, and sagittal planes suggest compensatory patterns, specifically:

1) Overall decreased flexion used by the RC repair group to perform sitting tasks, accompanied by decreased thorax flexion

2) Large, sudden increases in abduction and/or external/internal rotation at 50% task to accommodate for decreased motion in other planes

B. Thorax

The three ADLs which were significantly different in thorax kinematics (drinking from a cup, using a phone, and using a PC mouse) had increased average thorax sagittal maximums (thorax angles more extended during tasks) in the RC repair group compared to the HS group. Extension at the thorax causes a decrease in sagittal plane angle between the thorax and arm, and was used by the RC group to reduce the amount of GH joint flexion needed to reach ADL objects on the desk. For all three ADLs, average maximum thorax sagittal angle was increased on average 11.88°-13.93° degrees in the RC repair group, a large amount considering the maximum ROM used for any seated task or both group was 15.35°, and enough to reduce the amount of maximum flexion used to reach objects while seated at a desk. Similar findings of using thorax motion to compensate for reduced GH joint mobility were found in subjects with shoulder replacement (Masjedi, Lovell, & Johnson, 2011).

Yet, these ADLs had similar sagittal plane GH joint kinematics between the RC and HS groups, with only the combing task having significantly different flexion values. Extension at the thorax may have been used to compensate for the seated ADLs requiring flexion, but not engaged for the overhead task of combing hair. Thorax flexion and extension were not significantly different in any of the standing ADLs, indicating that motion at the thorax was not used compensate for and GH joint motion deficits for standing tasks.

The rehabilitation motion of passive rows values for right lateral thorax flexion (coronal max) and left axial rotation (transverse max) were significantly different between the RC repair and HS group and overall decreased in RC repairs, however passive rowing was controlled by an aide and differences in thorax kinematics were more attributed due to involuntary control and UE side use for motion analysis. Nine out of the ten of the HS subjects were analyzed on the right side, while only four out of ten RC repair subjects were analyzed on the left side.

C. Temporal Characteristics

Overall RC repair subjects performed the tasks within a similar amount of time compared to the HS subjects, including time to reach for ADL objects (Start-to-Object), perform ADLs and rehabilitation motions (Task Duration), and time to return to initial starting position (Object-to-End). Along with other studies of ADLs, these temporal characteristics also support the ability of RC repair to return range and quality of motion for performance of ADLs (Cofield, Parvizi, Hoffmeyer, & Lanzer, 2001; Galatz, Ball, Teefey, Middleton, & Yamaguchi, 2004).

Two tasks were significantly different in temporal characteristics, typing on a keyboard and the passive internal rotation rehabilitation motion. The typing task asked the subjects to type out their full name on a keyboard. Differences in duration may have been due more to name length and computer competency than to surgical intervention. The RC repair subjects were both older than the HS group, and both groups did not type the same amount of text. This is reflected in the average time taken for the typing task, 9.54 seconds for the RC repair group and 5.81 seconds for the HS group.

As previously stated, passive rehabilitation motions were not controlled by subject, but by a physician's assistant taking the arm through the motion. Significant differences in temporal characteristics during passive motions were not contributed by the subject, but rather by the physician's assistant. This is supported by increased, but not significantly different task performance times with the RC group during active rehabilitation motion trials. For instance, on average the RC group performed the active internal rotation, external rotation, and rowing for 3.77, 3.77, and 4.28 seconds. The HS group performed the same tasks in 3.24, 3.42 and 3.04 seconds on average.

D. Limitations

While the model used for this study was appropriate for determining sagittal, coronal, and transverse plane motion of the GH joint, other joints at the shoulder are also used to accomplish actions such as external rotation, which is accomplished by motion at both the scapulothoracic joint and glenohumeral joint. While the majority of motion at the shoulder occurs at the GH joint, inclusion of other joints (acromioclavicular, sternoclavicular, and scapulothoracic) in the model would give a more detailed analysis of shoulder motion. The current model is capable of determining the most clinically relevant motions, flexion/extension, internal/external rotation, and adduction/abduction. Furthermore, models including other joints of the shoulder have yet to be tested and other joints of the shoulder are difficult to track non-invasively.

Additionally, the ADLs of this study focused on common tasks performed anterior to the body. In light of the significant results, additional ADLs including more overhead, behind the back, and opposite sided tasks (tasks done with dominant limb on opposite side of body) may show more instances of significantly different GH joint and thorax kinematics and compensatory motions.

E. Further Investigation

Investigation of muscle recruitment patterns via electromyography during ADLs and rehabilitation motions would determine when certain muscles were active during the trials. Coupled with GH joint kinematics, this information would provide insight into the effects of activation of repaired muscles (in the case of this study, the supraspinatus) on joint mobility, both on limits of the action of the repaired muscle (e.g. supraspinatus and range of abduction) and limitation of mobility controlled by other muscles of the RC during repaired muscle activation.

Kinematic analysis of other joints of the UE would also provide insight into what compensatory motions may be utilized during ADLs by recent RC repair patients. While not investigated in this study, elbow and wrist joint motion may have been used in addition to thorax motion to complete the ADLs, especially ADLs with significantly different kinematics.

Additionally, implementation of models which define other joints of the shoulder, including the acromioclavicular joint, sternoclavicular joint, and scapulothoracic joint and GH joint, would provide more precise kinematics on motion at the shoulder, such as upward rotation, downward rotation, elevation and depression of the scapula. Analysis of motion at each joint would also elucidate any compensatory motions occurring within the shoulder.

The kinematics could also be further investigated in velocity, acceleration and jerk to analyze quality of motion beyond the temporal characteristics used in this study. These higher-order kinematics can be applied to any joint to determine rotational kinematics, or applied to each segment for translational kinematics as well.

V. Conclusion

RC repair is capable of returning GH joint mobility to a range appropriate for many ADLs. While limited abduction was expected due to repair of the supraspinatus tendon, only a single ADL (reaching to perineum) had a significantly different abduction ROM, with highly variable ROM used by the RC repair subjects to accomplish the task. However, while the supraspinatus is activated, either for abduction or to keep the GH joint stationary, other motions including flexion, extension, and external rotation may be limited. Thorax motion may also be used to compensate for limited GH joint mobility, especially during seated ADLs or when the tasks require use of objects in front of the subjects by inducing flexion at the GH joint by extension of the thorax rather than activation at the GH joint. Even with use of compensatory motions, ADLs can be accomplished within the same time frame and similar GH joint kinematics by those with RC repair compared to those with healthy shoulders.

Based on the results of this study, external rotation against resistance, combined extension and abduction, and combined flexion and external rotation are limited after recent rotator cuff repair. The reasons for these limitations in ADLS warrants further investigation of the mechanics and activation of the shoulder and other joints of the UE during ADLs. . ADLs which commonly use these motions can still be accomplished with compensatory motions at other joints (e.g. thorax, elbow, wrist, etc.).

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APPENDIX A

Table 15. Rotator cuff repair group coronal plane kinematics

Repairs (Coronal)	GHJ Minimum	GHJ Maxmimum	GHJ Range	Trunk Minimum	Trunk Maxmimum	Trunk Range
Comb	-34.90 ± 25.63	-3.35 ± 32.24	31.55 ± 22.19	-20.12 ± 14.09	-1.52 ± 17.79	18.60 ± 6.75
Drink	-28.26 ± 21.72	-6.17 ± 21.26	22.08 ± 12.38	-17.46 ± 14.30	-1.97 ± 16.89	15.48 ± 5.65
Type	-13.32 ± 20.33	-5.36 ± 15.50	17.41 ± 9.92	-8.35 ± 18.74	0.83 ± 16.28	9.18 ± 3.36
Call	-26.85 ± 17.57	-5.33 ± 20.10	21.52 ± 7.88	-17.73 ± 12.48	-1.70 ± 16.97	16.03 ± 6.77
Mouse	-20.45 ± 20.89	-9.519 ± 21.95	16.84 ± 10.80	-12.92 ± 15.71	-3.90 ± 17.32	9.01 ± 2.58
Reach	-23.52 ± 24.35	-8.78 ± 22.32	14.74 ± 6.64	-5.75 ± 18.15	4.18 ± 23.14	9.93 ± 9.62
Pulldoor	-25.58 ± 20.37	-2.71 ± 19.76	26.46 ± 11.19	-12.57 ± 17.82	2.92 ± 20.50	15.49 ± 7.32
Push Door	-24.22 ± 16.86	-0.87 ± 18.44	23.35 ± 10.61	-18.62 ± 16.19	1.43 ± 18.90	20.04 ± 9.21
Light	-20.08 ± 16.87	-3.82 ± 18.70	16.26 ± 12.64	-9.90 ± 15.79	0.60 ± 17.36	10.50 ± 4.82
Write	-34.12 ± 8.33	-9.60 ± 9.49	27.52 ± 9.69	-18.46 ± 16.62	2.56 ± 18.33	21.02 ± 4.84
P. Int. Rot.	-14.81 ± 13.33	-11.47 ± 14.68	3.44 ± 1.65	-3.67 ± 15.65	-1.61 ± 15.45	2.06 ± 0.77
P. Ext. Rot.	-16.85 ± 12.59	-12.25 ± 15.41	4.61 ± 3.25	-5.86 ± 15.24	-2.42 ± 14.45	3.44 ± 1.78
P. Rows	-14.23 ± 18.02	-2.53 ± 21.07	15.28 ± 7.23	-1.06 ± 14.65	-4.63 ± 14.71	9.28 ± 3.74
A.Int.Rot.	-15.90 ± 17.34	-7.27 ± 15.89	8.62 ± 6.37	-5.76 ± 17.82	0.95 ± 17.34	6.71 ± 3.72
A.Ext.Rot.	-18.19 ± 17.85	-10.79 ± 16.79	10.75 ± 4.54	-2.49 ± 18.75	3.54± 19.44	6.03 ± 2.92
A. Rows	-25.09 ± 19.83	-7.12 ± 19.07	17.97 ± 11.57	-8.33 ± 18.00	1.26 ± 18.91	9.59 ± 3.42

Table 16. Rotator cuff repair group transverse plane kinematics

Repairs (Transverse)	GHJ Minimum	GHJ Maxmimum	GHJ Range	Trunk Minimum	Trunk Maxmimum	Trunk Range
Comb	-18.16 ± 25.64	23.51 ± 17.03	41.67 ± 19.40	-3.36 ± 5.07	14.54 ± 10.52	17.90 ± 6.88
Drink	-11.65 ± 18.85	22.26 ± 14.93	33.91 ± 10.57	-2.48 ± 5.43	13.80 ± 10.89	16.28 ± 6.90
Type	-4.00 ± 16.67	23.66 ± 21.35	27.66 ± 11.00	-3.20 ± 4.62	3.31 ± 10.60	6.51 ± 7.50
Call	-16.03 ± 28.54	18.93 ± 18.22	34.97± 17.47	-2.68 ± 4.93	13.01 ± 10.55	15.69 ± 7.31
Mouse	-20.75 ± 35.05	19.45 ± 23.10	40.20 ± 22.51	-2.37 ± 5.87	7.83 ± 8.27	10.20 ± 3.18
Reach	-5.35 ± 38.02	29.99 ± 25.67	35.34 ± 20.45	-15.05 ± 19.69	1.20 ± 5.53	16.25 ± 19.59
Pulldoor	-7.76 ± 26.74	44.16 ± 29.69	51.92 ± 16.63	-7.65 ± 10.32	22.07 ± 12.69	29.73 ± 12.48
Push Door	-16.94 ± 42.43	46.43 ± 32.31	63.37 ± 22.58	-3.26 ± 4.72	35.20 ± 15.42	38.46 ± 12.20
Light	-0.61 ± 31.02	27.88 ± 32.10	28.49 ± 10.20	-2.66 ± 5.88	9.09 ± 9.60	11.75 ± 6.93
Write	-3.91 ± 21.45	30.57 ± 17.88	34.48 ± 10.11	-5.94 ± 4.23	4.57 ± 14.53	10.51 ± 10.83
P. Int. Rot.	-5.84 ± 22.21	35.93 ± 23.26	41.76 ± 9.87	3.60 ± 7.48	5.59 ± 7.08	1.99 ± 1.45
P. Ext. Rot.	-11.23 ± 20.18	26.94 ± 21.60	38.17 ± 11.72	5.09 ± 8.04	8.09 ± 8.04	3.00 ± 1.96
P. Rows	-2.58 ± 17.79	10.88 ± 12.03	13.46 ± 7.98	3.23 ± 9.34	15.16 ± 7.27	11.93 ± 5.58
A.Int.Rot.	-4.83 ± 25.18	48.00 ± 29.19	52.82 ± 18.04	-1.55± 6.85	4.38 ± 5.07	5.92 ± 3.32
A.Ext.Rot.	-5.54 ± 20.98	36.05 ± 21.74	41.58 ± 20.41	-2.54 ± 8.91	4.15 ± 8.43	6.69 ± 2.96
A. Rows	-2.29 ± 15.79	20.23 ± 15.31	22.52 ± 9.9	-3.33 ± 8.16	12.63 ± 6.02	15.96 ± 8.05

Table 17. Rotator cuff repair group sagittal plane kinematics

Repairs (Sagittal)	GHJ			Trunk		
	Minimum	Maxmimum	Range	Minimum	Maxmimum	Range
Comb	26.57 ± 12.30	96.22 ± 12.16	69.65 ± 11.95	-29.40 ± 11.50	-15.42 ± 12.97	13.98 ± 9.84
Drink	25.34 ± 11.59	82.88 ± 14.71	57.55 ± 12.60	-29.52 ± 12.11	-16.48 ± 11.23	13.04 ± 12.55
Type	28.83 ± 10.98	66.19 ± 14.32	37.27 ± 11.53	-30.80 ± 10.42	-18.12 ± 11.57	12.68 ± 12.35
Call	28.62 ± 12.43	86.48 ± 13.97	57.86 ± 11.03	-30.04 ± -37.90	-17.05 ± 10.28	12.99 ± 11.01
Mouse	27.74 ± 12.18	79.93 ± 14.34	52.19 ± 12.37	-28.31 ± 10.41	-20.49 ± 8.98	7.83 ± 8.37
Reach	-7.64 ± 14.66	26.49 ± 11.82	34.13 ±12.97	-34.62 ± 10.68	-19.93 ± 9.80	14.69 ± 8.47
Pulldoor	21.69 ± 15.07	65.71 ± 10.02	44.02 ± 9.22	-33.97 ± 8.61	-20.88 ± 10.84	13.09 ± 7.50
Push Door	26.52 ± 12.98	81.16 ± 11.74	54.64 ± 12.55	-36.57 ± 10.67	-20.45 ± 9.72	16.11 ± 8.18
Light	23.99 ± 11.61	64.76 ± 10.07	40.77 ± 10.5	-27.23 ± 6.00	-21.65 ± 6.90	5.58 ± 4.11
Write	35.47 ± 12.71	82.59 ± 8.8	47.12 ± 11.93	-35.95 ± 12.69	-20.60 ± 11.17	15.35 ± 14.99
P. Int. Rot.	42.88 ± 11.58	46.60 ± 11.67	3.72 ± 2.48	-24.80 ± 7.41	-23.75 ± 7.51	1.05 ± 0.33
P. Ext. Rot.	43.09 ± 10.08	46.66 ± 8.58	3.57 ± 2.21	-25.32 ± 7.93	-23.66 ± 7.90	1.57 ± 0.61
P. Rows	33.23 ± 19.40	84.31 ± 10.56	51.08 ± 13.14	-25.57 ± 7.27	-20.69 ± 9.02	4.88 ± 2.67
A.Int.Rot.	38.02 ± 12.71	47.41 ± 16.42	9.40 ± 5.26	-25.15 ± 8.11	-22.46 ± 7.58	2.69 ± 1.34
A.Ext.Rot.	36.66 ± 13.01	42.83 ± 13.75	6.17 ± 3.22	-25.36 ± 7.95	-22.62 ± 7.57	2.73 ± 1.20
A. Rows	12.56 ± 21.04	73.72 ± 10.66	61.16 ± 19.77	-24.78 ± 7.67	-18.24 ± 8.75	6.54 ± 3.94

Table 18. Healthy shoulder group coronal plane kinematics

Healthy (Coronal)	GHJ			Trunk		
	Minimum	Maxmimum	Range	Minimum	Maxmimum	Range
Comb	-37.35 ± 21.23	-9.88 ± 17.76	27.47 ± 7.95	-8.02 ± 7.78	9.91 ± 11.59	17.93 ± 8.55
Drink	-32.71 ± 19.92	-11.14 ± 13.65	21.58 ± 10.90	-9.24 ± 7.47	12.92 ± 17.03	22.17 ± 18.33
Type	-27.06 ± 19.64	-5.26 ± 10.71	21.80 ± 10.51	-1.65 ± 6.74	8.62 ± 12.02	10.27 ± 7.08
Call	-.32.26 ± 18.23	-9.59 ± 12.60	22.67 ± 9.26	-13.61 ± 11.93	11.77 ± 18.10	25.38 ± 26.42
Mouse	-31.36 ± 18.48	-17.05 ± 17.13	14.32 ± 3.45	-3.28 ± 8.38	8.66 ± 9.68	11.93 ± 6.39
Reach	-37.51 ± 18.02	-8.89 ± 16.32	28.62 ± 4.21	1.33 ± 9.05	10.25 ± 12.16	8.92 ± 4.95
Pulldoor	-20.04 ± 12.70	-0.76 ± 19.55	21.70 ± 9.19	-11.29 ± 8.05	8.79 ± 7.55	20.08 ± 8.40
Push Door	-26.22 ± 14.21	0.13 ± 13.22	26.35 ± 8.46	-20.51 ± 8.33	9.78 ± 13.94	30.29 ± 17.41
Light	-17.62 ± 14.21	-5.72 ± 10.99	11.89 ± 4.43	-4.09 ± 3.48	8.94 ± 8.46	13.03 ± 8.00
Write	-31.00 ± 21.07	-8.77 ± 11.28	22.22 ± 12.37	-7.57 ± 9.95	11.02 ± 13.46	18.59 ± 15.60
P. Int. Rot.	-9.49 ± 11.24	-10.30 ± 10.17	4.35 ± 2.26	4.64 ± 6.28	8.67 ± 7.98	4.03 ± 2.87
P. Ext. Rot.	-14.59 ± 12.53	-9.89 ± 12.60	4.71 ± 2.54	4.02 ± 8.20	7.86 ± 7.47	3.85 ± 1.46
P. Rows	-12.78 ± 15.88	-8.50± 10.24	12.45 ± 8.60	-0.87 ± 8.19	9.26 ± 8.67	10.14 ± 3.60
A.Int.Rot.	-14.54 ± 11.92	-3.21 ± 13.31	11.33 ± 5.95	3.11 ± 10.66	9.38 ± 10.59	6.27 ± 1.99
A.Ext.Rot.	-22.93 ± 14.41	-6.92 ± 11.37	16.02 ± 8.73	-0.63± 7.85	5.96 ± 8.34	6.59 ± 3.23
A. Rows	-28.31 ± 17.65	-10.77 ± 9.28	17.55 ± 10.35	-4.11 ± 5.69	5.01 ± 7.72	9.27 ± 4.63

Table 19. Healthy shoulder group transverse plane kinematics

Healthy (Transverse)	GHJ			Trunk		
	Minimum	Maxmimum	Range	Minimum	Maxmimum	Range
Comb	-8.30 ± 18.20	36.59 ± 29.43	44.90 ± 20.12	-6.87 ± 4.75	5.60 ± 4.21	12.47 ± 4.74
Drink	-4.83 ± 21.51	37.49 ± 29.76	42.32 ± 26.94	-6.66 ± 4.67	8.03 ± 3.60	14.69 ± 3.50
Type	0.31 ± 23.76	37.74 ± 22.24	36.27 ± 11.53	-5.65 ± 5.00	1.78 ± 2.04	7.42 ± 4.68
Call	-9.352 ± 19.9	30.83 ± 29.17	40.19 ± 28.72	-5.21 ± 2.93	10.78 ± 5.94	15.99 ± 5.68
Mouse	-8.02 ± 25.08	20.82 ± 23.33	28.85 ± 11.59	-5.45 ± 4.00	3.06 ± 5.35	8.51 ± 3.85
Reach	0.885 ± 29.22	47.68 ± 22.47	46.79 ± 18.57	-13.47 ± 16.21	-2.17 ± 4.16	11.30 ± 13.11
Pulldoor	-24.39 ± 30.53	46.50 ± 27.03	70.89 ± 16.73	-4.49 ± 6.02	24.91 ± 9.19	29.40 ± 10.68
Push Door	-41.48 ± 27.30	37.43 ± 24.17	78.91 ± 17.81	-3.76 ± 8.09	36.66 ± 6.55	40.42 ± 13.00
Light	-6.175 ± 30.21	31.37 ± 21.39	37.55 ± 18.44	5.52 ± 7.01	7.05 ± 8.65	12.57 ± 9.22
Write	-1.96 ± 24.02	36.44 ± 31.31	38.40 ± 21.83	-6.84 ± 4.5	2.30 ± 4.17	9.14 ± 3.91
P. Int. Rot.	0.91 ± 15.85	49.38 ± 21.71	48.46 ± 12.89	-4.83 ± 6.40	-1.61 ± 5.14	3.22 ± 2.67
P. Ext. Rot.	-29.19 ± 25.99	21.18 ± 17.49	46.08 ± 19.04	-5.42 ± 5.40	-1.67 ± 4.12	3.75 ± 2.10
P. Rows	0.13 ± 10.86	17.58 ± 18.59	17.45 ± 14.11	-8.04 ± 10.52	2.87 ± 6.79	10.91 ± 5.55
A.Int.Rot.	-5.02 ± 14.63	64.50 ± 20.44	69.52 ± 14.77	-6.76 ± 5.72	-0.87 ± 7.18	5.89 ± 3.20
A.Ext.Rot.	-40.08 ± 24.71	9.363 ± 18.71	49.44 ± 17.78	-3.39 ± 5.83	5.47 ± 4.38	8.86 ± 5.08
A. Rows	-11.08 ± 13.42	22.53 ± 13.02	33.61 ± 21.04	-7.50 ± 6.40	7.37 ± 4.64	14.87 ± 8.96

Table 20. Healthy shoulder group sagittal plane kinematics

Healthy (Sagittal)	GHJ			Trunk		
	Minimum	Maxmimum	Range	Minimum	Maxmimum	Range
Comb	36.74 ± 15.37	116.60 ± 14.49	79.87 ± 23.75	-37.34 ± 10.25	-28.07 ± 8.18	9.27 ± 4.18
Drink	36.79 ± 15.29	95.55 ± 14.21	58.79 ± 21.61	-40.69 ± 9.80	-30.41 ± 7.31	10.28 ± 6.33
Type	38.70 ± 16.9	74.56 ± 12.46	35.86 ± 15.8	-37.47 ± 6.76	-30.10 ± 8.17	7.36 ± 6.24
Call	36.17 ± 13.34	97.71 ± 13.34	61.54 ± 19.93	-37.90 ± 11.75	-28.93 ± 8.08	8.97 ± 8.18
Mouse	36.36 ± 15.37	91.09 ± 9.32	54.73 ± 15.8	-37.88 ± 8.19	-32.52 ± 7.66	5.362 ± 4.36
Reach	-21.00 ± 8.23	35.46± 7.22	56.45 ± 7.41	-37.42 ± 9.08	-25.79 ± 13.70	11.62 ± 10.97
Pulldoor	29.27 ± 7.92	74.89 ± 10.35	45.62 ± 8.80	-39.13 ± 8.55	-28.56 ± 7.77	10.57 ± 2.39
Push Door	31.51 ± 8.67	84.91 ± 5.46	53.41 ± 10.78	-39.00 ± 7.74	-25.92 ± 10.24	13.09 ± 7.37
Light	30.65 ± 8.24	67.58 ± 15.38	36.93 ± 14.86	-32.55 ± 9.72	-28.56 ± 8.59	4.00 ± 2.05
Write	38.72 ± 16.67	87.78 ± 12.92	49.05 ± 23.45	-40.84 ± 10.51	-30.41 ± 8.61	10.44 ± 7.47
P. Int. Rot.	48.82 ± 10.86	52.24 ± 12.66	3.43 ± 2.58	-28.58 ± 7.41	-27.14 ± 7.82	1.44 ± 1.05
P. Ext. Rot.	45.71 ± 11.05	49.91 ± 12.54	4.20 ± 2.71	-29.57 ± 6.90	-28.42 ± 6.80	1.16 ± 0.40
P. Rows	41.78 ± 13.51	91.28 ± 12.59	49.51 ± 13.60	-29.50 ± 9.94	-26.55 ± 10.60	3.15 ± 1.52
A.Int.Rot.	47.29 ± 16.80	57.12 ± 17.22	9.83 ± 3.89	-31.11 ± 8.82	-28.50 ± 8.12	2.61 ± 1.43
A.Ext.Rot.	42.05 ± 14.14	51.43 ± 13.65	9.38 ± 5.02	-30.30 ± 8.24	-27.80 ± 8.54	2.50 ± 0.94
A. Rows	12.37 ± 18.14	86.48 ± 19.93	74.11 ± 24.42	-24.78 ± 9.62	-23.43 ± 9.15	5.35 ± 2.62

APPENDIX B

Table 21: Rotator cuff repair group temporal characteristics

Repairs	Duration		
	To	Task	Back
Comb	1.36 ± 0.45	4.64 ± 1.57	1.29 ± 0.34
Drink	1.47 ± 0.61	5.04 ± 1.71	1.50 ± 0.34
Type	1.18 ± 0.53	5.35 ± 2.98	1.58 ± 0.79
Call	1.28 ± 0.40	4.49 ± 1.34	1.49 ± 0.82
Mouse	1.19 ± 0.52	3.35 ± 2.48	1.38 ± 0.52
Reach	N/A	4.65 ± 1.04	N/A
Pulldoor	1.02 ± 0.28	4.73 ± 1.82	1.19 ± 0.23
Push Door	0.80 ± 0.27	4.32 ± 1.58	1.21 ± 0.48
Light	N/A	3.83 ± 1.41	N/A
Write	1.11 ± 0.31	9.54 ± 3.78	1.19 ± 0.40
P. Int. Rot.	N/A	1.99 ± 0.24	N/A
P. Ext. Rot.	N/A	2.38 ± 0.79	N/A
P. Rows	N/A	3.80 ± 1.68	N/A
A.Int.Rot.	N/A	3.77 ± 2.09	N/A
A.Ext.Rot.	N/A	3.77 ± 1.40	N/A
A. Rows	N/A	4.28 ± 2.55	N/A

Table 22: Healthy shoulder group temporal characteristics

Healthy	Duration		
	To	Task	Back
Comb	1.12 ± 0.43	3.66 ± 0.94	1.17 ± 0.50
Drink	1.21 ± 0.33	4.31 ± 0.85	1.20 ± 0.30
Type	1.13 ± 0.61	1.76 ± 0.80	1.27 ± 0.53
Call	1.10 ± 0.37	3.83 ± 1.06	1.16 ± 0.43
Mouse	1.08 ± 0.51	2.40 ± 0.39	1.04 ± 0.36
Reach	N/A	3.65 ± 1.08	N/A
Pulldoor	0.99 ± 0.3	3.53 ± 1.22	1.09 ± 0.40
Push Door	0.94 ± 0.33	3.53 ± 1.62	1.13 ± 0.50
Light	N/A	3.36 ± 0.95	N/A
Write	0.89 ± 0.24	5.81 ± 2.28	0.92 ± 0.26
P. Int. Rot	N/A	2.77 ± 0.52	N/A
P. Ext. Rot	N/A	2.91 ± 0.48	N/A
P. Rows	N/A	3.45 ± 0.56	N/A
A.Int.Rot.	N/A	3.24 ± 1.15	N/A
A.Ext.Rot.	N/A	3.42 ± 0.88	N/A
A. Rows	N/A	3.04 ± 1.26	N/A

APPENDIX C

Table 23. ICC values of coronal plane kinematics for rotator cuff repair group

Repairs	GHJ			Trunk		
(Coronal)	Minimum	Maxmimum	Range	Minimum	Maxmimum	Range
Comb	0.9860	0.9528	0.7840	0.9342	0.8206	0.7078
Drink	0.9857	0.9784	0.9399	0.6520	0.9315	0.7822
Type	0.9695	0.9920	0.8676	0.9845	0.7930	0.4747
Call	0.9761	0.9568	0.8849	0.6198	0.9578	0.8618
Mouse	0.9854	0.9916	0.5772	0.8943	0.6587	0.5384
Reach	0.9617	0.8795	0	0.9607	0.9605	0.7816
Pulldoor	0.9593	0.9206	0.6199	0.6768	0.8976	0.6109
Push Door	0.9336	0.7511	0.5062	0.5377	0.9487	0.8238
Light	0.9647	0.9765	0.725	0.6208	0.7272	0.7460
Write	0.9912	0.9562	0.9432	0.9389	0.9755	0.9408
P. Int. Rot.	0.9893	0.9840	0.6778	0.9216	0.9345	0.7304
P. Ext. Rot.	0.9565	0.9748	0.2156	0.9642	0.9501	0.5262
P. Rows	0.9253	0.9339	0.8523	0.9462	0.9288	0.6707
A.Int.Rot.	0.9784	0.9508	0.7323	0.9690	0.9384	0.1936
A.Ext.Rot.	0.9128	0.9791	0.8104	0.9611	0.9279	0.7515
A. Rows	0.9607	0.9253	0.8919	0.5389	0.9168	0.3094

Table 24. ICC values of transverse plane kinematics for rotator cuff repair group

Repairs	GHJ			Trunk		
(Transverse)	Minimum	Maxmimum	Range	Minimum	Maxmimum	Range
Comb	0.9701	0.9233	0.8404	0.9038	0.9190	0.9109
Drink	0.9594	0.9634	0.8988	0.9141	0.8558	0.7379
Type	0.9672	0.9060	0.5091	0.9361	0.9066	0.9003
Call	0.837	0.9908	0.9167	0.9038	0.5873	0.5705
Mouse	0.9605	0.8808	0.8059	0.8321	0.9248	0.7264
Reach	0.9765	0.9263	0.8785	0.9305	0.8022	0.8973
Pulldoor	0.8729	0.8297	0.4686	0.8787	0.9037	0.8943
Push Door	0.7038	0.8900	0.3790	0.9239	0.4785	0.7795
Light	0.7849	0.8724	0.5503	0.7643	0.9529	0.8816
Write	0.9759	0.9767	0.9664	0.9307	0.9030	0.8078
P. Int. Rot.	0.9602	0.9700	0.8726	0.8746	0.8590	0.4930
P. Ext. Rot.	0.9585	0.9796	0.8956	0.8791	0.8082	0.5002
P. Rows	0.7924	0.9530	0.8871	0.9335	0.8773	0.7773
A.Int.Rot.	0.8099	0.9244	0.8414	0.8587\	0.9216	0.6600
A.Ext.Rot.	0.9455	0.9595	0.9237	0.8658	0.8500	0.8604
A. Rows	0.6085	0.818	0.8192	0.7121	0.8159	0.8674

Table 25. ICC values of sagittal plane kinematics for rotator cuff repair group

Repairs (Sagittal)	GHJ			Trunk		
	Minimum	Maxmimum	Range	Minimum	Maxmimum	Range
Comb	0.9308	0.8759	0.9186	0.9491	0.9584	0.6930
Drink	0.9568	0.9791	0.9676	0.9509	0.9190	0.8617
Type	0.9716	0.9264	0.9328	0.9831	0.9258	0.8664
Call	0.9362	0.9581	0.9584	0.9488	0.8267	0.8703
Mouse	0.9458	0.8995	0.9599	0.9524	0.9120	0.6598
Reach	0.7703	0.7671	0.5038	0.9333	0.9374	0.9027
Pulldoor	0.8409	0.8965	0.7324	0.9849	0.8033	0.0000
Push Door	0.9390	0.6916	0.8905	0.9209	0.6337	0.3548
Light	0.9269	0.9803	0.9523	0.9873	0.9824	0.6500
Write	0.9736	0.9522	0.9762	0.8804	0.9573	0.8148
P. Int. Rot.	0.9594	0.9774	0.8834	0.9805	0.9696	0.4526
P. Ext. Rot.	0.9652	0.9818	0.6125	0.9717	0.9638	0.0000
P. Rows	0.7765	0.9214	0.8546	0.9698	0.9814	0.6925
A.Int.Rot.	0.9559	0.9552	0.6792	0.9839	0.9745	0.6143
A.Ext.Rot.	0.9584	0.9657	0.7539	0.9712	0.9719	0.3423
A. Rows	0.9124	0.9814	0.9474	0.9762	0.9608	0.7877

Table 26. ICC values of coronal plane kinematics for healthy shoulder group

Healthy (Coronal)	GHJ			Trunk		
	Minimum	Maxmimum	Range	Minimum	Maxmimum	Range
Comb	0.9890	0.9967	0.9838	0.9721	0.9344	0.6694
Drink	0.9928	0.9952	0.9678	0.9933	0.9936	0.9418
Type	0.9831	0.9947	0.9252	0.9955	0.9895	0.6841
Call	0.9821	0.9835	0.8548	0.9844	0.9918	0.9247
Mouse	0.9955	0.9857	0.9279	0.9937	0.9944	0.7698
Reach	0.9296	0.9659	0.7412	0.9877	0.9691	0.8833
Pulldoor	0.9842	0.9857	0.9506	0.9934	0.9673	0.7580
Push Door	0.9867	0.9872	0.8630	0.9612	0.9651	0.9238
Light	0.9337	0.9862	0.9702	0.9831	0.9917	0.8126
Write	0.8867	0.9571	0.9024	0.9199	0.9852	0.4143
P. Int. Rot.	0.9649	0.9581	0.4031	0.9537	0.9570	0.0000
P. Ext. Rot.	0.9683	0.9642	0.6339	0.8945	0.8998	0.3821
P. Rows	0.9829	0.9339	0.8629	0.9835	0.9865	0.6452
A.Int.Rot.	0.9899	0.9459	0.7575	0.9612	0.9639	0.252
A.Ext.Rot.	0.9943	0.9858	0.7399	0.9890	0.9909	0.6456
A. Rows	0.9124	0.9834	0.9008	0.8060	0.9347	0.0000

Table 27. ICC values of transverse plane kinematics for healthy shoulder group

Healthy (Transverse)	GHJ			Trunk		
	Minimum	Maxmimum	Range	Minimum	Maxmimum	Range
Comb	0.9517	0.9231	0.5359	0.9025	0.9805	0.9281
Drink	0.8129	0.9682	0.5359	0.9692	0.9736	0.9248
Type	0.9768	0.9838	0.9246	0.9716	0.9772	0.9548
Call	0.9686	0.9751	0.9217	0.9242	0.9904	0.9572
Mouse	0.9911	0.9804	0.9835	0.9672	0.9888	0.8232
Reach	0.9626	0.8211	0.8508	0.9165	0.8552	0.9262
Pulldoor	0.9253	0.9603	0.7619	0.9133	0.9486	0.9576
Push Door	0.8838	0.9041	0.4680	0.5046	0.9671	0.9169
Light	0.9860	0.9792	0.7207	0.9066	0.7163	0.5266
Write	0.9249	0.9440	0.7154	0.9182	0.9828	0.9785
P. Int. Rot.	0.964	0.9565	0.8408	0.8761	0.8645	0.7418
P. Ext. Rot.	0.9257	0.8979	0.8362	0.9269	0.9200	0.5846
P. Rows	0.9215	0.8929	0.7302	0.9132	0.8814	0.7691
A.Int.Rot.	0.9733	0.9682	0.9359	0.9272	0.7591	0.6193
A.Ext.Rot.	0.9812	0.9736	0.9562	0.9265	0.9268	0.73
A. Rows	0.9332	0.9251	0.6978	0.8228	0.8753	0.7976

Table 28. ICC values of sagittal plane kinematics for healthy shoulder group

Healthy (Sagittal)	GHJ			Trunk		
	Minimum	Maxmimum	Range	Minimum	Maxmimum	Range
Comb	0.9109	0.7084	0.6132	0.9719	0.9813	0.9503
Drink	0.9133	0.9785	0.9053	0.9725	0.9575	0.9682
Type	0.7829	0.9574	0.8415	0.9762	0.8170	0.8461
Call	0.8787	0.9858	0.8334	0.9664	0.9705	0.9610
Mouse	0.9397	0.9909	0.9406	0.9846	0.9852	0.9692
Reach	0.9669	0.6403	0.7737	0.8095	0.7273	0.7251
Pulldoor	0.9529	0.9660	0.8664	0.9249	0.9798	0.8557
Push Door	0.9257	0.6015	0.5932	0.9647	0.8110	0.6386
Light	0.9499	0.9638	0.9250	0.9454	0.8035	0.6305
Write	0.8957	0.9185	0.8244	0.9833	0.9803	0.9801
P. Int. Rot.	0.9753	0.9745	0.7125	0.9537	0.9595	0.0000
P. Ext. Rot.	0.8846	0.8364	0.5070	0.9563	0.9658	0.2688
P. Rows	0.9748	0.9407	0.9532	0.9062	0.9402	0.7655
A.Int.Rot.	0.9683	0.9859	0.825	0.9741	0.9631	0.7578
A.Ext.Rot.	0.9385	0.9521	0.7496	0.9811	0.9466	0.386
A. Rows	0.9728	0.9133	0.9635	0.9542	0.9803	0.8660

Table 29. ICC values for temporal characteristics of rotator cuff repair group

Repairs	Duration		
	To	Task	Back
Comb	0.8024	0.8645	0.9137
Drink	0.6964	0.8644	0.6202
Type	0.8963	0.6698	0.8488
Call	0.7454	0.9380	0.8101
Mouse	0.8393	0.7569	0.6988
Reach	N/A	0.8398	N/A
Pulldoor	0.5729	0.6916	0.7713
Push Door	0.6019	0.7344	0.9052
Light	N/A	0.6522	N/A
Write	0.5209	0.9700	0.5171
P. Int. Rot.	N/A	0.6881	N/A
P. Ext. Rot.	N/A	0.7257	N/A
P. Rows	N/A	0.7351	N/A
A.Int.Rot.	N/A	0.9113	N/A
A.Ext.Rot.	N/A	0.7805	N/A
A. Rows	N/A	0.9306	N/A

Table 30. ICC values for temporal characteristics of healthy shoulder group

Healthy	Duration		
	To	Task	Back
Comb	0.7390	0.7750	0.6844
Drink	0.3945	0.6088	0.34478
Type	0.6998	0.7093	0.8001
Call	0.7365	0.8900	0.5559
Mouse	0.8788	0.9837	0.5114
Reach	N/A	0.0000	N/A
Pulldoor	0.6741	0.8376	0.000
Push Door	0.7742	0.7430	0.7314
Light	N/A	0.923	N/A
Write	0.6377	0.8912	0.4024
P. Int. Rot	N/A	0.4937	N/A
P. Ext. Rot	N/A	0.7194	N/A
P. Rows	N/A	0.8643	N/A
A.Int.Rot.	N/A	0.9549	N/A
A.Ext.Rot.	N/A	0.6817	N/A
A. Rows	N/A	0.9618	N/A

APPENDIX D

Table 31. Hotelling's T^2 p-values for GH joint kinematics

Hotelling's T2	GHJ		
	Minimum	Maxmimum	Range
Comb	0.4657	*0.0405	0.5245
Drink	0.322	0.3558	0.6285
Type	0.3121	0.2498	0.079
Call	0.6119	0.4168	0.9662
Mouse	0.5757	0.2995	0.4721
Reach	*0.0487	0.1539	*0.0004
Pulldoor	0.2411	0.2146	*0.046
Push Door	0.1978	0.795	0.5047
Light	0.4744	0.975	0.4451
Write	0.9782	0.8714	0.8952
P. Int. Rot.	0.4569	0.1872	0.1886
P. Ext. Rot.	0.4594	0.6579	0.8126
P. Rows	0.7416	0.6323	0.4451
A.Int.Rot.	0.4996	0.2044	0.0802
A.Ext.Rot.	*0.0237	*0.0286	0.0962
A. Rows	0.4384	0.3455	0.3321

indicates significantly different p-value with a=0.05

Table 32. Welch's t-test p-values for GH joint kinematics

	GHJ Min			GHJ Max			GHJ Range		
	Coronal	Transverse	Sagittal	Coronal	Transverse	Sagittal	Coronal	Transverse	Sagittal
Comb	N/A	N/A	N/A	0.6	0.249	*0.0039	N/A	N/A	N/A
Reach	0.1628	0.6862	*0.02474	N/A	N/A	N/A	*0.0004	0.2067	*0.0003
PullDoor	N/A	N/A	N/A	N/A	N/A	N/A	0.3127	*0.0204	0.6957
A.Ext.Rot.	0.5361	*0.0043	0.3664	0.5696	*0.01158	0.1905	N/A	N/A	N/A

**** indicates significant difference with a=0.05***

Table 33. Hotelling's T^2 P-values for thorax kinematics

Hotelling's T2	Trunk Minimum	Trunk Maxmimum	Trunk Range
Comb	0.1242	0.0537	0.1425
Drink	0.1774	*0.0313	0.3821
Type	0.4505	0.0611	0.6146
Call	0.418	*0.0464	0.1635
Mouse	0.229	*0.0357	0.1789
Reach	0.5883	0.2465	0.8251
Pulldoor	0.4184	0.3032	0.3848
Push Door	0.9242	0.434	0.1126
Light	0.3925	0.3161	0.3866
Write	0.2831	0.2266	0.8695
P. Int. Rot.	0.1245	0.1555	0.3251
P. Ext. Rot.	0.0554	0.0641	0.2646
P. Rows	0.0626	*0.0147	0.1968
A.Int.Rot.	0.3231	0.281	0.9865
A.Ext.Rot.	0.6476	0.4509	0.5214
A. Rows	0.6291	0.2229	0.8779

Table 34. Welch's t-test p-values for thorax kinematics

	Trunk Max Coronal	Trunk Max Transverse	Trunk Max Sagittal
Call	0.1033	0.569	*0.0105
Drink	0.06516	0.1398	*0.0048
Mouse	0.07817	0.1633	*0.0066
P.Rows	*0.02152	*0.001	0.2001

****indicates significant difference with a=0.05***

Table 35. Hotelling's T^2 p-values for temporal characteristics

Hotelling T2	Temporal characteristics p-value
Comb	0.4581
Drink	0.1753
Type	*0.0014
Call	0.7006
Mouse	0.1240
Reach	N/A
Pulldoor	0.1902
Push Door	0.2875
Light	N/A
Write	*0.0489
P. Int. Rot.	N/A
P. Ext. Rot.	N/A
P. Rows	N/A
A.Int.Rot.	N/A
A.Ext.Rot.	N/A
A. Rows	N/A

Table 36. Welch's t-test p-values for temporal characteristics

Welch's t-test	Temporal Characteristics		
	To	Task	Back
Type	0.845	*0.0040	0.3109
Write	0.2181	0.0933	0.2210
Reach	N/A	0.1034	N/A
Light	N/A	0.5330	N/A
P. Int. Rot.	N/A	*0.02969	N/A
P. Ext. Rot	N/A	0.3768	N/A
P. Rows	N/A	0.7573	N/A
A.Int.Rot.	N/A	0.6292	N/A
A.Ext.Rot.	N/A	0.6329	N/A
A. Rows	A. Rows	0.419	N/A

APPENDIX E

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clear all
close all
clc
%initializing c3d server
c3d = c3dserver()
ADL=0;
%Getting Comb data (ADL02-ADL04)
openc3d(c3d,2,'ADL02');
A = get3dtarget(c3d,'RShoulder');
%getting time frame (tf)
tf=nframes(c3d);
% Increment for frame
deltat = 1;
tspan = (1:deltat:tf);
T1 = rot90(tspan,-1);
z1 = A(:,1);
x1 = A(:,2);
y1 = A(:,3);
ADL=ADL+1;
openc3d(c3d,2,'ADL03');
A = get3dtarget(c3d,'RShoulder');
%getting time frame (tf)
tf=nframes(c3d);
% Increment for frame
deltat = 1;
tspan = (1:deltat:tf);
T2 = rot90(tspan,-1);
z2 = A(:,1);
x2 = A(:,2);
y2 = A(:,3);
ADL=ADL+1;
openc3d(c3d,2,'ADL04');
A = get3dtarget(c3d,'RShoulder');
%getting time frame (tf)
tf=nframes(c3d);
% Increment for frame
deltat = 1;
tspan = (1:deltat:tf);
T3 = rot90(tspan,-1);
z3 = A(:,1);
x3 = A(:,2);
y3 = A(:,3);
ADL=ADL+1
closec3d(c3d)
%loop to create max, max, and range or x,y, and z
n = 1; %initialize at data set 1
j= 0; %initialize j counter for loop
k= 1;%initialize k counter for rows of excel file
while j == 0
    if n+2 <ADL+2;
    %grouping 3 trials of x data
    xn1= sprintf('x%d',n);
    xn2= sprintf('x%d',n+1);
```

```
    xn3= sprintf('x%d',n+2);
    %grouping 3 trials of y data
    yn1= sprintf('y%d',n);
    yn2= sprintf('y%d',n+1);
    yn3= sprintf('y%d',n+2);
    %grouping 3 trials of z data
    zn1= sprintf('z%d',n);
    zn2= sprintf('z%d',n+1);
    zn3= sprintf('z%d',n+2);
    %getting average max, max, and range of trials
    %min
    minx= [min(eval(xn1)),min(eval(xn2)),min(eval(xn3))];
    miny= [min(eval(yn1)),min(eval(yn2)),min(eval(yn3))];
    minz= [min(eval(zn1)),min(eval(zn2)),min(eval(zn3))];
    mean_minx = mean(minx);
    mean_miny = mean(miny);
    mean_minz = mean(minz);
%{use xlsread and write record min, max, and range for ADLs and rehab)
    %max
    maxx= [max(eval(xn1)),max(eval(xn2)),max(eval(xn3))];
    maxy= [max(eval(yn1)),max(eval(yn2)),max(eval(yn3))];
    maxz= [max(eval(zn1)),max(eval(zn2)),max(eval(zn3))];
    mean_maxx = mean(maxx);
    mean_maxy = mean(maxy);
    mean_maxz = mean(maxz);
    %range
    rangex= [range(eval(xn1)),range(eval(xn2)),range(eval(xn3))];
    rangey= [range(eval(yn1)),range(eval(yn2)),range(eval(yn3))];
    rangez= [range(eval(zn1)),range(eval(zn2)),range(eval(zn3))];
    mean_rangex = mean(rangex);
    mean_rangey = mean(rangey);
    mean_rangez = mean(rangez);
%writing to excel file
    val= [minx, mean_minx,miny, mean_miny, minz, mean_minz, maxx,
mean_maxx, maxy, mean_maxy, maxz, mean_maxz, rangex, mean_rangex,
rangey, mean_rangey, rangez, mean_rangez];
    cells= sprintf('B%d:AK%d',k+1,k+1);
    xlswrite('RTC04_Values.xlsx',val,cells);
    n
        j=0;
        k=k+1;
        n=n+3;
    else
        j=1;
    end
end
```

Figure 31. Example MATLAB code for organizing c3d data for a single task for one subject

Code utilized MATLAB Toolbox for C3D server by Matthew Walker and Michael Rainbow