Risk of Reduced Subacromial Space During Activities of Daily Living for Users of Manual Wheelchairs

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Dedication

This dissertation is dedicated to my immediate and extended family for inspiring me to take this journey and providing understanding along the way. I hope I can provide the same inspiration and support for each of your respective dreams.

Abstract

Background and significance: Users of manual wheelchairs have to perform many movements within the confines of the wheelchair as well as utilize the wheelchair as a means of locomotion, for transferring to adjacent seating, and performing weight relief lifts, among other activities. The shoulder does not normally function as a weight bearing joint; however, users of manual wheelchairs rely heavily on their shoulder joints for these activities and shoulder pain is prevalent. There is general consensus that reduced subacromial space caused by altered glenohumeral kinematic patterns during wheelchair activities exposes the soft tissues at the shoulder, primarily the rotator cuff tendons, to mechanical compression during movement. The purpose of this study was to model the potential impact of angular kinematics during activities of daily living (wheelchair propulsion, weight relief raises, and scapular plane abduction) on the underlying subacromial space and resulting proximity of anatomical structures in a population of manual wheelchair users with reported shoulder pain.

Research Methods: Fifteen spinal cord injured individuals participated in the study. The individuals used manual wheelchairs as their primary means of mobility and reported anterolateral shoulder joint pain presumed to be caused by mechanical impingement. The three-dimensional position and orientation of the subjects' thorax, scapula, and humerus were collected using an electromagnetic tracking system during weight relief, propulsion, and scapular plane abduction. Scapulothoracic (3 rotations), glenohumeral (3 rotations) and thorax flexion/extension angles were determined throughout the tasks. Each subject's glenohumeral rotation values were combined with CT-generated bone models of the scapula and humerus to simulate all three tasks. At each of the time steps, the proximity (distance) mapping and minimum distance from each of three tendon footprints (infraspinatus, supraspinatus, and subscapularis) to the acromion and coracoacromial ligament were determined.

Analysis: Between-task and within-task comparisons of the angular kinematics were performed using repeated-measures ANOVA. Between-task comparisons of the minimum distance were performed using repeated-measures ANOVA, while the proximity maps were qualitatively assessed. Sensitivity of the linear distance values to errors in kinematic values were computed as well as an exploratory regression to predict linear distances from glenohumeral kinematics.

Results: Significant between-task and within task differences were observed in many of the kinematic variables. The weight relief task possessed peak values for scapulothoracic internal rotation and anterior tilt, and glenohumeral internal rotation, and when comparing mean event data, it possessed greater anterior tilt (equal to propulsion) and glenohumeral internal rotation. Scapular plane abduction possessed the least at-risk kinematics, with the smallest event data across tasks for anterior tilt and glenohumeral internal rotation as well as for peak scapular internal rotation, anterior tilt, and glenohumeral internal rotation. Further, significant between-task differences were seen in linear distance values and risk (area between linear distance curves and 5.0mm threshold). In general, linear distances were smaller and risks were higher between the tendon footprints and the acromion (versus the coracoacromial ligament). Further, linear distances were smaller and risks higher during propulsion and scapular plane abduction, than during weight relief. Sensitivity analysis of the linear distance values resulted in sub millimeter changes for ± 3 degree changes in glenohumeral rotations and less than 2.0 mm for ± 6 degree changes. Proximity maps (within 2.0 mm and 5.0 mm thresholds) depicted changes in location of the maps on the tendon footprints and acromion, as well as coverage area, between tasks and muscles. The supraspinatus proximity area within a 2.0 mm threshold was greater than the infraspinatus area for both propulsion and scapular plane abduction, and within the 5.0 mm threshold for scapular plane abduction. Significant differences were only seen between the two tasks for the infraspinatus areas within 2.0 mm and 5.0 mm with larger areas during propulsion.

Discussion and conclusions: When the current study findings were evaluated according to currently-held beliefs about at-risk scapulothoracic kinematics, the weight relief task placed the shoulder at greater risk for reduction in the subacromial space. Findings from the linear distance and risk analysis, however, did not support this result. Scapular plane abduction and propulsion were found to cause substantial risk of impingement using these measures. As subacromial impingement risk is defined based on glenohumeral motion changes, future research should focus on the glenohumeral articulation rather than on the scapula and humeral motions independently to attempt to define risk.

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CHAPTER I

A. INTRODUCTION

A.1. Background and clinical significance

Although spinal cord injury (SCI) is a fairly uncommon disability, occurring at a rate of 40 cases per million[1], its economic and social costs are not proportional to the number of cases in which it occurs[1]. In 2004, there were 200,000 persons in the United States living with chronic spinal cord injury[2]. Over the last forty years, the mean age at which spinal cord injuries occurred has increased significantly, with tetraplegia and complete injuries occurring more often than paraplegia[1]. However, in the last 50 years, long term survival after SCI has become a reality[3, 4] with the life expectancy of paraplegics now almost equaling that of the able-bodied population[5]. Rates of shoulder pain in SCI individuals have been reported to be as high as 70% during activities of daily living, negatively affecting their quality of life and independence[2]. Further, increased time since injury, advanced age, female gender, higher level of injury, low activity level, and later injury onset have all been attributed to higher levels of shoulder pain[6-15].

Wheelchair users rely heavily on their shoulder joints to ambulate and exercise, but perhaps most importantly, to provide a means for an independent lifestyle. The shoulder does not normally function as a weight bearing joint, but in this population, the shoulder serves as the primary load bearing part of the anatomy. Manual wheelchair users are forced to perform many movements within the confines of the wheelchair as well as use the wheelchair as a means of locomotion, for transferring to adjacent seating, and performing weight relief lifts, among other activities. Pentland and Twomey[5] reported that paraplegic subjects under the age of 45 years performed 15 transfers per day and loaded the wheelchair into and out of a car 5 times per day. The nature of functioning from a seated position requires that many activities of daily living will be performed with the shoulder in an elevated posture or overhead, which has been implicated as a risk factor for shoulder pain in previous investigations of glenohumeral kinematics[16]. In summary, there is a clinical impetus to better understand and reduce the incidence of shoulder pain in the manual wheelchair population.

A.2. Shoulder pain in manual wheelchair users

Understanding the mechanisms of shoulder pain is a crucial first step in formulating a research design to help alleviate pathology in this population so that their level of independence is preserved or improved. The shoulder is uniquely layered with the bony anatomy as the deepest structures, followed by cartilage, joint capsule, ligaments, and musculotendon units more superficially. Important anatomical structures in the anterior shoulder include the coracoid process, acromion, subacromial bursa, supraspinatus tendon, biceps tendon coursing through the bicipital tendon sheath and the acromioclavicular joint (**Figure A.1**). The subacromial space is the space or void between the coracoacromial arch (acromion, coracoacromial ligament, coracoid, and acromioclavicular joint) superiorly and humerus inferiorly (**Figure A.2**).

The rotator cuff tendons, biceps tendon, and bursa reside within the space without pain in healthy shoulders; therefore, reduction in the space provides a potential mechanism for injury or pain to the shoulder joint[17-19]. While these cadaveric and animal studies[17-19] clearly capture a “mechanical impingement” phenomenon, clinicians lack a clear diagnostic test to isolate this impingement in patients. As a result, multiple tests are often used to help improve their ability to correctly characterize the source of shoulder pain[20].

A number of studies have focused on correlating shoulder clinical diagnoses through physical exams with symptoms of pain in the spinal cord injured population[15, 21, 22]. In these reports, the descriptions are limited and the included tests variable. Further, the clinical diagnoses were quite diverse including atrophy, supraspinatus and infraspinatus tendinitis, biceps tenderness, and impingement[15, 21, 22]. Similarly, findings from imaging studies were equally diverse including, but not limited to, joint narrowing, osteophytes, rotator cuff tears, and bursitis[23-27]. Although the physical exam and imaging findings are quite variable, some commonality among the various findings can be extrapolated in general. For example, most of the described diagnoses and imaging assessments focused on the anterior shoulder and, more specifically, the rotator cuff region[15, 21-23, 26]. The subacromial space between the humerus and scapula contains important soft tissue structures that, if compromised, may ultimately lead to the described physical exam and imaging findings. Soslowsky et al.[19] and Schneeberger et al.[18] both utilized a rat model to investigate the mechanical characteristics and environment within the subacromial space. They found that narrowing of the space and repetitive motion both lead to physical changes in the rotator cuff tendons including reduced modulus of elasticity, abrasion of the tendons, and rotator cuff tears.

A.3. Shoulder kinematics

The subacromial space is defined and directly affected by the orientations of the humerus and scapula. The glenohumeral joint possesses many degrees of freedom and can be moved through a large range of motion in most directions. Common techniques for measuring glenohumeral kinematics in vivo utilize surface-based marker techniques (optical, video, and electromagnetic); however there are a few investigators using direct measurement (bone-pin mounted sensors) and imaging techniques[28-33]. Comparison of bone-mounted and skin sensor data have shown errors in humerus and scapula skin sensor acquisitions of less than four degrees during shoulder movements below 60 degrees of humeral elevation[34, 35]. Regardless of the measurement technique, orthogonal local anatomical coordinate systems are defined on each bone such that glenohumeral and scapulothoracic motions can be defined according to an established standard[36]. Scapulothoracic rotation is comprised of internal/external rotation, upward/downward rotation, and posterior/anterior tilting. Glenohumeral motions of interest include plane of elevation (anterior or posterior to the scapular plane), elevation, and axial rotation (internal/external) about the humeral long axis (**Figure A.3**).

Much attention has been paid to quantifying scapulothoracic and glenohumeral rotations during arm raise tasks (primarily scapular plane abduction) in healthy normal subjects. The general pattern of motions during humeral elevation includes scapulothoracic upward rotation, posterior tilting, and glenohumeral elevation, movement anterior to the thorax (plane of elevation), and external rotation. However, ultimately, reduced subacromial space has been hypothesized to follow from decreased scapular upward rotation, external rotation, and posterior tilt during humeral elevation as well as decreased glenohumeral external rotation[37]. Cadaver and imaging studies show some evidence of this phenomenon[38-40]. While numerous studies have been conducted to determine whether kinematic alterations exist between shoulders with impingement and asymptomatic shoulders, the results are quite variable as are the study methodologies[16, 31, 41-46]. Even among the group of investigators that quantified shoulder kinematics dynamically with reportedly similar methods, the findings of kinematic differences between symptomatic and asymptomatic groups were still quite variable.

A.4. Kinematics and subacromial space in manual wheelchair users

A few investigations of shoulder kinematics have been performed to quantify activities commonly performed by manual wheelchair users[28, 47-50]. Weight relief maneuvers were performed by 25 able-bodied subjects without shoulder pain and significant differences were found between different phases of the movement in scapular upward and internal rotation as well as for tilting[48]. The weight relief task was discretized into 4 phases corresponding to preparation for the lift (phase1), lift (phase 2), hold (phase 3), and descent (phase 4). Significant differences were found between the beginning of phases 1 and 2, and the beginning of phases 1 and 3, for scapular upward and internal rotation as well as for tilting. Significant differences between the beginning of phases 1 and 3 were found for internal rotation. Morrow[47] quantified scapula and humeral kinematics during level and ramp propulsion as well as during weight relief lifts in 12 manual wheelchair users; all tasks were characterized by positions of internal rotation and anterior tilt of the scapula. Peak internal rotation occurred near hand-off for propulsion and onset of hold for the weight relief. Peak anterior tilt occurred at the end of recovery for propulsion and did not vary much across the weight relief task. Riek et al.[49] analyzed the shoulder kinematics of various activities of daily living in five spinal cord injured individuals. They found that during the initial loading phase of the weight relief raise, the scapular anterior tilt was significantly greater than in standing posture (using a standing frame). Additionally, during the initial and maximum loading phases, the humerus was significantly more internally rotated than in standing posture. Lu et al.[28] investigated the kinematics of wheelchair propulsion and found the orientation of the scapula to be in internal rotation and anterior tilt during the entire movement. The question remains whether the position and orientation of the scapula during activities in this population are dictated by the constraints of the wheelchair and movement demands, or if these movement patterns can be altered with an intervention. In addition, it is unclear whether the movement patterns inherent to these tasks are extreme enough or alter the subacromial space in such a way to compromise the soft tissues lying within the space.

While it is important to try and understand the kinematics of the tasks and their effects on the subacromial space, it is difficult to draw conclusions given the different kinematic approaches employed by various research groups. It is for this reason that new measures of mechanical impingement risk should be used that are invariant to coordinate system definitions and measurement techniques, and which have more clinical relevance. Recently, researchers have quantified the relationship of relevant anatomical structures to neighboring bony structures[38, 51-54] during dynamic movement with the subacromial space defined as the Euclidean distance determined from three-dimensional coordinates. Linear minimal distances from the footprint of the rotator cuff muscles to potential impinging anatomical structures have clinical significance and are invariant to kinematic approaches. Further, following the concept of Flatow et al.[17], proximity mapping of the distances from the humeral head to any point on the undersurface of the acromion have been determined to aid in interpretation of the relationship of soft tissue structures and bony anatomy.

A.5. Proposed research

There are no previous published investigations which have utilized kinematic measurement techniques to compare between activities in a population of manual wheelchair users with shoulder pain. Further, no study exists which has attempted to relate the kinematic information to the size of the subacromial space, nor between the kinematic data and the location of soft tissues relative to the overlying bony structures. The overarching goal of this project is to record the glenohumeral and scapulothoracic kinematics as well as model the potential impact of these motions on the underlying subacromial space and resulting proximity of anatomical structures. The central hypothesis is that experimentally-acquired shoulder kinematics can be combined with models of the shoulder geometry to elucidate which movement tasks (weight relief, propulsion, and scapular plane abduction) most significantly reduce the subacromial space, thereby potentially impinging underlying soft tissue structures in a population of wheelchair users with shoulder pain.

A.6. Aims and hypotheses

Aim 1: Quantify three-dimensional glenohumeral, scapulothoracic, and thoracic kinematics throughout level propulsion, weight relief, and scapular plane abduction in manual wheelchair users with shoulder pain.

H1.1: Propulsion will result in greater scapular internal rotation than weight relief and scapular plane abduction.

H1.2: Weight relief will result in greater scapular anterior tilting than propulsion and scapular plane abduction.

H1.3: Weight relief will produce glenohumeral axial rotation that is more internally rotated than propulsion and scapular plane abduction.

H1.4: The hand-off position during propulsion will be characterized by more scapular internal rotation and less humeral internal rotation than early (hand-on) and mid-propulsion positions.

H1.5: The hold phase of weight relief will result in greater scapular internal rotation and humeral internal rotation than the lift phase.

H1.6: Late scapular plane abduction will result in greater scapular upward rotation and glenohumeral external rotation than the early phase.

Aim 2: Assess risk of damage to the rotator cuff by quantifying a) the minimum linear distances from the coracoacromial arch to the rotator cuff tendons throughout level propulsion, weight relief, and scapular plane abduction, and b) the

proximity maps between the tendon footprints and coracoacromial arch during tasks demonstrating significant risk in a).

H2.1: There will be significant differences in minimal distances to the coracoacromial arch across tasks.

Aim 3: Determine a) the sensitivity of linear distances to glenohumeral rotation and humeral translation changes, and b) the ability of glenohumeral and trunk flexion/extension rotation values to predict linear distances during weight relief, propulsion, and scapular plane abduction using a regression approach.

A.7. Definition of terms

Subacromial space: The subacromial space is the void defined by humeral head inferiorly, the anterior edge and under surface of the anterior third of the acromion, coracoacromial ligament and the acromioclavicular joint superiorly[55].

Subacromial impingement**:** *Mechanical* impingement is defined as a compromise of the subacromial space such that encroachment of the underlying soft tissues occurs. The tissues consist of the supraspinatus tendon, subacromial bursa, long head of the biceps brachii tendon, and the capsule of the shoulder joint. Any of these structures may be affected[37]. *Clinically*, subacromial impingement was first described by Neer[56] who established the Neer test which induced pain with forward elevation of the humerus against the acromion which was then eliminated with a 1.0% injection of Xylocaine beneath the anterior acromion. In practice, the Neer test is not strictly utilized; instead a modified Neer test (without an injection) as well as four others [Hawkins-Kennedy, painful arc, empty can (Jobe), and external rotation resistance tests] are commonly used with varying sensitivity and specificity[20].

Wheelchair propulsion**:** The use of the hands on the manual wheelchair hand rim or wheel to exert a force/moment on the hand rim. The cycle typically involves a hand-on to hand-off phase where the pushing occurs, and a recovery phase, when the hands are off of the hand rim and returning to the hand-on position (**Figure A.4**).

Weight relief lift**:** Maneuver whereby manual wheelchair users lift their body off of their wheelchair using the hand rim or wheel, to help prevent pressure-related sores (**Figure A.5**).

Scapular plane abduction: Elevation of the humerus in the plane of the scapula which typically lies 30 to 45 degrees anterior to the coronal plane (**Figure A.6**).

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CHAPTER II

B. LITERATURE REVIEW

B.1. Clinical significance

B.1.a. Wheelchair users and shoulder pain

A total of 1.7 million community-dwelling individuals in the United States use wheelchairs/scooters as their assistive device; 90% of these individuals use manual wheelchairs[57]. Among community-dwelling 18-64 year olds, paraplegia is the second leading condition associated with wheelchair or scooter use, while tetraplegia is the fourth leading condition[57]. Although spinal cord injury (SCI) is a fairly uncommon disability, occurring at a rate of 40 cases per million[1], its economic and social costs are not proportional to the number of cases in which it occurs[1]. In 2004, there were 200,000 persons in the United States living with chronic spinal cord injury[2]. These individuals accrue initial hospital expenses on average of $95,203 and lifetime expenses of $500,000 to greater than 2 million dollars depending on the type and level of injury[58].

Over the last forty years, the mean age at which spinal cord injuries occurred has increased significantly, with tetraplegia and complete injuries occurring more often than paraplegia[1]. However, in the last 50 years, long term survival after SCI has become a reality[3, 4] with the life expectancy of paraplegics now almost equaling that of the able-bodied population[5]. This positive development has complicated the design and interpretation of research in this population as aging effects are superimposed on preexisting disabilities[5]. In addition, wheelchair design and rehabilitation knowledge have evolved over time[3]. These factors put an important historical context on the interpretation of previous research.

Spinal cord injured individuals suffer from many types of pain post-injury including neuropathic pain which results from damage to the spinal cord, nociceptive pain caused by demands placed on the upper extremities, as well as “mixed” pain[4]. In addition, these users may suffer from other sources of chronic pain similar to the uninjured population (headaches, etc)[4]. In the context of their daily lives, however, eliminating chronic pain was not a priority for tetraplegic individuals injured less than 3 years; however, it became increasingly important after three years[2]. Anderson[2] questioned 681 SCI individuals via a survey (51% tetraplegics, 49% paraplegics, 25% female, 65% male, 10% anonymous) and asked them to rank seven areas for importance to their quality of life. The tetraplegic patients categorized hand and arm function by far the highest priority with return of sexual function being the top priority for paraplegic individuals. Regaining bladder and bowel function and eliminating autonomic dysreflexia was similarly important to both groups. So, while multiple studies have reported on the high levels of upper-extremity (especially shoulder) pain in the SCI wheelchair user population[6-14], it is pertinent to realize the other relevant health challenges these persons may be experiencing.

Wheelchair use can be categorized into an acute period just following injury (3-6 mos.) and a chronic period (greater than 1 year) during which time the user is an experienced user[59]. Shoulder pain in the acutely injured person has been hypothesized as being caused by the large demands that are being placed on the under or unconditioned shoulder musculature. However, in the chronic phase, the pain is thought to be a result of overuse injuries from propulsion and transfer activities[59].

Rates of shoulder pain in SCI individuals have been reported to be as high as 70% during activities of daily living, negatively affecting their quality of life and independence[2]. However, the heterogeneity of sample populations with respect to diagnosis, age, level of injury and time since injury, and lack of identification of the period of wheelchair use has made the literature reports quite variable. The causes of shoulder pain are clearly multifactorial with previous research having identified many factors. Increased time since injury, advanced age, female gender, higher level of injury, low activity level, and older age at injury onset have all been attributed to higher levels of shoulder pain[6-15].

B.1.b. Importance of shoulder in manual wheelchair population

Wheelchair users rely heavily on their shoulder joints to ambulate and exercise, but perhaps most importantly, to provide a means for an independent lifestyle. The wheelchair users' shoulder joints function as weight bearing structures. As manual wheelchair users, their daily activities consist of repetitive low-load movements, such as propelling the wheelchair, as well as weight transfer and relief maneuvers, which induce higher load requirements at the shoulder joint[47]. The shoulder does not normally function as a weight bearing joint, but in this population, the shoulder serves as the primary load bearing part of the anatomy. Further, in the SCI manual wheelchair user population, trunk stability can be compromised depending on the level of injury and its effect on the innervation of the trunk musculature. Paraplegics have full control of the shoulder musculature, with the nerves deriving from the brachial plexus between the upper trunk and posterior cord[60]. However, they have varying levels of trunk control depending on the level of injury. The trunk provides a base of support for the shoulder and its posture, and its motion can greatly affect shoulder kinematics[61] which in turn can affect impingement risk[62]. Finally, manual wheelchair users are forced to perform many movements within the confines of the wheelchair as well as use the wheelchair as a means of locomotion, for transferring to adjacent seating, and performing weight relief lifts, among other activities. Pentland and Twomey[5] reported that paraplegic subjects under the age of 45 years performed 15 transfers per day and loaded the wheelchair into and out of a car 5 times per day. The nature of functioning from a seated position requires that many activities of daily living will be performed with the shoulder in an elevated posture or overhead, which has been implicated as a risk factor for shoulder pain in previous investigations of glenohumeral kinematics[16].

In summary, there is a clinical impetus to better understand and reduce the incidence of shoulder pain in the manual wheelchair population. This population is predominantly SCI individuals who have financial and other health-related concerns, but who ultimately rely on their shoulder as a load bearing structure for all activities of daily living. Understanding the mechanisms of shoulder pain is a crucial first step in formulating a research design to help alleviate pathology in this population so that their level of independence is preserved or improved.

B.2. Mechanisms of shoulder pain

B.2.a. Anatomy of the anterior shoulder

The shoulder complex (clavicle, scapula, and humerus) has three true articulations: glenohumeral, acromioclavicular, and sternoclavicular. The sternoclavicular is the only joint that connects the shoulder complex to the axial skeleton. With the thorax functioning as a base, the shoulder joint has a unique mobility that exceeds all other joints in the body[63]. The shoulder is uniquely layered with the bony anatomy as the deepest structures, followed by cartilage, joint capsule, ligaments, and musculotendon units more superficially. Important anatomical structures in the shoulder include the coracoid process, acromion, subacromial bursa, supraspinatus tendon, biceps tendon coursing through the bicipital tendon sheath and the acromioclavicular joint (**Figure A.1**).

The ligaments include the coracoacromial, coracoclavicular, superior glenohumeral, middle glenohumeral, and inferior glenohumeral and the rotator cuff muscles are comprised of the supraspinatus, infraspinatus, teres minor and subscapularis. The subacromial space is the space between the coracoacromial arch (acromion, coracoacromial ligament, coracoid, and acromioclavicular joint) superiorly and humerus inferiorly (**Figure A.2**). The rotator cuff tendons, biceps tendon, and bursa reside within the space without pain in healthy shoulders; therefore, reduction in the space provides a potential mechanism for injury or pain to the shoulder joint[17-19].

The shoulder joint is stabilized by passive and active constraints that guide shoulder motion with passive subdivided into articular and capsuloligamentous components. Passive constraints include soft tissue (coracohumeral ligament, glenohumeral ligament, labrum, and joint capsule) and articular surfaces (joint contact, scapular inclination, and intra-articular pressure). Active constraints include the rotator cuff muscles, biceps, and deltoid[63].

B.2.b. Documented pathologies

There have been a plethora of investigators reporting prevalence of shoulder pain in this population through the use of surveys and questionnaires[6-15] with the prevalence of shoulder pain in the study population ranging from 30% to 70%. A commonly-used and validated questionnaire for this population is the WUSPI (wheelchair user's shoulder pain index)[64, 65] which asks users to assess their level of pain on a 10 point scale during 15 activities of daily living. In addition, various populations of manual wheelchair users have been shown to have more pain relative to their respective study populations. For example, Sawatzky et al.[66] determined that users with adult-onset wheelchair use had more pain than users with childhood onset wheelchair use. Also, time since injury affects reported shoulder pain. A greater time since injury results in a greater prevalence of shoulder pain (2% at 1-5 yrs. since injury and 100% by 16-20 yrs.)[10]. In addition, users with tetraplegia and higher cervical injuries reported more pain than users with paraplegia and lower level injuries (59-81% vs. 42-58%) [7, 8, 12].

A number of studies have focused on correlating shoulder clinical diagnoses through physical exams with symptoms of pain in the spinal cord injured population. In the reports that include physical exams, the descriptions are limited and the included tests variable. Further, the clinical diagnoses were quite diverse. Samuelsson et al.[15] reported muscular atrophy, pain, impingement and tendinitis of the supraspinatus and infraspinatus as determined by a physiotherapist in subjects who reported shoulder pain. Brose[21] reported positive clinical findings as a percent of users with shoulder complaints, as follows: bicipital tenderness with palpation (23.4%), supraspinatus tenderness (25%), acromioclavicular joint tenderness (18%), supraspinatus test (35.5%), resisted external rotation (12.6%), resisted internal rotation (23%), painful arc test (27%), Neer sign (27%), and Hawkins'sign (33%). Similarly, Finley and Rogers[22] reported that in the painful shoulders tested, 44% were positive for impingement, 50% were positive for biceps tendonitis, and 28% were positive (positive sulcus sign) for instability.

Clinical diagnosis of impingement is a challenge and subject to differing specificity and sensitivity depending on the exam used[20]. Michener et al.[20] compared five different clinical exams commonly used to diagnose impingement to arthroscopic observation of the anterior shoulder. A positive sign operatively consisted of one of the following: visually enlarged bursa, fibrotic appearing bursa, or degeneration of the supraspinatus tendon at the superficial aspect. Briefly, the Neer test[56] was a modified test (without the injection) which consists of stabilization of the scapula with a downward force while fully flexing the humerus overhead maximally; a positive test is indicated by superior shoulder pain. The Hawkins-Kennedy test[67] involves flexion of the humerus and elbow to 90° and then maximally internally rotating the shoulder; a positive test is indicated by superior shoulder pain. The painful arc test involves the patient actively abducting his/her shoulder and reporting pain during abduction; a positive test is indicated by pain in the superior shoulder between 60° and 120° of abduction[68]. The empty can test (i.e. Jobe test)[69] involves elevation of the shoulder to 90° in the scapular plane followed by internal rotation such that the subject's thumb is pointing toward the floor; a positive test is indicated by weakness of the involved shoulder (as compared to contralateral limb) when trying to resist a downward force. The external rotation resistance test[70] is performed with the patient's elbow flexed to 90° while the humerus is in neutral; a positive test is indicated by weakness as compared to the contralateral limb when resisting a medial force applied on the distal forearm. While the authors found all the tests to be reliable for clinical use, they varied in their accuracy/specificity and therefore suggested using the full battery of tests and requiring 3 out of 5 positive exams for confirmation of the diagnosis.

While these tests may be able to re-create a subject's anterior/superior shoulder pain, it is not entirely clear what mechanism is causing the painful outcome (i.e., the specificity of the tests). Indeed, it is not a confirmation that *mechanical* impingement, defined as a compromise of the subacromial space such that encroachment of the underlying soft tissues (supraspinatus tendon, subacromial bursa, long head of the biceps brachii tendon, and the capsule of the shoulder joint), is occurring. Therefore, the exams should be utilized but with the understanding that the underlying mechanisms may not be entirely consistent across subjects. However, subjects will be suffering from anterior shoulder pain.

Findings from imaging studies were equally diverse. Boninger et al.[25] reported cases of distal clavicular edema, acromioclavicular joint DJD/edema, acromial edema, osseous spur, entheseal edema, coracoacromial ligament edema/thickening as determined by a radiologist using a 1.5T GE MRI scanner and standard linear shoulder coil. Sequences were obtained for axial fast spin echo fat suppressed T2, oblique coronal fast spin echo proton density, oblique coronal fast spin echo T2, and oblique sagittal fast spin echo proton density, as well as fast spin echo fat suppressed T2. However, they determined that individuals who had experienced pain in the last month were not significantly more likely to have abnormalities in their imaging as compared to those without pain. Akbar et al.[23] primarily reported on the prevalence of partial and full rotator cuff tears in the paraplegic population as determined by a musculoskeletal radiologist from oblique coronal, oblique sagittal, and axial planes on a 1.0-T MRI scanner. In total, 61% had supraspinatus tears, 12% had subscapularis tears, and 19% had infraspinatus tears while full-thickness tears accounted for 78% and partial-thickness tears accounted for 22% of all tears. They also noted that 52% of wheelchair users had bursitis, 26% had joint effusion, and 42% had acromioclavicular joint arthritis. Similarly, Escobedo et al.[26] imaged symptomatic and asymptomatic paraplegic and able-bodied individuals on a l.5-T MR scanner using a surface coil. Coronal oblique T1-weighted, T2-weighted, and axial gradient-echo images were obtained. All but one examination included a sagittal oblique T2-weighted image. Except for one partial-thickness tear, all rotator cuff tears in the paraplegic population occurred in the symptomatic group.   All of the shoulders that had a full-thickness tear had involvement of the supraspinatus tendon. 63% of shoulders also showed a tear of one or more additional rotator cuff tendons, including 9 in the infraspinatus tendon, 7 in the subscapularis tendon, and 2 in the teres minor tendon. Finally, among all the paraplegic subjects, there was a positive correlation between prevalence and severity of tears, and age and duration of spinal cord injury.

Wylie and Chakera[27] conducted a chart review and characterized previous x-ray films to quantify shoulder joint degeneration as early (joint space narrowing less than 3 mm), moderate (joint narrowing, osteophytes, and subchondral sclerosis), or severe (moderate characteristics plus subarticular cysts, and loose bodies) and determined that 3 out of 13 active paraplegic wheelchair users showed degenerative changes as early/moderate while 5 out of 11 inactive wheelchair users showed degenerative changes almost equally as early/moderate/severe. X-rays of the glenohumeral joint were also obtained in a population of 89 spinal cord injured individuals who were at least 9 months post-injury and joint narrowing was shown to be the most common issue (14.0%) followed by calcification (11.2%), osteophytosis (9.0%), and heterotopic ossification (9.0%)[24].

While it is clear that spinal cord injured individuals suffer from shoulder pain in great numbers, it is also clear that many variables impact the level of pain in this population, including time since injury, level of injury, etc. Therefore, the subject inclusion/exclusion criteria are crucial for making definitive conclusions that can be generalized to the population at large. Unfortunately, the studies to date have focused on small subsets of individuals which may have limited applicability to the entire population of SCI individuals. Likewise, the physical exam and imaging findings are quite variable; however, some commonality among the various findings can be extrapolated in general. For example, most of the described diagnoses and imaging assessments focused on the anterior shoulder and, more specifically, the rotator cuff region.

B.2.c. Mechanical consequences of subacromial space narrowing

Animal studies have been performed which suggest that a reduction in subacromial space can cause mechanical injury of the soft tissue in the subacromial space. Soslowsky et al.[19] and Schneeberger et al.[18] both utilized a rat model to investigate the mechanical characteristics and environment at the shoulder. Soslowsky et al. investigated the concept of whether there is a mechanical effect on the underlying soft tissue due to repetitive motion at the shoulder joint. He found that the supraspinatus tendon in rats that were part of an overuse decline-treadmill running group had a decreased modulus of elasticity as compared to the group with normal cage activity implicating mechanical wear as a potential factor in rotator cuff degeneration[19]. Further, Soslowsky conducted a study[71] using a rat model where rats were placed in one of three groups: extrinsically reduced space (a thawed Achilles tendon allograft was inserted so that it lay just underneath the acromion), overuse, or both extrinsic and overuse. The overuse protocol consisted of a decline treadmill-running protocol. They found that the injury created by overuse plus extrinsic compression was greater than injuries due to either extrinsic or overuse alone. Schneeberger et al.[18] demonstrated in young adult rats that by experimentally thickening the underside of the acromion by transplantation of the bony spine of the ipsilateral scapular spine, mechanical abrasion of the infraspinatus occurred, resulting in bursal side rotator cuff tears. In addition, chondrocytes were found in the tendon adjacent to the bony implant and bursal thickening was observed.

In summary, the subacromial space between the humerus and scapula contains important soft tissue structures that, if compromised, could lead to pain during activities of daily living. Narrowing of the space could lead to a variety of shoulder pathologies as shown in imaging and physical examination of manual wheelchair users; however, encroachment by the bony anatomy is a likely source of many of the pathologies. Therefore, quantifying the movements and activities which may cause narrowing of the subacromial space is crucial for our understanding of the mechanisms of pain in this population.

B.3. Kinematics and measurement techniques

B.3.a. Quantifying glenohumeral and scapulothoracic kinematics

The glenohumeral joint possesses many degrees of freedom and can be moved through a large range of motion in most directions. Common techniques for measuring glenohumeral kinematics in vivo utilize surface-based marker techniques. Optical systems that require visibility of markers by cameras for accurate quantification need a sufficient number of cameras for accurate data acquisition. Both electromagnetic and video-based methods sometimes utilize a scapula-tracking device to attempt to improve on the ability to track the scapula which can be a challenge due to overlying skin movement[34]. Other investigators use electromagnetic surface-based systems and generally track the scapula using a marker placed over the acromion to track scapula motion[16, 31, 44, 46]. Additional techniques exist which improve on kinematic data acquisition accuracy but are technically and computationally challenging, including the use of invasive bone-pin mounted sensors[30, 31] and image-based kinematic techniques[72-74] with reported accuracy of < 1 degree for both methods. Comparison of bone-mounted and skin sensor data have shown errors in humerus and scapula skin sensor acquisitions of < 4 degrees during shoulder movements below 60 degrees of elevation[34, 35].

Standards have been developed for analyzing rotations of all bones in the shoulder complex[36] so that resulting data from different researchers can be seamlessly compared. Coordinate systems are defined on each bone using a digitizing stylus such that the orientation and definition of orthogonal local anatomical coordinate systems are consistent[36]. Relevant glenohumeral and scapulothoracic motions are defined in **Figure A.3**. Scapulothoracic rotation is comprised of internal/external rotation, upward/downward rotation, and posterior/anterior tilting. Glenohumeral motions of interest include plane of elevation (anterior or posterior to the scapular plane), elevation, and axial rotation (internal/external) about the humeral long axis. International Society of Biomechanics standards[36] suggest the use of Euler/Cardan sequences for each of the motions. However, authors[75-80] have assessed and suggested other sequences and techniques (e.g. helical axis approach) since the standards were developed.

Much attention has been paid to quantifying scapulothoracic and glenohumeral rotations during arm raise tasks in healthy normal subjects. Scapulothoracic rotations have been investigated statically during scapular plane abduction[81] using a custom digitizing apparatus and arm positioning control device. Scapular orientation was measured in 25 asymptomatic subjects at 0, 90 and 140 degrees of humeral elevation. As the humeral elevation angle increased, the scapula demonstrated a pattern of progressive upward rotation, decreased internal rotation, and rotation from an anterior tilted to a posteriorly tilted position. Researchers have also captured scapular kinematics using a direct approach using bone-pin mounted kinematic sensors. McClure et al.[82] captured scapular kinematics in 8 asymptomatic subjects during tasks including scapular plane abduction using this direct approach. They similarly found a pattern of scapular upward rotation (50 degrees), posterior tilting (30 degrees), and external rotation (24 degrees) during elevation of the humerus. Scapular motion has also been quantified in a group of 8 asymptomatic subjects during functional movements, including forward reaching, glenohumeral horizontal adduction, and “hand behind the back” (glenohumeral extension, adduction, and internal rotation) using a direct bone-pin technique[32]. They reported complex movement of the scapula across the various tasks and noted that scapular movement patterns cannot be extrapolated from the well-studied scapular plane abduction movements to other functional tasks. For example, during horizontal adduction, the scapula tilted anteriorly 8 degrees, rotated upward 5 degrees and internally 27 degrees while during “hand behind the back”, the scapula motion fell below 15 degrees for most of the rotations.

Glenohumeral rotations during arm raise tasks in asymptomatic groups have been the focus of only a single investigation. Ludewig et al.[30] conducted a study in which 12 asymptomatic subjects performed arm elevation in different planes with a direct approach, attaching sensors to the scapula and humerus via bone-pins. Across the elevation trials, they noted increasing glenohumeral external rotation (10-51 degrees, depending on elevation plane).

B.3.b. Kinematics of arm raise tasks in symptomatic and asymptomatic individuals

While numerous studies have been conducted to determine whether kinematic differences exist between impingement shoulders and asymptomatic shoulders, the results are quite variable as are the study methodologies (**Table B.1**)[16, 31, 41-46]. Common to most studies, however, is their ability to detect group differences in spite of study design and analysis differences. Numerous researchers have captured the glenohumeral and/or scapulothoracic kinematics at positions throughout scapular plane abduction using *static* techniques. Lukasiewicz et al.[45] used an electromechanical digitizer to determine scapular kinematics in 20 asymptomatic and 17 subjects with impingement using a projection angle technique. They found that posterior tilt was reduced by 9 degrees in the impingement group as compared to the asymptomatic subject group. Endo et al.[41] captured anteroposterior x-rays of 27 subjects with unilateral impingement during positions of arm elevation and used two-dimensional measures to calculate scapular angle values. They found a reduced upward rotation of 4 degrees in the impingement side versus the asymptomatic contralateral shoulder. Hebert et al.[42] used an optical system to capture static measures of scapulothoracic rotation in 41 subjects with impingement and 10 asymptomatic subjects. Using coordinate systems and Euler angle definitions that were not ISB-standard, they found a reduction in scapula internal rotation in the impingement group as compared to the asymptomatic group. Static measures of arm elevation were determined in an open MR scanner[52] and principal components analysis to calculate internal joint angles in 20 subjects with impingement and 14 asymptomatic subjects. They found no significant differences between groups. Finally, a digital inclinometer was used to capture static positions during an arm raise in two groups of swimmers (20 asymptomatic, 20 impingement). Upward rotation of the scapula was decreased (3-5 degrees) in the group of swimmers with impingement as compared to the asymptomatic swimmers following swimming practice. In summary, these static investigations utilized quasi-static testing and analysis techniques which differed across the studies. And, although the studies used different approaches and had variable findings, almost all resulted in detection of a significant difference between groups in one or more variables.

Among the group of investigations that quantified shoulder kinematics *dynamically* with reportedly similar methods, the findings were still variable. Ludewig and Cook[16] assessed glenohumeral kinematics in two groups of individuals (26 with and 26 without symptoms of impingement) with similar occupational exposure to overhead work. Using electromagnetic surface sensors and analysis techniques based on International Society of Biomechanics standards[36], they found reduced upward rotation (by 4 degrees) and reduced posterior tilting (by 6 degrees) of the scapula during humeral elevation in the scapular plane in the symptomatic group. The same methodology and analysis was used in a study of 45 asymptomatic and 45 symptomatic individuals during scapular plane abduction[83]. They found an increase in upward rotation (of 4 degrees) and posterior tilt (of 3 degrees) in the impingement group relative to the asymptomatic group. Finally, Lin et al.[84] used the same techniques in a group of 14 impingement and 7 asymptomatic subjects and found a reduction in posterior tilting of 7-14 degrees. So, although similar methodologies were used, results were not consistent across investigations implying that recruitment of subjects may not have been consistent across studies or the study's power may not have been sufficient to detect changes.

B.3.c. Relationship of kinematics to reduction in subacromial space

Potential contributing tissue pathologies or impairments that may accompany subacromial impingement are quite varied and can include inflammation of the tendons and bursa, degeneration of the tendons, and weak or dysfunctional rotator cuff and scapular musculature[37]. However, ultimately, reduced subacromial space has been hypothesized to follow from decreased scapular upward rotation, external rotation, and posterior tilt, as well as decreased glenohumeral external rotation during humeral elevation.

Karduna et al.[39] conducted an in vitro investigation using 8 specimens in which he mounted the glenohumeral specimens in a material testing device and simulated joint compression and deltoid loading. Superior humeral translation was imposed and the distance recorded at which 20N of subacromial contact force was measured. The specimens were tested at multiple positions of scapular posterior tilting, upward rotation, and external rotation. Statistical analyses demonstrated no effect of posterior tilting and external rotation on subacromial clearance as defined by the distance before the 20N load was detected; however, the "clearance" significantly decreased with increases in upward rotation. These findings are contrary to previous beliefs about the relationship between the shoulder kinematics and subacromial clearance. However, these authors quantified the "clearance" as a single measure in one dimension and did not attempt to relate the values to locations of relevant anatomy of interest. An in vivo study[40] in 4 healthy subjects investigated the effect of shoulder kinematics on the subacromial space using MRI. During passive supine positioned retraction and protraction, T1-weighted MR images were obtained and the width of the subacromial space in the sagittal and coronal planes were quantified as well as an acromial angle measurement, all from 2D slices of the MR images. The authors found reductions in the sagittal acromial angle and width of the subacromial space when comparing protraction to retraction. Finally, investigators have explored the relationship between kinematics and minimum bone-to-bone distances using gradient echo MR on 5 healthy subjects during arm abduction[38]. In general, in higher degrees of humeral elevation, the minimum distance from the acromion to the humerus was the smallest (2.4-7.0 mm). Also, at higher degrees of elevation the minimal acromiohumeral distance is located lateral to the supraspinatus. At 90 degrees of abduction with internal rotation, the minimal distance passed through the supraspinatus.

B.3.d. Kinematics during wheelchair activities

A few investigations of shoulder kinematics have been performed to quantify activities commonly performed by manual wheelchair users[28, 47-49]. Weight relief maneuvers were performed by 25 able-bodied subjects without shoulder pain and kinematics were measured using an electromagnetic tracking system and surface markers and analyzed using ISB standard techniques[48]. The weight relief task was discretized into 4 phases corresponding to preparation for the lift (phase1), lift (phase 2), hold (phase 3), and descent (phase 4). The scapula externally (by 5 degrees) and upwardly (by 4 degrees) rotates, and then tilts anteriorly (by 15 degrees) from the preparatory phase to the lift phase. Then, in transition to the hold phase, the scapula internally rotates (by 15 degrees), downwardly rotates (by 20 degrees), and the humerus internally rotates relative to the glenoid (by 20 degrees). Significant differences were found between the beginning of phases 1 and 2, and the beginning of phases 1 and 3, for scapular upward and internal rotation as well as for tilting. Significant differences between the beginning of phases 1 and 3 were found for internal rotation.

Recently[50], the same research team quantified scapulothoracic (3 rotations) and glenohumeral internal/external rotation kinematics in spinal cord injured subjects with and without shoulder pain using the same methodology. They did not detect differences between the two groups in any kinematic measure but they detected significant changes between phases 2 and 3 (lift and hold) for all measures. Between the lift and hold phase, they noted a 9.7 degree increase in downward rotation, a 7.0 degree increase in internal rotation, and a 4.9 degree increase in posterior tilt of the scapula as well as a 16.8 degrees increase in glenohumeral internal rotation.

Morrow[47] quantified scapula and humeral kinematics during level and ramp propulsion as well as during weight relief lifts in 12 manual wheelchair users using an optical-based motion capture system and a scapula tracker[34]. The scapula tracker data were transformed to anatomical coordinate systems (ISB standard) based on average digitized data from cadaveric specimens. While the magnitude of the values may have been affected by this methodology, the within-subject comparisons can help us gain insight into the global kinematic features of the movements. All tasks were characterized by positions of internal rotation and anterior tilt of the scapula, with peaks in internal rotation occurring near hand-off for propulsion and onset of hold for the weight relief. Peaks in anterior tilt occurred at the end of recovery for propulsion and did not vary much across the weight relief task.

Riek et al.[49] analyzed the shoulder kinematics of various activities of daily living in 5 spinal cord injured individuals using an electromagnetic device and ISB-standard techniques. They found that during the initial loading phase of the weight relief raise the scapular anterior tilt was significantly greater than in standing posture (using a standing frame) (28 degrees vs. 5 degrees). Additionally, during the initial and maximum loading phases, the humerus was significantly more internally rotated than in standing posture (15 degree and 38 degree differences, respectively).

Koontz et al.[85] and Lu et al.[28] both investigated the kinematics of wheelchair propulsion. The former study quantified the movement quasi-statically in 10 manual wheelchair users throughout the propulsion cycle using an optoelectric system to capture the torso and humerus position, and an optoelectric digitizer to capture landmarks on the scapula. ISB standard-definition Euler angles were determined. During the initial push, the scapula was slightly rotated upward (1.5 degrees), had minimal internal rotation (15 degrees), and was in maximal anterior tilt (22 degrees) and the humerus was maximally extended (31 degrees), abducted (28 degrees) and internally rotated (28 degrees). As the subjects moved through the propulsion, the scapula internal rotation increased and the anterior tilt decreased. Lu et al.[28] captured level propulsion kinematics in 5 healthy male volunteers using an ISB-standard approach and a video-based technique. A bone-pin mounted sensor was attached to the acromion while the humerus was tracked using surface sensors. During the propulsion, the scapula internally rotated through a range of 17 degrees (from 12 degrees of internal rotation to 29 degrees of internal rotation), downwardly rotated through a range of 8 degrees, and tilted posteriorly through a range of 8 degrees (from 16 degrees of anterior tilt to 8 degrees).

The question remains whether the position and orientation of the scapula during activities in this population are dictated by the constraints of the wheelchair and movement demands, or if these movement patterns can be altered with an intervention. In addition, it is unclear whether the altered movement patterns are extreme enough or alter the subacromial space in such a way to compromise the soft tissues lying within the space.

B.3.e. Subacromial space measurement

The volume and shape of the subacromial space is directly related to the position and orientation and anatomy of the humerus and scapula bones. Subacromial space itself has been quantified in vitro and in vivo by researchers using various measurement techniques and outcome measures during both static and dynamic experimental paradigms. Radiographic, ultrasound, and magnetic resonance imaging techniques as well as intraoperative measures have been utilized extensively in vivo to quantify a two-dimensional measure of acromiohumeral distance[86-95]. Images are obtained with the humerus in a static posture and measures are obtained manually from the 2-D images and are typically defined as the minimum linear distance between the inferior surface of the acromion and the head of the humerus. Radiographic and ultrasound techniques are inherently two-dimensional; however, the magnetic resonance investigations utilized only a single image slice for quantification in these investigations. Further, investigators have utilized imaging techniques which enabled them to capture the full three-dimensional geometry at the glenohumeral joint during quasi-static[38, 52] and dynamic[51] movements. However, measures of subacromial space were reported as linear distance measures rather than capitalizing on the three-dimensional data to determine volume or proximity maps. Graichen et al.[38] used an open MR scanner to image the shoulder of 5 healthy subjects quasi-statically during arm abduction. Following reconstruction of the 3-D bone geometry in each position, a Euclidean distance transformation (distance along straight line connecting two points in three-dimensional space) was used to determine the location at which the minimum linear distance occurred between the acromion and humeral head. In general, at higher degrees of abduction, the minimum distance from the acromion to the humerus is the smallest (2.4-7.0 mm). At 90 degrees of abduction with internal rotation, the minimal distance passes through the supraspinatus. Bey et al.[51] utilized a biplanar fluoroscopy shape matching technique to capture dynamic glenohumeral joint movement during shoulder elevation in a group of healthy normal subjects and following a rotator cuff repair surgery. A linear 3D distance from every defined point on the humeral head to those on the acromion was determined and the overall minimum value of all the distances was taken to be the subacromial space width. Subacromial space width decreased with elevation, with the minimum distance between the humerus and acromion passing through the anatomical region occupied by the supraspinatus tendon's insertion site, from 27.7° to 36.1° of elevation.

Zuckerman et al.[96] formulated a three-dimensional space measure while other investigators have quantified the relationship between space reduction and the underlying anatomical structures[17, 53]. Zuckerman et al.[96] quantified a true three-dimensional space measure in their in vitro investigation of cadaveric shoulder specimens with and without rotator cuff tears. They manually digitized four anatomical reference points in 140 shoulders from 70 cadavers and calculated 24 measures from these digitized values. Of importance, they defined the "supraspinatus outlet" which is the available area within the coracoacromial arch not intersected by the humeral head, calculated by subtracting the area of the humeral head within the coracoacromial arch from the calculated coracoacromial arch area. The study found that cadaver shoulders with full thickness rotator cuff tears have a significantly smaller supraspinatus outlet (22.5% smaller) when compared to intact shoulders. Soft tissue geometry as well as bone-to-bone distances were obtained by Flatow et al.[17] in a cadaveric investigation of subacromial contact during humeral elevation using radiographic (for bone-to-bone distances) and stereophotogrammetric (to assess contact on soft tissue) techniques in 9 specimens. Subacromial contact patterns were constructed with gray levels representing the proximity of one surface to the other, with important anatomical structures delineated. They found the acromial undersurface and rotator cuff tendons to be in closest proximity between 60 and 120 degrees of scapular plane abduction with the greater tuberosity lying close to the acromion undersurface. Pappas et al.[53] also emphasized the importance of underlying soft tissue structures in their in vivo investigation of eight normal patients using an open MR scanner. Three-dimensional surface models of the glenoid, coracoid, acromion, labrum, and supraspinatus, infraspinatus, and subscapularis insertion sites were created from the images and minimum distances were computed between the greater and lesser tuberosities and supraspinatus, infraspinatus, and subscapularis insertion sites on the humerus and the glenoid, acromion, and coracoid process of the scapula.

Recent research has combined the strengths of these previous investigations of subacromial space during shoulder movement by providing both a three-dimensional measure of space as well as quantifying the relationship of relevant anatomical structures to neighboring bony structures[54] during dynamic movement. Subject-specific CT image volumes were combined with the subject's kinematic measures, obtained using bone-fixed electromagnetic sensors, to model shoulder movements. A subacromial volume was defined as an extension of the supraspinatus outlet area described by Zuckerman et al.[96]. Linear minimal distances from the footprint of the rotator cuff muscles to potential impinging anatomical structures were determined. Finally, following the idea of Flatow et al.[17], proximity mapping of the distances from the humeral head to any point on the undersurface of the acromion (<2.5 mm, 2.5-5 mm, 5-7.5 mm) were determined to aid in interpretation of the relationship of soft tissue structures and bony anatomy.

B.3.f. Soft tissue/rotator cuff tendon thickness measurements

Knowledge of the geometry of the soft tissue lying within the subacromial space is important for understanding the potential for space narrowing to induce pain due to mechanical abrasion or impingement. While numerous investigations have quantified the length and width of the supraspinatus tendon[97-101], there is a paucity of literature which has quantified the thickness of the tendon. Collinger et al.[102] used clinical ultrasound in fifteen individuals, including 5 manual wheelchair users, to determine the thickness of the supraspinatus tendon in the widest part of the supraspinatus tendon. Mean values for the two raters were 4.87 and 4.78 mm. Manual measures taken on dissected, embalmed cadaveric specimens resulted in a mean supraspinatus thickness of 3.1 mm[103]. Recently, supraspinatus thicknesses were acquired in eight fresh-frozen cadaveric specimens at the most medial aspect of the supraspinatus. The anterior and posterior bundles were separated and measured using calipers. Mean values for the anterior and posterior bundles were 4.7 and 2.6 mm, respectively[104].

Given the limited investigations of the thickness of the soft tissue structures within the subacromial space during loaded movements in vivo, it is necessary to approximate the values given what is known.

B.4. Relevance of the proposed study

Manual wheelchair users rely on their shoulder musculature to perform all of their activities of daily living. However, up to 70% of manual wheelchair users report pain in the shoulder joint. Therefore, it is imperative to gain a better understanding of the mechanisms of shoulder pain in this population as well as which activities may be most responsible for this pain. Researchers report varied diagnoses in the manual wheelchair population, so the identification of the mechanisms is not entirely clear. However, the involvement of the anterior shoulder soft tissue components, along with cadaver-based and animal investigations, logically implicates narrowing of the subacromial space as a potential cause. The subacromial space is a function of the kinematics of the glenohumeral joint so the potential for underlying structures to be mechanically impinged during movement depends on both the three-dimensional shape of the space as well as the location of soft tissues relative to the overlying bony structures. Therefore, it is necessary to both record the glenohumeral and scapulothoracic kinematics as well as model the potential impact of these motions on the underlying anatomical structures to gain a better understanding of whether particular movements (i.e. propulsion or weight relief lifts) have more potential for inducing pain through subacromial space reduction in this population.

CHAPTER III

C. METHODS

C.1. Subject population

15 spinal cord injured individuals (25-59 yrs.; 13 males/2 females) with anterior shoulder joint pain who use manual wheelchairs as their primary means of mobility were recruited and consented for the study. Subjects were recruited as part of a larger IRB-approved study investigating the effectiveness of a rehabilitation intervention in this population (consent form, **Appendix 1**).

C.1.a. Physical exam and questionnaires

A physical exam was performed in the Mayo Clinic Motion Analysis Laboratory by a licensed physical therapist to determine if subjects qualified for the study. A patient history as well as observations and tests were performed including: instability tests, tendon palpation tests (bicipital groove, pectoralis minor, supraspinatus, infraspinatus), impingement exams (Neer[56], Hawkins-Kennedy[67]), and a crank test[105].

Subjects were invited to participate if they: were 18-60 years of age; had a spinal cord injury; had anterior shoulder pain during daily activities determined by the therapist to be consistent with a mechanical reduction of the subacromial space; used a manual wheelchair as their primary means of mobility in the home and community; were able to perform independent transfers and sit independently. Subjects were excluded if they had cognitive impairments that limited the ability to independently follow instructions; their pain was deemed to be of cervical origin; they had presence of adhesive capsulitis (loss of greater than 25% of range of motion); they had significant injury to the shoulder in which pre-injury status was not attained; or gross instability or suspected labral tears were noted. Finally, subjects were not included in the study if they had allergies to the adhesive tape used to attach the motion sensors. Subjects were pre-screened by a licensed physical therapist by phone; no subjects were excluded after the physical exam.

Following the informed consent process, subjects were asked to complete three questionnaires. The Wheelchair User Shoulder Pain Index (WUSPI)[64, 65] was scored as a 0 to 10 rating on 15 common daily activities. A total score of zero indicated no pain while 150 indicated severe pain. The Disabilities of the Arm, Shoulder, and Hand (DASH)[106] (**Appendix 2**) was scored and ranged from 0 (no limitations) to 100 (many limitations) on a 30-item questionnaire for measuring physical function and symptoms in the upper limb. Finally, subjects completed a Shoulder Rating Questionnaire (SRQ)[107] (**Appendix 2**) which included 21 items that measured severity of symptoms and functional status of the shoulder on a scale of 17 (very severe) to 100 (no symptoms).

C.1.b. Study risk

The risks in this study were minimal. The testing performed in the Motion Analysis Laboratory does not subject the participants to any risks that they would not already experience in the normal propulsion of their wheelchairs.

C.2. Data collection

C.2.a. Instrumentation

The three-dimensional position and orientation of the subject’s thorax, scapula, and humerus were quantified throughout the dynamic movements using a Liberty (Polhemus, Inc., Colchester, VT) electromagnetic tracking device and accompanying data collection/analysis software, MotionMonitor (Innovative Sports Training, Chicago, IL). The data collection system was integrated with a laptop personal computer. The data was sampled at a rate of 240 Hz per sensor using three sensors (RX2, 0.9" L x 1.1" W x 0.6" H, 0.32 oz.), and a digitizing stylus attached to a fourth sensor was used to digitize anatomical landmarks for assigning local anatomical coordinate systems to the scapula, humerus, and thorax. The reported static accuracy of the sensors relative to the transmitter of electromagnetic waves (TX2 extended range) is 0.15° root-mean-square (RMS) for orientation and 0.71 mm RMS for position at a distance of up to 1.5m from the transmitter. The MotionMonitor software provides graphical animations and data visualization during data collection, as well as the ability to perform simple data analysis tasks and exporting of data in numerous kinematic formats (i.e. Euler angles, transformation matrices, helical parameters).

C.2.b. Subject set-up

Subjects were asked to wear a sleeveless shirt or to remove their shirt to allow placement of the electromagnetic sensors on the subject’s skin over the anatomy of interest on his/her painful limb. Sensors (RX2, Pohemus, Inc.) were attached via double-sided medical-grade adhesive tape to the sternum (just beneath to the sternal notch), the skin overlying the flat superior surface of the scapular acromion process (just anterior to the posterior acromion), and to a thermoplastic cuff secured to the distal humerus (just proximal to the epicondyles). Three sizes of thermoplastic cuffs were available to ensure proper fit thereby reducing artifact due to motion of the cuff relative to the skin. Thin medical tape was secured over the sensors and attached to approximately 0.5 cm of adjacent skin to minimize sensor movement (**Figure C.7**). The same tape was used to create a guide for the acromial sensor cable, and was adhered to the subject's back.

Each subject's wheelchair was tested to determine if the metal composites in the chair frame interfered with the recording equipment by affixing two sensors to a rigid rod and sweeping the rod in the vicinity of the chair. Inter-sensor distance was displayed in real-time to observe variations due to metal interference. All subjects' wheelchairs were deemed acceptable so they used their own chairs during the data collection. The subject sat in his/her wheelchair atop aluminum rollers with a resistance that was similar to over ground propulsion; the resistance was the same for all subjects. The subject sat in a neutral posture with his/her hands in their lap as anatomical landmarks were palpated and digitized to define local anatomical coordinate systems on each body segment according to International Society of Biomechanics standards[36]. The shoulder joint center was defined using a functional approach: first, the humerus was passively moved through a series of motions spanning the shoulder range of motion; then, a sphere was fit to the humeral sensor data such that the radius defined the location of the joint center relative to the sensor. A licensed physical therapist trained in palpation techniques performed the digitization of anatomical landmarks for coordinate system definition for all subjects in the study. For the right arm, the anatomical X axis was positive anteriorly, the Y axis positive superiorly, and the Z axis positive laterally for all three segments. Left arm kinematic data was transformed to right-side equivalents prior to data processing. Verification of coordinate system setup and sensor placement were verified by collecting a trial of scapular plane abduction to confirm the rotation values obtained with previously-published values.

C.2.c. Experimental conditions

Before each activity, the movements were explained to the subject and they were encouraged to become familiar with the experimental setup and practice the movements. First, the subject was asked to rest his/her hands on his/her thighs and a neutral static posture was obtained. Then the subjects were asked to perform a single trial each of two repetitions of scapular plane abduction, treadmill propulsion, and weight relief raises. For the scapular plane abduction trials, subjects were asked to hold their instrumented arm in a neutral position, resting against their wheelchair hand rim (thumb oriented upward) and then move their arm through a full scapular plane abduction and adduction movement, at an angle oriented 40° anterior to the coronal plane. Subjects were asked to perform the movement at a self-selected speed, returning to contact the hand rim between trials. For the weight relief movement, the individual was asked to start with their hands in their lap, and then after a verbal clue, move at a comfortable pace and place their hands on the wheelchair hand rim, lift their weight until their arms were extended, and hold for two seconds before lowering their body weight; the second trial was performed identically. For propulsion, subjects were asked to start with their hands in their lap and then when verbally prompted to begin, proceed with placing their hands on the hand rim followed by at least two full propulsion movements in the style they normally use to propel. Electromagnetic data were sampled at 240 Hz throughout all movement cycles.

C.3. Methods for Aim 1- Quantify three-dimensional glenohumeral, scapulothoracic, and thoracic kinematics throughout level propulsion, weight relief, and scapular plane abduction in manual wheelchair users with shoulder pain.

C.3.a. Independent and dependent variables

Independent variables: task (propulsion, weight relief, scapular plane abduction), phase of movement (events)

Dependent variables: glenohumeral internal/external rotation, plane of elevation, and elevation angles, scapulothoracic internal/external, upward/downward, and anterior/posterior tilt angles, and trunk flexion/extension defined at each of the event times as well as maximum and minimum values across the trials.

C.3.b. Data analysis

A Fourier analysis of the sensor coordinate data for all three sensors during all three tasks was performed to reveal if higher order noise in the data was present (indicating a need to filter the kinematic data). Euler angles were generated to describe the position and orientation of the scapula relative to the thorax (scapulothoracic), the humerus relative to the scapula (glenohumeral), and the humerus relative to the thorax (humerothoracic) at each frame. The ISB standard definitions were used for the scapulothoracic (YX'Z"), humerothoracic (YX'Y"), and thorax (ZX'Y") rotations; however, an alternative sequence[77] was used to describe glenohumeral rotations (XZ'Y") to avoid singularity positions near the neutral position.

After obtaining the kinematics, movement events were defined for each task (**Figure C.8**). The four events for weight relief were chosen interactively based on the vertical displacement of the trunk sensor. The start of the raise (event 1, WR) was chosen as an upward vertical displacement. The start of the hold (event 2, WR) was chosen as the end of the upward vertical displacement. The end of the hold (event 3, WR) was chosen as the initiation of downward vertical movement of the trunk sensor. And, the return to the start position (event 4, WR) was chosen as the end of downward vertical movement of the trunk. The four propulsion events were also selected interactively, but were based on the humerothoracic plane of elevation rotation values (**Appendix 3**). The start of propulsion (event 1, PROP) was chosen as the initiation of forward movement of the humerus. The point that the hand left the hand rim at the end of the push phase (event 3, PROP) was chosen as the end of forward movement of the humerus. Half way through the push phase (event 2, PROP) was calculated as half the time to event 3. The end of propulsion (event 4, PROP) was chosen as the end of backward movement of the humerus. Scapular plane abduction events were determined automatically based on the humerothoracic elevation values. The start of scapular plane abduction (event 1, SCAP) was selected as the time at which 25 degrees of elevation occurred. Events 2, 3, and 4 were defined as the times at which 37, 49, and 61 degrees of elevation occurred, respectively. 25 degrees was chosen as the minimum elevation value that all subjects could attain while seated in their wheelchairs. 61 degrees was chosen as the expected peak elevation for the other two tasks and was chosen so that all three tasks were taking place in similar regions of the movement space. Values for all seven dependent variables (three glenohumeral, three scapulothoracic, and trunk flexion/extension rotations) were selected from the time series curves based on the event times described above.

The reliability of the four events for each variable, for each task, were determined using intraclass correlation coefficients and standard errors of measurement[108] as:

$$\mathrm{ICC}(1,1) = \frac{\mathrm{BMS} - \mathrm{WMS}}{\mathrm{BMS} + \mathrm{WMS}}$$

where BMS is the between-subjects mean square and WMS is the within-groups (error) mean square as obtained from a one-way ANOVA in which subjects were treated as the independent variable. The standard error of measurement was determined as the square root of WMS[109]. The last movement trial for each task was used for the statistical analysis.

C.3.c. Statistics

A search of the literature revealed no previous studies that have looked at within subject measures of linear distances during propulsion, weight relief, and scapular plane abduction in wheelchair users with shoulder pain. Therefore, it was necessary to utilize the first five subjects' data to perform a power/sample size analysis. A paired t-test was performed on the minimum linear distance values for each of the three muscles; differences that could be detected between any 2 of the 3 tasks were determined at 80%

power (given 15 subjects). Additionally, sample sizes were estimated that had 70, 80, and 90% power to detect a 3 mm differences in linear distances between any two tasks.

For Aim 1 analyses, the normality of the data was determined for each data cell. If necessary, non-parametric statistics were used for the analysis containing the values in question. The statistical approach for this aim included separate one-way repeated measures ANOVAs with either the task condition (propulsion, weight relief, and scapular plane abduction) or the phase of movement (four events) as within-subject factors. The data was checked for sphericity. If the Mauchly's criterion was violated, the p values were corrected; bonferroni post-hoc tests were used in all instances. All statistical analyses were performed using SAS Enterprise Guide 4.3 (Cary, NC).

C.3.d. Potential covariates

Potential covariates for this analysis included age, height, injury level, years of wheelchair use, and level of pain (WUSPI). Coefficients of variation (R^2) were determined between these values and the dependent variables with a threshold of 0.5 for inclusion in the statistical model.

C.4. Methods for Aim 2- Assess risk of damage to the rotator cuff by quantifying a) the minimum linear distances from the coracoacromial arch to the rotator cuff tendons throughout level propulsion, weight relief, and scapular plane abduction, and b) the proximity maps between the tendon footprints and coracoacromial arch during tasks demonstrating significant risk in a).

C.4.a. Independent and dependent variables

Independent variables: task (propulsion, weight relief, scapular plane abduction)

Dependent variables: minimum linear distances between the supraspinatus, infraspinatus, and subscapularis tendon footprints and the acromion; minimum linear distances between the supraspinatus, infraspinatus, and subscapularis tendon footprints and the coracoacromial ligament; and proximity maps between the tendon footprints and the overlying structures at the point during the trials when the distances were at a minimum.

C.4.b. Model description and simulations

Reconstructed left-sided humerus and scapula bone surface models (comprised of triangular mesh elements) were defined based on a previously-acquired CT scan (1 mm slice thickness) from an individual of similar stature to the subjects in this study (gender: male, height: 168cm, weight: 79.5kg); coordinate systems were defined on the bone surface models identically to the method used in vivo[36]. Each subject's respective glenohumeral rotation values (in 2% increments of each task) were then used to model the motion for all three tasks using a custom Matlab program. All kinematic data were transformed to the left-hand equivalent prior to using as input to the the left-sided bone model. The humeral head was centered on the glenoid for all simulations; this was justified based on in vivo bone-pin data of various shoulder movements (**Appendix 4**). This process included first fitting the humeral head to a sphere, and the lower glenoid to a circle, using an optimization approach. The radius of the sphere and perpendicular to the plane of the circle were subsequently defined. The humeral head center was defined as the center of the sphere, and the center was positioned on a line perpendicular to the glenoid plane, at a lateral distance equal to the humeral head, plus 2.5 mm. The additional 2.5 mm is to account for the articular cartilage on the glenoid and humeral head that is not accounted for in the CT scan[110-112]. In each position, proximity maps and linear distances were determined.

C.4.c. Data analysis

The footprint areas of the rotator cuff muscles (supraspinatus, infraspinatus, and subscapularis) were previously identified on the 3D humerus surface model using CT images of the same individual (**Figure C.9**). The Euclidean distances between all of the points on the surface mesh model within each tendon insertion footprint to all points on the undersurface of the acromion and coracoacromial ligament surface meshes were determined using a custom Matlab program. Mean edge lengths for the triangles comprising the surface meshes for the acromion, coracoacromial ligament, supraspinatus, infraspinatus, and subscapularis meshes were: 1.2, 1.6, 0.7, 0.7, and 0.7 mm respectively. Proximity maps were generated on the tendon footprint meshes as well as on the underside of the acromion and coracoacromial ligament; these are color mapped areas representing the minimum Euclidean distance values from 0-5 mm. Using the surface normals of the mesh elements on both surfaces, the program ensured that a distance was not calculated if more than 90 degrees existed between the two surface normals, preventing distances from being measured through bone interiors or other spurious directions. For each glenohumeral position throughout the trials, the areas of the proximity maps that fell within a 2.0 mm threshold (0.0-2.0 mm) and the areas that fell within a 5.0 mm threshold (0.0-5.0 mm) were calculated. The minimum distance values for each time step were determined as the minimum value across the entire proximity map for the given glenohumeral position. Finally, after the minimum linear distances were determined for the complete trials, a measure of injury risk was defined as the area between the linear distance versus time curve and the 5.0 mm threshold for all portions of the movement in which the linear distance lay below 5.0 mm. Risk was expressed in units of mm-% (where % indicates percent cycle) to account for differences in movement times.

C.4.d. Statistics

The normality of the data was determined within each data cell. If necessary, non-parametric statistics were used for the analysis. The statistical approach for this aim included a one-way repeated measure ANOVA with task condition (propulsion, weight relief, and scapular plane abduction) as the within-subject factors and minimum distances (for all three muscles summed together, and for each muscle individually) and risk (summed across all three muscles, and summed across supraspinatus and infraspinatus) as the outcome measures. Additionally, paired t-tests (Wilcoxon signed rank tests for nonparametric comparisons) were used to assess the difference in proximity areas for infraspinatus and supraspinatus within each task (one area value per subject per muscle per task), as well as the difference in proximity area between propulsion and scapular plane abduction for each of the muscles (one area value per subject per task per muscle). For all analyses, alpha was set at 0.05 and Bonferroni post-hoc analysis was used. All statistics were completed using SAS Enterprise 4.3 (Cary, NC).

C.4.e. Potential covariates

Potential covariates for this analysis included age, height, injury level, years of wheelchair use, and level of pain (WUSPI). Coefficients of variation (R^2) were determined between these values and the dependent variables with a threshold of 0.5 for inclusion in the statistical model.

C.5. Methods for Aim 3- Determine a) the sensitivity of linear distances to glenohumeral rotation and humeral translation changes, and b) the ability of glenohumeral and trunk flexion/extension rotation values to predict linear distances during weight relief, propulsion, and scapular plane abduction using a regression approach.

C.5.a. Analysis

A representative subject (subject 14) was selected from the study participants for the analysis based on the subject's kinematics; they fell within the midrange of all subjects for all three tasks. Following the nominal value simulations (**C.4.b.**), simulations were run for a) ± 3.0 and ± 6.0 degree increments about the subject's measured values of glenohumeral elevation, horizontal abduction, and axial rotation, and b) ± 2.0 mm incremental translations of the humeral head in the anterior, posterior, superior, and inferior directions. The incremental rotation values (3.0, 6.0 degrees) were selected based on previous reports of error in skin surface marker methods as compared to bone-fixed marker values in the range of humerothoracic elevation relevant to the three tasks (approximately 30-60 degrees)[34, 113]. The incremental translation value (2.0 mm) was obtained from literature reports of humeral translation values during arm raise tasks[72, 73,

[114]. Rotations and translations were imposed on the model independently, and the minimum linear distances (to the acromion and coracoacromial ligament) were calculated identically to **C.4.c**. In addition, a measure of injury risk was defined for all portions of the movement in which the linear distance lay below 5.0 mm. Calculated as the area between the 5.0 mm threshold and the linear distance curves, each trial resulted in one risk value, expressed in mm-%.

C.5.b. Regression

To determine the ability of glenohumeral and trunk flexion/extension angular kinematics to predict minimum linear distances between the acromion and supraspinatus and infraspinatus, a multiple regression model was generated for each task. The three glenohumeral rotations, and trunk flexion/extension were the predictor variables and the linear distances to the acromion from the infraspinatus and supraspinatus footprints were the response variables. Coefficients of determination (R^2) between the predictors were determined within subjects for each task to decide which predictors to include in the regression model (to satisfy the independence assumption). If 60% of the subjects had an R^2 of 0.8 or greater between two predictors, only one was included in the model. Independent predictors were included in the model if they significantly predicted the response variable ($p< 0.05$) using a linear regression approach. A multiple regression approach was run for each task including the appropriate predictors, and significant parameter estimates ($p < 0.05$) were explored. For the multiple regression analysis, the predictor and response variables were down sampled from 51 time points to 11 time points for each movement.

CHAPTER IV

D. RESULTS

In the respective plots for each statistical analysis, letters indicate statistical significance. Data with different letters have been determined to be significantly different ($p < 0.05$) using the described statistical approach. In addition, all differences described in the text are significant differences.

D.1. Power analysis

Power analysis after the first five subjects' data collections and analysis informed that a difference between any two conditions of 3.4, 2.7, and 2.0 mm for the infraspinatus, supraspinatus, and subscapularis, respectively, could be determined at 80% power. Additionally, sample sizes to detect a 3 mm effect size between any two tasks were determined at 70% power (n=15, 10, and 7 for infraspinatus, supraspinatus and subscapularis, respectively), 80% power (n=19, 13, and 8 for infraspinatus, supraspinatus and subscapularis, respectively), and 90% power (n=25, 16, and 10 for infraspinatus, supraspinatus and subscapularis, respectively).

D.2. Subjects

Fifteen subjects (13 males, 2 females) were recruited according to the recruitment criteria for study participation. Subjects had a mean age of 39 years, mean weight of 81 kg, and averaged 14 years of manual wheelchair use (**Table D.2**). Subjects' injury levels ranged from C6-7 to L2 with one subject who was post-polio that presented clinically as a lower lumbar spinal cord injury. Physical examination findings were variable across subjects (**Tables D.3 and D.4**) including 6 with positive Speed's test, 4 with positive Neer's test, 8 with positive Hawkins-Kennedy test, and 7 with positive empty can test. Glenohumeral orientations with subjects' hands on top dead center on their hand rim (**Table D.5**) varied across subjects. Glenohumeral elevation varied from near zero to 30.8 degrees of elevation; glenohumeral horizontal abduction varied from 2.8 to 37.3 degrees; and glenohumeral axial rotation ranged from 3.7 degrees of internal rotation to 55.1 degrees of external. Camber ranged from 0 to 10 degrees, with most chairs at 5 degrees of camber, and seat dump ranged from 0 to 15 degrees. Finally, in their normal seated posture, subjects' shoulder joint centers ranged from 10 cm anterior to 7 cm posterior to their wheelchair axis.

Subjects' responses on three questionnaires were rated according to the appropriate respective guidelines (**Table D.6**). The Wheelchair User Shoulder Pain Index (WUSPI) scores ranged from 1.2 to 62 with a mean value of 37.9. The Disabilities of the Arm, Shoulder, and Hand (DASH) scores ranged from .8 to 52.5, with a mean value of 27.8. Finally, subjects' Shoulder Rating Questionnaire (SRQ) had a mean value of 72.0. One subject omitted questions worth 15 points on the survey and had the lowest score of 36.2. The next lowest value was 47.7, while the greatest was 95.6.

D.3. Processing of kinematic data

Cartesian coordinate data (X, Y, Z) for all three electromagnetic sensors (acromion, humerus, and trunk) for all trials were analyzed using a Fast Fourier Transform (FFT) to assess the frequency components of the kinematic data. For all weight relief and scapular plane abduction trials, the frequency components of the signals remained below 1.0 Hz and for all propulsion trials, frequencies remained below 2.0 Hz. Given the lack of higher order frequencies in the signals, no filtering was performed on the kinematic data. Event data were selected from the final two trials of movement for each task; weight relief, propulsion, and scapular plane abduction.

Repeatability of trial event data for all seven outcome variables, for all three movement tasks, were determined using intraclass correlation coefficients ICC(1,1) and standard errors of measurement (SEMs). The mean ICC value for weight relief was .92 (range, .62-.99); the mean SEM was 2.3 degree (range, 1.0-5.7 degrees). The mean ICC for propulsion was .95 (range, .84-1.00) with a mean SEM of 1.6 degrees (range, 0.6-3.8 degrees). Scapular plane abduction had a mean ICC of .98 (range, .93-1.00) with mean SEM of 1.1 degrees (range, 0.7-1.5 degrees). Due to the high repeatability of the data, the second trial was used for further analysis in the study.

Linear regression was used to determine if covariates correlated with any outcome measures. For each task, the event data for each outcome variable for all subjects were regressed against each covariate in turn to assess whether a linear relationship existed. Covariates included age, weight, level of injury, years of wheelchair user, and WUSPI scores. None of the models reached an R^2 of .5 so covariates were not included in subsequent analyses.

D.4. RESULTS AIM 1: Quantify three-dimensional glenohumeral, scapulothoracic, and thoracic kinematics throughout level propulsion, weight relief, and scapular plane abduction in manual wheelchair users with shoulder pain.

D.4.a. Event data analysis (between tasks) (Figure D.10)(Appendix 5)

The repeated measures ANOVA approach included the mean of all four events for each task, for each of the seven outcome measures. Skewness and kurtosis were assessed for the event data for each task and they were found to range from -1.3 to 1.1.

D.4.a.1. Hypothesis testing

H1.1: Propulsion will result in greater scapular internal rotation than weight relief and scapular plane abduction.

Analysis of the event data between tasks did not result in greater scapular internal rotation during propulsion. Scapular plane abduction had greater scapular internal rotation than both weight relief and propulsion (32.0 vs. 25.7 and 28.5 degrees of scapular internal rotation)(F(2,28)=11.14,p=.0003).

H1.2: Weight relief will result in greater scapular anterior tilting than propulsion and scapular plane abduction.

Analysis of the event data between tasks did not fully support this hypothesis. Anterior tilt was greater in weight relief and propulsion than during scapular plane abduction (23.5, 22.9, and 12.9 degrees of anterior tilt, respectively)(F(2,28)=51.03,p<.0001). Weight relief and propulsion were not significantly different with respect to anterior tilt.

H1.3: Weight relief will produce glenohumeral axial rotation that is more internally rotated than propulsion and scapular plane abduction.

Event data analysis supported this hypothesis. Glenohumeral axial rotation during weight relief was more internally rotated than during propulsion (9.0, 26.0, and 51.0 degrees of external rotation, respectively)(F(2,28)=121.42,p<.0001). Propulsion, in turn, resulted in more internal rotation than scapular plane abduction.

D.4.a.2. Other outcome measure results

Analysis of event data resulted in glenohumeral elevation values that were significantly greater during scapular plane abduction than propulsion, which was in turn greater than weight relief (34.0, 18.0, and 4.3 degrees of elevation, respectively) (F(2,28)=184.98,p<.0001). Glenohumeral horizontal abduction was found to be greater during propulsion than weight relief, which was in turn greater than scapular plane abduction (14.8, 7.5 degrees of horizontal abduction, and 14.7 degrees of horizontal adduction, respectively)(F(2,28)=82.48,p<.0001). Scapulothoracic upward rotations were greater during scapular plane abduction (9.6 degrees) and weight relief (8.4 degrees) than propulsion (0.3 degrees); no differences were found between scapular plane abduction and weight relief (F(2,28)=22.79,p<.0001). Trunk flexion was greater during weight relief (12.0 degrees) and propulsion (12.9 degrees) than scapular plane abduction (4.2 degrees); no differences were found between propulsion and weight relief(F(2,28)=17.97,p<.0001).

D.4.b. Peak rotation data analysis (between tasks) (Figures D.11-D.15)

Skewness and kurtosis for the event data for each task were found to lie between -1.1 and 1.2, and between -1.3 and 1.7, respectively. Mean static kinematics from subjects' natural seated posture were included in **Figures D.13-D.15** for reference and comparison to ranges of motion.

D.4.b.1. Hypothesis testing

H1.1: Propulsion will result in greater scapular internal rotation than weight relief and scapular plane abduction.

Analysis of the maximum and minimum scapular internal rotation data did not fully support this hypothesis. While propulsion (39.4 degrees) resulted in greater internal rotation than scapular plane abduction (33.5 degrees), it did not significantly differ from weight relief values (35.2 degrees)(F(2,28)=4.07,p=.0282).

H1.2: Weight relief will result in greater scapular anterior tilting than propulsion and scapular plane abduction.

Analysis of the scapular anterior tilt partially supported this hypothesis. Peak anterior tilt during weight relief (28.0 degrees) was greater than scapular plane abduction (14.3 degrees) but not significantly different than propulsion (27.6 degrees)(F(2,28)=40.83,p<.0001).

H1.3: Weight relief will produce glenohumeral axial rotation that is more internally rotated than propulsion and scapular plane abduction.

This hypothesis was supported by the analysis. Maximum glenohumeral internal rotation was greater during weight relief (0.4 degrees of external rotation) than propulsion (18.6 degrees of external rotation) and scapular plane abduction (41.2 degrees of external rotation)(F(2,28)=75.44,p<.0001).

D.4.b.2. Other outcome measure results

Analysis of maximum and minimum rotation values resulted in the following findings. Maximum (F(2,28)=58.15,p<.0001) and minimum (F(2,28)=231.12,p<.0001) glenohumeral elevations were greater for scapular plane abduction than propulsion, which was in turn greater than weight relief. Values for maximums and minimums during all tasks remained in an elevated position. Glenohumeral horizontal abduction was greater in propulsion than weight relief which was greater than scapular plane abduction (which did not reach horizontal abduction)(F(2,26)=126.26,p<.0001). Glenohumeral horizontal adduction was greater in scapular plane abduction than propulsion which in turn was greater than weight relief (F(2,28)=17.19,p<.0001). Scapular upward rotation was greater during scapular plane abduction and weight relief than propulsion (F(2,28)=14.49,p=.0004). Finally, peak trunk flexion during weight relief and propulsion were greater than during scapular plane abduction (F(2,28)=35.44,p<.0001).

D.4.c. Event data analysis (within tasks) (Figures D.16, D.17, D.18)

Skewness and kurtosis for the event data for each task were between -0.48 and 2.8, respectively.

D.4.c.1. Hypothesis testing

H1.4: The hand-off position during propulsion will be characterized by a) more scapular internal rotation and b) less glenohumeral internal rotation than early (hand-on) and mid-propulsion positions.

H1.4a was supported by the results of the analysis. The scapulothoracic internal rotation was greater at hand off (38.6 degrees) than at 50% of push (24.7 degrees), which was in turn greater than the two hand on positions (19.5 and 20.2 degrees, respectively) (F(3,42)=82.55,p<.0001). *H1.4b* was not supported by the analysis; glenohumeral internal rotation did not differ across the four events during propulsion (27.0, 25.5, 23.9, and 27.5 degrees of external rotation, respectively).

H1.5: The hold phase (events 2 and 3) of weight relief will result in a) greater scapular internal rotation and b) glenohumeral internal rotation than the lift phase (event 1).

Both a) and b) were supported by the analysis. Events 2 and 3 (the hold phase) had significantly greater scapular internal rotation (34.2 and 33.9 degrees) than event 1 (lift phase, 23.4 degrees)(F(3,42)=49.98,p<.0001). Events 2 and 3 were more internally rotated at the glenohumeral joint (2.3 and 2.7 degrees of glenohumeral external rotation, respectively) than event 1 (16.7 degrees of glenohumeral external rotation)(F(3.42)=17.49,p=.0002).

H1.6: Late scapular plane abduction (event 4) will result in a) greater scapular upward rotation and b) glenohumeral external rotation than the early phases (events 1 and 2).

H1.6 a) and b) were supported by the analysis. Event 4 (61 degrees of elevation) resulted in greater scapular upward rotation (14.0 degrees) (F(3,42)=63.68,p<.0001) and glenohumeral external rotation (60.2 degrees) (F(3,42)=256.20,p<.0001) than events 1 (5.8 and 41.2 degrees) and 2 (7.7 and 48.2 degrees) which corresponded to the start (25 degrees of elevation) and 37 degrees of elevation positions.

D.4.c.2. Other outcome measure results

Weight relief

Events 1 and 4 (start and end) do not differ for any of the outcome measures for the weight relief task. Similarly, events 2 and 3 (begin hold and end hold) do not differ for any outcome measures. Glenohumeral elevation is greater during events 1 and 4 (7.2 and 9.8 degrees) than events 2 and 3 (0.1 and 0.1 degrees)(F(3,42)=19.01,p=.0002). The glenohumeral joint is more horizontally abducted at events 1 and 4 (18.9 and 14.4 degrees of horizontal abduction) than at events 2 and 4 (1.8 and 1.4 degrees of glenohumeral horizontal adduction)(F(3,42)=34.47,p<.0001). There were no significant differences across events for the scapulothoracic upward rotation or anterior tilt. Trunk flexion at event 1 (14.7 degrees) was greater than at event 2 (9.6 degrees)(F(3,42)=4.58,p=.0168).

Propulsion

Events 1 and 4 (hand on positions) do not differ for any of the outcome measures. Glenohumeral elevation was greater at event 3 (hand off, 30.7 degrees) than at events 1, 2 (50% of push), and 4 (12.2, 17.2, and 12.2 degrees, respectively)(F(3,42)=33.03,p<.0001). The glenohumeral joint was more horizontally adducted at hand off (11.2 degrees of glenohumeral adduction) than at the other events(F(3,42)=192.27,p<.0001). Scapulothoracic upward rotation was greater at 50% of the push phase (4.2 degrees) than at the other event times (F(3,42)=8.63,p=.0034). Scapulothoracic anterior tilt was greater at events 1 and 4 (hand on positions, 26.8 and 26.2 degrees) than at event 2 (50% of push phase, 22.3 degrees) which, in turn, was greater than event 3 (hand off, 16.4 degrees)(F(3,42)=33.27,p<.0001). Finally, the trunk was more extended at hand off (9.1 degrees) than at the 3 other event times (14.6, 14.5, and 13.3 degrees)(F(3,42)=13.67,p=.0003).

Scapular plane abduction

Events 1-4 resulted in progressively increasing glenohumeral elevation values (20.5, 29.1, 38.6, and 47.7 degrees, respectively). However, glenohumeral horizontal abduction did not differ across events (15.1, 15.1, 15.0, 13.8 degrees of glenohumeral adduction, respectively). Scapulothoracic axial rotation did not change across events, remaining internally rotated (31.2, 31.8, 32.3, and 32.8 degrees respectively. Scapulothoracic anterior tilt decreased from event 1 to 2 (14.2 and 13.3 degrees) and 2 to 3 (13.3 and 12.4 degrees)(F(3,42)=23.58,p<.0001). However, events 3 and 4 were not different (12.4 and 11.7 degrees). Trunk flexion did not change across events for the scapular plane abduction movement.

D.5. RESULTS AIM 2: Assess risk of damage to the rotator cuff by quantifying: a) the minimum linear distances from the coracoacromial arch to the rotator cuff tendons throughout level propulsion, weight relief, and scapular plane abduction, and b) the proximity maps between the tendon footprints and coracoacromial arch during tasks demonstrating significant risk in a) .

Linear regression was used to determine if covariates correlated with minimum distance data within each task. For each task, the minimum distance data for each outcome variable for all subjects were regressed against each covariate in turn to assess whether a linear relationship existed. Covariates included age, weight, level of injury, years of wheelchair user, and WUSPI scores. None of the models reached an R^2 of .5 so covariates were not included in subsequent analyses.

D.5.a. Minimum distance data analysis (between tasks) (Figure D.19) (Appendix 6)

First, the mean of the minimum distances for all three muscles were included in the analysis between tasks for each anatomical structure, the acromion and coracoacromial ligament. Subsequently, the minimal distances for each of the muscles alone were compared across tasks. The skewness of the distance data for each task was found to lie between -0.6 and 1.3 and the kurtosis between -1.1 and 1.1.

D.5.a.1. Hypothesis testing

H2.1: There will be significant differences in minimal distances to the coracoacromial arch across tasks.

Minimal distance to the acromion was found to be greater for weight relief (14.4 mm) than propulsion (6.9 mm) , which was in turn, greater than scapular plane abduction (4.7 mm)(F(2,28)=81.09,p<.0001). Minimal distance to the coracoacromial ligament was found to be smaller during propulsion (7.7 mm) than during either weight relief (12.4 mm) or scapular plane abduction (12.5 mm)(F(2,28)=18.04,p<.0001).

D.5.a.2. Other outcome measure results (Figures D.20, D.21, D.22)

The minimum distance to the acromion from the infraspinatus footprint was found to be smaller for propulsion (1.7 mm) than either weight relief (6.5 mm) or scapular plane abduction (5.2 mm)(F(2,28)=13.77,p<.0001). Minimal distance to the coracoacromial ligament was found to be greater for scapular plane abduction (20.9 mm) than either weight relief (10.8 mm) or propulsion (7.6 mm)(F(2,28)=38.65,p<.0001). The minimal distance from the supraspinatus footprint to the acromion was significantly greater for weight relief (7.6 mm) than either propulsion (1.7 mm) or scapular plane abduction (2.6 mm)(F(2,28)=29.9,p<.0001). The minimal distance from the supraspinatus footprint to the coracoacromial ligament was smaller during propulsion (4.6 mm) than either weight relief (8.2 mm) or scapular plane abduction (9.3 mm)(F(2,27)=15.69,p<.0001). Finally, the minimum distance from the subscapularis footprint to the acromion was found to be smaller for scapular plane abduction (6.4 mm) than for propulsion (17 mm) which, in turn, was less than during weight relief (29 mm) (F(2,28)=233.47,p<.0001). Minimum distance to the coracoacromial ligament from the subscapularis showed the same trend with values of 6.3, 10.7, and 18 mm during scapular plane abduction, propulsion, and weight relief, respectively (F(2,28)=28.88,p<.0001).

D.5.b. Risk data analysis (between tasks) (Figures D.23 and D.24)

Calculated as the area between the 5.0 mm threshold and the linear distance curves, each trial resulted in one risk value. A maximum risk value if the distance were 0.0 across 100% of a movement cycle, would equate to 5.0 (difference between 5.0 mm threshold and 0.0) x 100% cycle = 500 mm-%. The analysis was performed first by summing the risk for all three muscles, followed by analysis of the sum of supraspinatus and infraspinatus. The data was confirmed to be non-normal by assessing the kurtosis and skewness values (0 to 3.9 skewness, -0.9 to 15.0 kurtosis). A Friedman’s procedure was used to assess the differences across task; it is a repeated measures nonparametric test that is used for one-way ANOVA comparisons.

D.5.b.1 Hypothesis testing

H2.1: There will be significant differences in risk to the coracoacromial arch across tasks.

With all three muscles' risk summed together, the risk of mechanical impingement with the acromion was greater in propulsion (334 mm-%) and scapular plane abduction (277 mm-%) than during weight relief (6 mm-%)(F(2,28)=23.32,p<.0001). With only the supraspinatus and infraspinatus risk values summed, the risk of acromial impingement was, once again, greater in propulsion (334 mm-%) and scapular plane abduction (269 mm-%) than in weight relief (2 mm-%)(F(2,28)=24.79,p<.0001). With all three muscles included, the risk of mechanical impingement with the coracoacromial ligament was greater in propulsion (37 mm-%) than weight relief (6 mm-%) but not greater than scapular plane abduction (27 mm-%)(F(2,28)=5.24,p=.0117). With supraspinatus and infraspinatus only, propulsion (35 mm-%) was greater than weight relief (6 mm-%) and scapular plane abduction (4 mm-%)(F(2,27)=7.57,p=.0025).

D.5.d. Proximity maps for distances less than 5.0 mm

Since minimum linear distance and risk measures implicated supraspinatus and infraspinatus risk (with the acromion) during the activities of propulsion and scapular plane abduction, these were the focus of the proximity analysis.

D.5.d.1. Supraspinatus to acromion (propulsion) (Figure D.25)

One subject did not exhibit a proximity less than 5.0 mm between the supraspinatus tendon footprint and the overlying acromion. Proximity between the supraspinatus footprint and the overlying acromion, at the time when minimum distance between the two structures occurred during propulsion, was similar across the rest of the subjects. For most subjects, the proximity was below 5.0 mm on the underside of the acromion, in the anterolateral region of the structure. The region of the supraspinatus footprint where this generally occurred was in the lateral or posterolateral region.

D.5.d.2. Supraspinatus to acromion (scapular plane abduction) (Figure D.26)

Three subjects did not have proximities of less than 5.0 mm between the supraspinatus and acromion during scapular plane abduction. Proximity between the supraspinatus footprint and the overlying acromion, at the time when minimum distance between the two structures occurred during scapular plane abduction, was similar across subjects. For most subjects, the proximity was below 5.0 mm on the underside of the acromion, in the mid-acromial region of the structure. The region of proximity was more posterior on the acromion than during propulsion. The region of the supraspinatus footprint where this generally occurred was in the lateral or anterolateral region.

D.5.d.3. Infraspinatus to acromion (propulsion) (Figure D.27)

Proximity between the infraspinatus tendon footprint and the overlying acromion, at the time when minimum distance between the two structures occurred during propulsion, was similar across subjects. For most subjects, the proximity was below 5.0 mm on the underside of the acromion, in the anterolateral and mid-acromial regions of the structure. The region of the infraspinatus footprint where this generally occurred was in the lateral or anterolateral region.

D.5.d.4. Infraspinatus to acromion (scapular plane abduction) (Figure D.28)

Proximity between the infraspinatus footprint and the overlying acromion, at the time when minimum distance between the two structures occurred during scapular plane abduction, was similar across subjects. For most subjects, the proximity was below 5.0 mm on the underside of the acromion, in the midacromial to posterolateral region of the structure. The proximity occurred in a more posterior location than during propulsion. The region of the infraspinatus footprint where this generally occurred was in the lateral or anterolateral region.

D.5.d.5. Proximity areas (Tables D.7 and D.8)

The supraspinatus proximity area within a 2.0 mm threshold was greater than the infraspinatus area for both propulsion ($p=.0010$) and scapular plane abduction ($p=.0078$); the supraspinatus area within a 5.0 mm threshold was greater than infraspinatus for scapular plane abduction ($p=.0005$). Significant differences were seen between the two tasks for the infraspinatus areas within 2.0 mm ($p=.0174$) and 5.0 mm ($p<.001$) with larger areas during propulsion. Differences between tasks for the supraspinatus areas were not significant. The smallest area was seen in the scapular plane abduction task at 2.0 mm with a value of 2.0 mm^2. Some subjects did not have proximities of less than 5.0 mm and more subjects lacked proximities less than 2.0 mm.

D.6. RESULTS AIM 3: Determine a) the sensitivity of linear distances to glenohumeral rotation and humeral translation changes, and b) the ability of glenohumeral and trunk flexion/extension rotation changes to predict linear distances during weight relief, propulsion, and scapular plane abduction.

D.6.a. Sensitivity analysis

D.6.a.1. Rotations/Linear distances

Propagation of changes in glenohumeral rotation values resulted in mean peak absolute differences in linear distances to the acromion (**Figure D.29**) across muscles and movement directions of 1.5(0.7), 1.5(0.5), and 1.3(0.4) mm in weight relief, propulsion, and scapular plane abduction tasks, respectively, with 6 degree changes. 3 degree changes resulted in 0.7(0.3), 0.8(0.3), and 0.7(0.2) mm values in weight relief, propulsion, and scapular plane abduction, respectively. During weight relief, glenohumeral elevation had the greatest effect on infra- and supraspinatus distance values while glenohumeral horizontal abduction had the greatest effect on the subscapularis distance values. During propulsion, the subscapularis was most affected by glenohumeral axial rotation while glenohumeral elevation had a great effect on all three muscles. During scapular plane abduction, the subscapularis was most affected by glenohumeral elevation and the infraspinatus by glenohumeral axial rotation.

Propagation of rotation changes in glenohumeral rotation values resulted in mean peak absolute differences in linear distances to the coracoacromial ligament (**Figure D.30**) across muscles and movement directions of 1.4(0.8), 1.5(0.7), and 1.4(0.8) mm in weight relief, propulsion, and scapular plane abduction tasks, respectively, with 6 degree changes. 3 degree changes resulted in 0.7 (0.4), 0.8 (0.3), and 0.7 (0.4) mm values in weight relief, propulsion, and scapular plane abduction, respectively. During weight relief, glenohumeral elevation had the greatest effect on infra- and supraspinatus distance values while glenohumeral horizontal abduction and elevation had variably high values during propulsion and scapular plane abduction.

D.6.a.2. Rotations/Risk

Propagation of glenohumeral rotation values primarily affected the risk values with respect to the acromion (**Figure D.31**). Values ranged from 0 to 113 mm-% and were most affected by changes in glenohumeral elevation and horizontal abduction.

D.6.a.3. Translations/Linear distances

Linear distances to the acromion and coracoacromial ligament (**Figure D.32**) were most affected by superior and inferior changes in the location of the humeral head. However, the subscapularis distance to the acromion was affected by anterior translations during all tasks while infraspinatus distance was affected by anterior and posterior translations of the humeral head during propulsion and scapular plane abduction. Linear distance changes to the acromion ranged from 0.4 to 2.1 mm while linear distance changes to the coracoacromial ligament ranged from 0.2 to 2.1 mm.

D.6.a.4. Translations/Risk

Risk values changed relative to baseline values for only a few conditions of humeral head translation (**Figure D.33**). Supraspinatus and infraspinatus values changed most significantly during superior and inferior translations of the humeral head. Smaller changes were observed resulting from anterior and posterior translations of the humeral head. Changes ranged from 0 to 185 mm-%.

D.6.b. Regression analysis

D.6.b.1. Regression with glenohumeral and trunk kinematics as predictors

Independence testing for the predictors, glenohumeral elevation, horizontal abduction, and internal/external rotation, and trunk flexion/extension, resulted in independence for all predictors during weight relief, and lack of independence between any predictors during scapular plane abduction. Propulsion resulted in dependence between glenohumeral horizontal abduction and trunk flexion/extension. A multiple regression model was not completed for the scapular plane abduction task for either muscle due to the violation of independence among the predictors.

D.6.b.2. Weight relief

For the regression model that predicted the linear distance from the supraspinatus to the acromion during weight relief (**Table D.9**), it was determined that glenohumeral elevation (p=.1086) and horizontal abduction (p=.1256) did not predict the supraspinatus distance independently, so the final model predictors were glenohumeral axial rotation and trunk flexion/extension; glenohumeral axial rotation had a significant ($p<0.05$) parameter estimate of 0.07 (internal rotation corresponded to increased distance) and trunk flexion/extension was 0.09 (extension corresponded to increased distance), with an intercept of 11.31.

For the regression model predicting the linear distance from the infraspinatus to the acromion during weight relief (**Table D.10**), it was determined that glenohumeral horizontal abduction (p=.1218) did not predict the distance values. Glenohumeral elevation and axial rotation as well as trunk flexion/extension predicted the infraspinatus minimum distance so they were included in the model. Glenohumeral elevation (adduction corresponded to increased distance) and axial rotation (internal rotation corresponded to increased distance) had significant parameter estimates of 0.21 and 0.08, respectively.

D.6.b.3. Propulsion

For the regression model that predicted the linear distance from the supraspinatus to the acromion during propulsion (**Table D.11**), glenohumeral elevation, horizontal abduction, and axial rotation predicted the supraspinatus distance independently. Results of the regression model revealed that glenohumeral elevation (adduction corresponded to increased distance) and axial rotation (internal rotation corresponded to increased distance) had significant parameter estimates of 0.17 and 0.11, respectively, with an intercept of 10.72.

Glenohumeral horizontal abduction (p= 0.7674) and axial rotation (p=0.0818) did not significantly predict the linear distance from the infraspinatus to the acromion during propulsion (**Table D.12**). Glenohumeral elevation significantly predicted the distance with a parameter estimate of 0.11 (adduction corresponded to increased distance) and intercept of 5.98.

CHAPTER V

E. DISCUSSION

E.1. Study participants

Study participants were included who were assessed to have anterolateral shoulder pain consistent with a mechanical reduction of the subacromial space. This inclusion criterion necessitated the phone screening of many potential subjects and limited the number of potential participants. This, in turn, affected the homogeneity of other demographics. While we expected a low female-to-male participant ratio, age, weight, injury level, and years of wheelchair use were quite variable. While not ideal for a study cohort, this population is reflective of the population of users of manual wheelchairs and is reflected in many other studies in this population.

Further, we characterized the static seating postures of the participants by quantifying their shoulder orientations while their hands were positioned in the top dead center position on the hand rim as well as the anterior/posterior location of their shoulder joint center relative to the wheelchair axle of the drive wheel. The data were quite variable as expected due to the subjects' use of their own wheelchairs and unique anthropometrics. Also, it was noted that approximately 1/3 of our participants were observed to have forward head postures and rounded shoulders in their natural seating position. Forward head angle and forward shoulder angle for our representative subject were found to be far outside the ideal range (forward head angle ≤ 36 degrees, forward shoulder angle ≤ 22 degrees) as defined by Thigpen et al.[115] (**Appendix 5**).

Of note, the subjects' shoulder positions relative to the wheelchair axle were variable, with some posterior and some anterior to the axle. This may reflect variability in prescription by seating professionals, or purchase or modification of the wheelchairs by the participants directly. The majority of participants' wheelchair camber and dump measures were within the range of prescribed values[116].

Subjects' responses on three questionnaires were variable but mean values were representative of their described daily functioning. They all reported some level of pain with daily activities that was exacerbated by certain shoulder movements or repetitive movement tasks. A mean WUSPI score of 37.9, DASH of 27.8, and SRQ of 72.0 indicate that participants had moderate levels of pain that could be tolerated and did not dramatically influence their activities of daily living. Almost all subjects reported avoidance behaviors (avoiding ramps or long periods of propelling) which allowed them to not have flare-ups of pain on a daily basis. Many reported predictable pain episodes with ramp propulsion and with long bouts of propulsion during day-long recreational outings in the community. Additionally, of note, subjects' subjective report of pain was not always reflected in their WUSPI pain survey; some subjects reported high levels of pain to our team, but did not indicate as much on the survey.

In summary, this population of wheelchair users mirrors the participants in other manual wheelchair investigations with respect to variability in demographics and level of functioning. While subject demographics were not deemed to be statistical covariates in this study, future considerations of the impact of these variables both psychologically and biomechanically, on manual wheelchair users' pain tolerance, avoidance, and etiology are of interest. These individuals are often managing multiple health issues including urinary issues and skin health concerns that may minimize the importance of shoulder issues relative to their other health concerns. And while numerous investigations of wheelchair seating prescriptions have been investigated[117-119], it is important to understand why our population (and presumably others) does not appear to conform to a single standard of seating prescription. Further, an important direction for further research is the assessment of the impact of level of injury and seating postures (including forward head posture, spinal curvature, and seating prescription) on balance and glenohumeral motion during static and dynamic activities.

E.2. Kinematics

E.2.a. Analysis methods in kinematic studies

E.2.a.1. Variability in methods for quantifying shoulder kinematics

Even though the International Society of Biomechanics established standards for defining anatomical coordinate systems for most joints in 2005[36], reports of shoulder kinematics during wheelchair activities and other tasks were published prior to the publication using various digitization methods, coordinate system definitions, and Euler angle decomposition sequences[85, 120, 121]. Further, since 2005, researchers have proposed and compared alternative coordinate systems definitions and Euler sequences[75-80] which they believe are more clinically-appropriate or accurate measures of glenohumeral, scapulothoracic, and thorax motion. Investigators use a pure ISB-standard, an alternative approach, or some combination of the two approaches; the current study falls in the latter category.

There are two factors which are driving the proposal and utilization of new approaches to describe shoulder and trunk motion. The first factor is that the shoulder is a true six degree-of-freedom articulation which is difficult to mathematically characterize and describe. Further, the range of motion at the joint is large, and many tasks function within the whole movement space. Therefore, certain Euler decomposition approaches may be more advantageous for some movements of the shoulder, but not others due to gimbal lock concerns[78]. In addition, the Euler angle decomposition approach suffers from the fact that it is being used to describe bone and joint movement *trajectories* by decomposing each position (of the respective bones) in time. While a helical axes approach has been proposed intermittently as a solution to the position/trajectory issue, the methodology has never been adopted universally.

The second factor driving the use of new analysis approaches is the need to convey clinically-meaningful results to clinicians. As biomechanical research becomes more translational, it is imperative that we find ways of describing measures which align with the clinical understanding of anatomical planes of movement. Originally, kinematics research was dominated by engineers and others with previous experience in describing movement using robotics approaches. The focus was placed on accurately describing motion without too much concern for the anatomical and clinical relevance. With the increasing number of alternative methods being proposed (to the 2005 standard), it seems clear that a standard method for quantifying joint kinematics may not be feasible. Instead, an important direction to proceed may be to find clinically-relevant measures which are independent of the method used to describe the underlying joint kinematics. The minimum linear distance measure calculated in this study and others[38, 51-54] is an example of a measure which does not depend on the method used to describe the joint motion. Additional examples would include ligament and muscle lengths determined throughout joint motion.

E.2.a.2. Current study method versus other wheelchair study methods

While this variability in methods exists and investigators are reporting rotations about various coordinate axes, it is important to have an understanding of how the coordinate systems are defined and which Euler rotation sequences are used to describe the kinematics, in order to make comparisons between studies. The current investigation used the current ISB standard for describing the scapula coordinate system which involves digitization of the angulus acromialis (posterior lateral aspect of the acromion)[36]. Others continue to use an older standard which digitizes the acromioclavicular joint for coordinate system definition. These two coordinate systems have been compared and differences in resulting rotations described[76]. In the range of humeral elevation experienced during wheelchair activities (20 to 60 degrees), the current ISB standard used in the current study reports approximately 12 degrees less scapular internal rotation, 10 degrees less upward rotation, and 4 degrees less anterior tilt than the older standard.

These differences can be hypothesized to result in changes in glenohumeral (humerus relative to the scapula) rotation as well; however, the exact effects will depend on the position of the humerus in the movement space. Further, the glenohumeral rotation sequence (XZ'Y") used in the current study was not the ISB standard[77]. Because the sequence is a Cardan sequence (each axis is rotated about once), the characterization of the glenohumeral internal/external rotation has been deemed to be more clinically-relevant (values are on the order of goniometric measures) as compared to the ISB standard. Further, for purposes of comparison, it should be noted that during wheelchair activities, the internal rotation values obtained from the XZ'Y" sequence (Y") are nearly the same as the sum of the two rotations about Y (Y+Y") using the ISB Euler sequence (YX'Y") (**Figures E.34, E.35, and E.36**).

Finally, the ISB standard coordinate system definition and Euler sequence (ZX'Y") were used in this study to define the thorax movement. However, of note, users of manual wheelchairs typically had some spinal curvature (kyphosis) which resulted in a thorax long axis which was tilted anteriorly to varying degrees, as compared to the thorax long axis in able-bodied individuals. This forward axis tilt likely affected not only the trunk flexion values but the scapulothoracic rotations as well. One can hypothesize that the forward tilt most likely reduces the scapulothoracic anterior/posterior tilt values as compared to able-bodied or subjects with less postural curvature to some degree.

E.2.b. Comparison of wheelchair activities to previous studies

E.2.b.1. Weight relief

Mean time series data for weight relief activities in 12 manual wheelchair users were presented by Morrow et al.[122] for the three scapulothoracic rotations and glenohumeral internal/external rotation using the standard ISB sequences and digitization of the posterior lateral acromion for scapula coordinate system definition. Trends for the ranges of rotations were similar between the two studies; mean time series curves for the current study were determined by obtaining the mean at every time point throughout the cycles (**Figure E.37**).

Both investigations found the scapula to primarily remain in internal rotation, upward rotation, and anterior tilt throughout the weight relief activity; the glenohumeral joint was found to remain in external rotation throughout the movement. Morrow et al. reported scapulothoracic internal/external, upward/downward, and anterior/posterior tilt rotation values that ranged from approximately 29 to 37 degrees of internal rotation, 0 to 10 degrees of upward rotation, and 52 to 55 degrees of anterior tilt, as well as glenohumeral internal/external rotation that ranged from 5 to 20 degrees of external rotation. The current study found ranges of 21.2 to 35.2 degrees of internal rotation, 4.6 to 14.9 degrees of upward, and 19.7 to 28.1 degrees of anterior tilt rotation values for the scapulothoracic joint, as well as glenohumeral internal/external rotation values of 0.4 to18.8 degrees of external rotation (**Figure D.13**). Anterior tilt values differed between the two investigations. The anterior tilt value differences may be attributed to the use of a scapular tracker (versus an acromial sensor) for tracking scapula motion in the Morrow et al. investigation. A scapula tracker would be most sensitive to error in the anterior/posterior tilt rotation values due the nature of its attachment to the scapular spine. Additionally, subject-specific coordinate systems were not assigned for each subject in the Morrow study.

Another study team has published three studies focusing on the various phases of weight relief in able-bodied and spinal cord injured subjects. Methods included the use of electromagnetic surface sensors and ISB-defined coordinate systems; however, the acromioclavicular joint was digitized rather than the posterior lateral acromion. Trends were consistent in their reports of scapulothoracic and glenohumeral rotations in able-bodied[48] and spinal cord injured subjects[50] between the lift phase (event 2 in the current study) and hold phase (event 3 in the current study); however the data presented on five spinal cord injured subjects in comparing different daily activities[49] were not in full agreement. In the study of spinal cord injured subjects, from the lift to hold phase, the scapula internally rotated 7.0 degrees, downwardly rotated 9.7 degrees, and posteriorly tilted 4.9 degrees; the glenohumeral joint internally rotated 16.8 degrees. In the current study, the scapula internally rotated 10.8 degrees, downwardly rotated 1.2 degrees, and posteriorly tilted 1.0 degrees; the glenohumeral joint internally rotated by 14.4 degrees. The change in scapula anterior/posterior tilt and upward/downward rotation between the two studies were not similar. It is possible that events/phases were not selected in the same way between the two studies or that the weight reliefs were not completed in the same manner. In the current study, the participants were asked to complete the weight relief as they would normally, raising their body weight as high as possible. Some subjects were not able to obtain a position with arms fully extended. This introduced additional variability to the measures.

E.2.b.2. Propulsion

Time series data for scapula and glenohumeral rotations during level wheelchair propulsion have been presented by a few investigators[28, 122]. Lu et al.[28] reported wheelchair propulsion kinematics during over ground propulsion in a laboratory using retro-reflective surface markers for the thorax and humerus; a bone- mounted sensor cluster recorded the scapula movements. They found the scapula to primarily remain in internal rotation, and anterior tilt throughout the propulsion activity; the glenohumeral joint was found to remain in external rotation throughout the movement. Their recording of healthy normal subjects had similar trends to our scapulothoracic and glenohumeral rotation values, with some differences noted in the ranges and values of rotation. Lu et al. reported scapulothoracic internal rotation values of 12 to 29 degrees, while our range of values was approximately 18.6 to 39.4 degrees; upward rotation values of approximate 3.0 to -5.0 degrees of downward rotation were reported while our range of values was -5.4 to 4.7 degrees of downward rotation; anterior tilt values of 16.0 to 8.0 degrees were reported, while our values ranged from 17.6 to15.1 degrees (**Figure D.14**). Glenohumeral rotation values were reported using the ISB sequence. An assessment of the glenohumeral rotations (adding the first and third rotation in the sequence) would place the mean values across subjects in 5 to10 degrees of internal rotation throughout the propulsion cycle whereas our mean values ranged from 18.6 to 35.4 degrees of external rotation.

Differences in scapulothoracic and glenohumeral internal/external rotation ranges may be attributed to the study populations. Due to variable innervation of the trunk musculature in our spinal cord injured subjects, we have noted that subjects often sit in a posture with rounded shoulders and forward head posture. This posture would encourage scapular internal rotation which would in turn cause the glenohumeral rotation to be more externally rotated given a similar humerus position. Scapulothoracic measures in a spinal cord injured population[122] support our findings with similar scapula internal/external rotation values (33.0 to 40.0 degrees).

E.2.b.3. Scapular plane abduction

Time series data for scapular plane abduction were presented in two studies which used direct bone-pin sensor attachments for data collection in able-bodied subjects while standing. The first study by McClure et al[31] reported scapulothoracic rotations determined using the ISB sequence; however, they used the acromioclavicular joint for coordinate system setup. Between 25 and 60 degrees of humeral elevation (the range measured in the current study) they reported an approximate range of 3 degrees of posterior tilt (5 to 8 degrees posterior tilt), 10 degrees of upward rotation (18 to 28 degrees), and very little change in internal/external rotation of the scapula (35 degrees internal). Using nearly identical techniques, Ludewig et al.[30] reported approximate ranges of 5 degrees of posterior tilt (12 to 7 degrees anterior tilt), 12 degrees of upward rotation (14 to 26 degrees), and very little change in internal/external rotation (38 degrees internal). Further, they reported an approximate increase in glenohumeral external rotation of 12 degrees (46 to 58 degrees). The magnitude and direction of the change in scapula kinematics for able-bodied subjects performing scapular plane abduction in a standing posture were nearly identical for the range of 25 to 60 degrees of humeral elevation. However, the anterior/posterior tilt differed, with one study reporting the scapula in anterior tilt throughout the motion and the other reporting a posteriorly positioned scapula. The current study reported changes in scapulothoracic posterior tilt of 2.7 degrees (14.3 to 11.6 degrees of anterior tilt), upward rotation of 8.4 degrees (5.7 to 14.1 degrees), and 2.9 degrees of internal rotation (30.6 to 33.5 degrees); glenohumeral external rotation changed by 18.9 degrees (41.2 to 60.1 degrees)(**Figure D.15**).

In spite of the differences in scapula coordinate system setup and the fact that subjects were seated (and manual wheelchair users), the ranges of scapula movement were very similar across the three studies. Differences can be noted in the values for scapular internal rotation and anterior tilt after the coordinate system correction however. After a 12 degree correction, the scapula internal rotation would increase to as much as 45 degrees while the other studies reported 35 and 38 degrees of internal rotation. Similarly, with an increase of 4 degrees in anterior tilt, the anterior tilt in our participants (18.3 to 15.6 degrees) was greater than Ludewig et al. (12 to 7 degrees)[30] and much greater than McClure (5 to 8 degrees posterior tilt)[31]. These findings can potentially be attributed to the seated posture of manual wheelchair users who lack postural stability and have rounded shoulders and/or to differences in thorax coordinate system definition between the studies.

E.2.b.4. Summary

Scapulothoracic and glenohumeral time series data during weight relief were similar in ranges and values to previous data obtained from spinal cord injured individuals; except for scapula tilt values which can be attributed to differences in data collection techniques (Morrow et al.[122] used a scapula tracker and did not set up subject-specific scapula coordinate systems; these may have introduced variability). In comparison to previous studies that identified phases of weight relief[48, 50], there were some differences in scapula anterior/posterior tilt and upward/downward rotation; the current study had smaller ranges. It is possible that events/phases were not selected in the same way between the two studies or that subjects in the current study were not raising their thorax to the same height. When comparing to previously published data in able bodied subjects during propulsion[28], differences in scapulothoracic and glenohumeral internal/external rotation ranges may be attributed to the study populations. Due to variable innervation of the trunk musculature in our spinal cord injured subjects, we have noted that subjects often sit in a posture with rounded shoulders and forward head posture. This posture would encourage scapular internal rotation which would in turn cause the glenohumeral rotation to be more externally rotated given a similar humerus position. Scapulothoracic measures in a spinal cord injured population[122] found similar scapula internal/external rotation values (33.0 to 40.0 degrees) to the current study. Comparisons were made to previous scapular plane abduction studies which included time series data from 25-60 degrees of humerothoracic elevation[30, 31]. Ranges of rotations were similar between the previous work and the current study; however, in the current study, the scapula was in greater internal rotation and anterior tilt. These findings can potentially be attributed to the seated posture of manual wheelchair users who lack postural stability and rounded shoulders. Overall, the similarities between studies, despite the different samples and methods, suggest reasonable validity of the measurements.

E.2.c. Comparison between weight relief, propulsion, scapular plane abduction

When comparing the event data between the three tasks, the mean of all four events were included in the repeated-measures ANOVA analysis. Therefore, the results imply differences characteristic of the entire movements (**Figure D.10**). Results from the maximum/minimum angle analysis reflect differences in the peak values reached during each task (**Figures D.11 and D.12**).

E.2.c.1. Hypotheses findings

The hypotheses were focused on kinematic measures thought to place the shoulder at risk for subacromial impingement[62], scapulothoracic internal/external rotation (internal greater risk) and anterior/posterior tilting (anterior greater risk), and glenohumeral internal/external rotation (internal greater risk). Mean time series data for the subjects can be seen in **Figure E.37** and elucidate the following findings. Event data revealed a slightly greater overall scapulothoracic internal rotation during scapular plane abduction than during the other two movements. The maximum rotation values revealed that the weight relief and propulsion reached greater values than scapular plane abduction for internal rotation. Weight relief and propulsion were shown to have greater anterior tilt than scapular plane abduction throughout the tasks as well as reach greater peak anterior tilt values. Weight relief had greater glenohumeral internal rotation than during the propulsion task as well as reached greater peak internal rotation values than propulsion, which in turn had greater rotation and reached greater internal rotation values than scapular plane abduction. According to these findings, the weight relief task placed the shoulder at greater risk for reduction in the space as it possessed peak values for scapulothoracic internal rotation and anterior tilt (both equaled propulsion) and glenohumeral internal rotation, and when comparing event data, it possessed greater anterior tilt (equal to propulsion) and glenohumeral internal rotation. Scapular plane abduction possessed the least at-risk kinematics, with the smallest event data across tasks for anterior tilt and glenohumeral internal rotation as well as for peak scapular internal rotation, anterior tilt, and glenohumeral internal rotation. Previous literature has implicated scapulothoracic internal rotation and anterior tilt, and glenohumeral internal rotation for reducing the subacromial space and placing the underlying tendons at risk for impingement[16, 41, 45]. If these views are correct and all rotations contribute equally to the magnitude of risk, our kinematic data imply that weight relief places the tendons at the greatest risk of impingement while scapular plane abduction places them at the least risk; however, these interpretations do not account for differences in humeral elevation angle, which is also known to affect rotator cuff tendon proximity.

E.2.c.2. Other kinematic findings

Clearly, glenohumeral elevation also places the rotator cuff tendons at risk as the subacromial space is reduced with elevation of the humerus. Our data found greater elevations across the task as well as peak values, during scapular plane abduction than during propulsion, which were, in turn, greater than during weight relief. Downward rotation of the scapula has also been implicated by some as responsible for reduction in subacromial space[16, 41]. Downward rotation was significantly greater across the movement, and reached greater peak values, during propulsion than during weight relief and scapular plane abduction. Further, trunk flexion has been hypothesized to be an important measure, as it may be responsible for influencing scapular positioning[123, 124]. Trunk flexion during the weight relief and propulsion tasks were greater, and reached greater peak values, than during scapular plane abduction. Assuming these risks are equal contributors to reduction in subacromial space, these data suggest that propelling a wheelchair may cause greatest risk as it has the greatest downward rotation of the scapula during the task as well as peak values. Further it has the greatest trunk flexion (equal to weight relief) and peak values than scapular plane abduction. Scapula plane abduction, however, had greater glenohumeral elevation and peak values than propulsion which, in turn, was greater than weight relief.

Comparison of subjects' kinematics measures during static seated posture with their hands resting in their laps to the ranges of motion during the tasks demonstrates some interesting findings (**Figures D.13, D.14, D.15**). During weight relief, the subjects move into scapulothoracic external rotation, upward rotation, anterior tilt, as well as glenohumeral internal rotation and adduction relative to their natural seated posture. Two of the measures are in relatively more detrimental positions during motion (scapulothoracic anterior tilt and glenohumeral internal rotation) while the others are in improved positions relative to neutral posture. During propulsion, for the majority of measures, the subjects' neutral seated postures lay within the range of their movement ranges of motion. During scapular plane abduction, the subjects moved into improved positions relative to their neutral posture for all scapulothoracic measures as well as glenohumeral external rotation. However, they operate in a much more elevated position (glenohumeral elevation) during scapular plane abduction. As such, it is recognized that there is a complex interplay of angular changes that confounds prediction of impingement risk from angular data alone.

E.2.d. Within-task differences

When comparing the event data within the three tasks, differences were discerned for the different phases (4 events) of each task (**Figures D.16, D.17, D.18**).

E.2.d.1. Weight relief

Subjects performed the weight relief symmetrically, with events 1 and 4 (start and end) not differing for any measures, nor did events 2 and 3 (the hold phase). The movement initiated (event 1) with the hand on the hand rim with the trunk slightly flexed, the scapula in internal rotation, and the glenohumeral joint in external rotation, slight elevation, and abducted. The transition to the hold phase was characterized by an increase in scapular and glenohumeral internal rotation, as well as glenohumeral horizontal adduction and less elevation. The hypothesized greater scapular and glenohumeral internal rotation were present during events 2 and 3 of the weight relief as compared to event 1, potentially placing the shoulder at risk for reduced space during the hold phase. However, the glenohumeral elevation was greater at events 1 and 4 (than 2 and 3) implicating the start and end of the movement. While not all users of manual wheelchairs use the same technique for performing their weight relief maneuvers, it is imperative for skin health that the tissue is offloaded multiple times per day. There is potential for altering the kinematics of the movement if necessary to reduce the amount of internal rotation or avoid use of the hands by performing lateral weight shifts in the chair. Further analysis in Aims 2 and 3 will quantify the risk associated with changes in kinematics during the weight relief task.

E.2.d.2. Propulsion

Propulsion kinematics were identical for events 1 and 4 (the hand-on positions). In general, the 50% of push event (2) was characterized by a value in between events 1 and 3 (hand-off position). The movement initiated (event 1) with the trunk slightly flexed and the scapula in anterior tilt and internally rotated; the glenohumeral joint was externally rotated, horizontally abducted, and slightly elevated. The transition to the hand-off phase (event 3) was characterized by slight trunk extension, scapular posterior tilting and external rotation; the glenohumeral joint horizontally adducted and elevated. The hypothesized increase in scapular internal rotation was present; however, the glenohumeral axial rotation did not change as the scapular internal rotation was accompanied by glenohumeral adduction, resulting in no relative change in glenohumeral axial rotation. Of note, the glenohumeral elevation was greater at event 3 than at the other event times, perhaps indicating some risk due to assumed reduction in subacromial space while anterior tilt was greater at events 1 and 4, potentially placing these event times at increased risk. Wheelchair propulsion is the means by which manual wheelchair users ambulate about their homes and community. It is important to understand the risk fully since, to date, there are no other options for these individuals to ambulate. Additionally, due to its repetitive nature, the risk is compounded. Finally, since propulsion (during the push phase) is a constrained, closed-chain task, it is unclear how much the kinematics of the task can be altered without significant changes to the chair or propulsion style. Further analysis in Aims 2 and 3 will address the risk to rotator cuff tendons associated with the kinematics of propulsion.

E.2.d.3. Scapular plane abduction

As shown in previous studies[30, 31], scapular plane abduction was characterized by linear increasing values for many of the kinematic measures. Subjects started and ended in approximately 25 and 60 degrees of humerothoracic elevation, respectively. Subjects started (event 1) in their neutral trunk posture and slight scapular anterior tilt, upward rotation, and internal rotation; the glenohumeral joint was externally rotated and slightly horizontally adducted and elevated. In transition to the final arm position (event 4), the scapula posteriorly tilted slightly and upwardly rotated; the glenohumeral joint externally rotated, and elevated. The hypothesized greater scapular upward rotation and glenohumeral external rotation were present. Of note, the glenohumeral horizontal abduction, scapulothoracic axial rotation, and trunk flexion did not change across events during the movement. While the scapular plane abduction task is not a functional task, it is indicative of overhead tasks that are performed by individuals operating from a seated position during activities of daily living. Further, there is a plethora of research on populations of individuals who are at-risk or demonstrating pain consistent with reduction of the subacromial space. Subjects in the current study possessed similar movement patterns (increased scapular anterior tilt and increased internal rotation) to the measures identified previously from other populations of at-risk individuals[16]. Ludewig and Cook (2000)[16]obtained kinematics from two groups of individuals exposed to overhead use of their arms, one group with symptoms and one without symptoms of subacromial impingement. They reported increased scapulothoracic internal rotation, anterior tilt, and decreased upward rotation during various phases of the scapular plane abduction movement. In the current study, during scapular plane abduction, the manual wheelchair users had increased scapulothoracic internal rotation and anterior tilt as compared to normative data in the literature[30, 31]. Further analysis in Aims 2 and 3 will elucidate the relationships between the kinematic measures and the risk to the rotator cuff tendons.

E.3. Minimum distances/risk/proximity

Minimum distances, calculated as a single measure per trial for each muscle and overlying structure, are reflective of one time point during the movements when the proximity between the tendon footprints and coracoacromial arch is at a minimum. At the same time point, the proximity maps were assessed to determine what portions of the tendon footprints were at risk. Both of these measures can give insight into a single snapshot of the movements while the risk accounts for the time during which the tendons are at risk of mechanical impingement.

E.3.a. Comparison between weight relief, propulsion, scapular plane abduction

E.3.a.1. Minimum distances and risk

It is clear from the mean minimal distance measures for all three muscles assessed independently to both the acromion and coracoacromial ligament that, during weight relief, none of the tendons reach the 5.0 mm proximity threshold (**Figures D.20-D.22**). Further, when the mean of all three muscles are assessed (**Figure D.19**), the distances during weight relief to the acromion and coracoacromial ligament overall were greater than 10.0 mm. The risk assessment including all three muscles, as well as that which included only the supraspinatus and infraspinatus confirmed the lack of risk of mechanical impingement during the weight relief activity (**Figures D.23 and D.24**). The risk values were negligible during weight relief for both structures, the acromion and coracoacromial ligament. These findings are in stark contrast to the observations in Aim 1 which, based on the current understanding of the effect of kinematics on the subacromial space[62], indicated that the weight relief maneuver placed the shoulder at most risk. This discrepancy can likely be attributed to the translation of kinematic findings in a commonly-studied movement, scapular plane abduction, to other tasks. For example, glenohumeral internal rotation can be attributed to reduction in space during scapular plane abduction because the joint is in external rotation for most of the movement. Internal rotation would bring the greater tuberosity closer to the acromion undersurface. For movements where the joint is primarily in internal rotation, further internal rotation would likely increase the space. Further, scapular kinematics that may place the joint at risk when the humerus is elevated are likely different than those which are detrimental with the humerus in a more neutral posture, as is the case with the weight relief maneuver. If distance measures cannot be obtained, conclusions based on kinematics should be drawn based on glenohumeral kinematics, as they are directly related to the space measures and incorporate the humeral position.

Scapular plane abduction was characterized by small distances to the acromion for both the infraspinatus and supraspinatus (**Figures D.20-D.22**); however, the opposite was true for the coracoacromial ligament. The subscapularis had almost equivalent and borderline linear distance values at approximately 6.0 mm. With all three muscles distances included in the analysis, the acromion had clearly lower distance values overall (**Figure D.17**). The risk data (**Figures D.23 and D.24**) further clarified that the risk during scapular plane abduction was significant when assessed relative to the acromion; however, the risk was minimal to the coracoacromial ligament when all three (or two) muscles were included in the analysis.

Propulsion exhibited extremely small distances to the acromion from the infraspinatus and supraspinatus footprints. Infraspinatus had a mean distance to the coracoacromial ligament that was greater than 5.0 mm while the supraspinatus was less than 5.0 mm. Subscapularis distances to the acromion and coracoacromial ligament were both well above the 5.0 mm threshold (**Figures D.20-D.22**). When including all three muscles in the analysis (**Figure D.19**), the mean distance values were above the 5.0 mm threshold for both structures. Risk analyses with all three (and two) muscles included in the analysis revealed that the risk was negligible relative to the coracoacromial ligament, but significant with respect to the acromion for the propulsion movement (**Figures D.23 and D.24**).

So, it can be concluded that the minimal distance and risk values suggest lack of risk of compression of the supraspinatus, infraspinatus, and subscapularis by the overlying coracoacromial ligament as it was modeled in the current study, assuming a healthy, non-thickened ligament structure during any of the three tasks. Data for the individual linear distance curves clearly depict that the distances are well above the 5.0 mm threshold for all muscles and tasks except for the distance from the supraspinatus footprint to the coracoacromial ligament during propulsion. The supraspinatus may be at risk for mechanical compression with the coracoacromial ligament with small changes in kinematics of the task or with inflammation or thickening of the ligament. Focusing attention on the acromial risk, it is clear that only the propulsion and scapular plane abduction movements are at risk of mechanical impingement throughout a portion of the movement (as indicated by the risk values with three muscles included), with the minimum distance generally occurring in the mid-to-late cycle for propulsion and during the second half of the cycle for scapular plane abduction (**Appendix 6**). Further, the risk values do not change when subscapularis is removed from the model, confirming the lack of involvement of subscapularis. These findings are further elucidated by the individual muscles' distance values in which the subscapularis distance values to the acromion are well above the 5.0 mm threshold for propulsion and scapular plane abduction.

E.3.a.2. Proximity maps

Proximity maps were generated for the supraspinatus and infraspinatus proximity to the acromion during propulsion and scapular plane abduction as they had been identified as the most at-risk for mechanical impingement (**E.3.a.1.**). During the propulsion movement (**Figures D.25 and D.27**), the region of contact lay in the anterolateral to middle aspect of the acromion for both muscles (more middle for infraspinatus) and the contact region on the footprints was lateral/posterolateral for the supraspinatus and lateral/anterolateral for the infraspinatus. Further, the region of contact on the footprints was approximately 50% of the footprint areas for both muscles. Scapular plane abduction (**Figures D.26 and D.28**), in comparison, resulted in slightly more posterior contact areas on the acromion than during propulsion for both muscles. Also, the contact on the footprints was generally lateral for the supraspinatus and anterolateral (with minimal contact) for the infraspinatus. The region of contact on the footprints within a 5.0 mm threshold was less for scapular plane abduction than for propulsion, at 42% and 9% for the supraspinatus and infraspinatus, respectively.

When assessing the potential risk to the supraspinatus, it is clear that both propulsion and scapular plane abduction impose similar areas of contact between the footprint and the acromion. However, there is a trend for the contact with the footprint to occur on the posterolateral region of the footprint during propulsion (versus anterolateral during scapular plane abduction). Recent data suggest that the posterior region of the supraspinatus tendon, as it inserts on the rotator cuff is significantly thinner than the anterior region[104]. These data may suggest that the threshold for mechanical risk should be reduced for this portion of the tendon in future investigations. It also implies that the risk associated with propulsion for the supraspinatus may be somewhat less than that during scapular plane abduction. However, the risk for the infraspinatus is clearly greater for propulsion, as the area of contact is negligible during scapular plane abduction and reaches 48% of the area during propulsion. Of note, the contact regions for all tendon footprints and all conditions were in the lateral (versus medial) regions of the footprints. Additionally, the contact areas for the supraspinatus and infraspinatus during propulsion lay on the border between the two muscles, a region that has been implicated for tendinopathies and tears in individuals with potential subacromial impingement[125].

E.3.a.3. Summary

In summary, linear distance data elucidated the offending coracoacromial arch structure (the acromion) as well as the most detrimental movements (propulsion, scapular plane abduction) and affected tendons (supraspinatus and infraspinatus). Further, the proximity maps implied that the infraspinatus tendon may not be as affected as the supraspinatus during scapular plane abduction due to the negligible area of contact with the acromion, and the supraspinatus may be at slightly less risk during propulsion based on the contact area lying in a more posterior region of the footprint. However, of note, the contact area on the two muscles during propulsion was clearly on the border between the two, a region that has been implicated clinically in subjects with tendinopathy and rotator cuff tears. Additionally, the contact areas only lie in the region of the acromion, which is commonly surgically-altered during an anterior acromioplasty, during propulsion (not during scapular plane abduction); these findings may help guide the use or location for this procedure. These data are in opposition to the commonly-held beliefs that weight bearing and closed chain tasks place the rotator cuff at more risk for mechanical impingement in the population of manual wheelchair users. The weight relief task was clearly not implicated in this study, while the open-chain scapular plane abduction caused risk of impingement in this population. This finding is likely related to the lack of humeral elevation during the weight relief maneuver, allowing the tendon footprints to remain at a healthy distance from the coracoacromial arch. While this finding is in contrast to accepted beliefs about weight bearing tasks placing the shoulder at greater risk, wheelchair users are still faced with performing many activities of daily living in an elevated shoulder position and so are at-risk during these movements. Propulsion, also implicated in this study, is of great concern due to the loading and kinematic profiles which place the rotator cuff at risk. Further, it is an activity which is highly repetitive and necessary for an independent lifestyle.

E.4. Error evaluation

The effect of three and six degree changes in the glenohumeral rotations on resultant minimum linear distances were determined for each task (**Figures D.29 and D.30**), each muscle, and each overlying structure (acromion and coracoacromial ligament) to assess how error in measurements would impact the linear distance values. Rotation changes resulted in mean peak absolute differences of 0.7-1.5 mm to either structure. Three degree changes resulted in sub millimeter differences while six degree changes resulted in mean differences of approximately 1.5 mm. Six degree changes are mostly likely to occur, if at all, with glenohumeral internal/external rotation[35]; the infraspinatus was the most affected by these errors. The greatest effect on distance measures was shown to occur across movements for glenohumeral elevation and horizontal abduction. Similarly, risk vales were most affected by changes in glenohumeral elevation and horizontal abduction (**Figure D.31**), with some effect on infraspinatus with changes in glenohumeral axial rotation also noted. Linear distance changes to the acromion and coracoacromial ligament were most affected by superior and inferior changes to the humeral head (range, 0.4-2.1 mm)(**Figure D.32**); however anterior translation affected subscapularis measures and both anterior and posterior changes affected infraspinatus measures. Risk values supported these trends (**Figure D.33**). In future investigations, these data can be probed to understand how angular changes at the glenohumeral joint impact the linear distances and risk to help inform future intervention strategies in this population (**Appendix 7**). While the errors noted can reach mean values of 1.5 mm, it is likely that these errors would not have significantly altered the findings in the current study. Tendon footprint minimum linear distances were found to either lie well below 5 mm for a large portion of the movements (supraspinatus and infraspinatus during scapular plane abduction and propulsion) or they did not reach close to the threshold value (subscapularis, all movements). It is possible, however, that errors may have altered the contact patterns between the infraspinatus and acromion during scapular plane abduction.

E.5. Regression analysis

A regression analysis was performed between the three glenohumeral and thorax flexion/extension rotation values and the resultant linear distance values from the infraspinatus and supraspinatus footprints to the acromion during weight relief and propulsion (**Tables D.9-D.12**). While the analysis was exploratory due to the limited number of subjects for this type of analysis, some potential relationships were found. During weight relief, a one degree increase in glenohumeral internal rotation was associated with a .07 mm increase in linear distance for the supraspinatus (alternatively, a one degree increase in external rotation was associated with a .07 mm decrease in linear distance). Therefore, a 10 degree change would be associated with a 0.7 mm distance change. For the infraspinatus, a one degree increase in glenohumeral adduction was associated with a 0.21 mm increase in distance (abduction was associated with decrease in distance), while a 1 degree increase in internal rotation would be associated with a 0.08 mm increase in distance. These models suggest that glenohumeral horizontal abduction/adduction and trunk flexion/extension were not associated with significant changes in linear distances during the weight relief task, while glenohumeral adduction and internal rotation were correlated with increases in distances for the infraspinatus and supraspinatus. Similarly, during propulsion, glenohumeral horizontal abduction was not associated with distance changes for either muscle. For the supraspinatus, a one degree increase in glenohumeral adduction resulted in a .17 mm increase in linear distance and a one degree increase in internal rotation was associated with a 0.11 mm increase in distance. For the infraspinatus, glenohumeral adduction increases of one degree were associated with 0.1 mm increases in distance. In summary, it appears that glenohumeral elevation/lowering plays an important role in prediction of linear distance measures to the three tendon footprints during weight relief and propulsion while glenohumeral axial rotation plays a secondary role. These findings, if supported in adequately powered studies, have implications for determining clinical interventions for individuals in manual wheelchairs to help reduce risk of mechanical impingement to the rotator cuff.

E.6. Summary of risk in the current study

Certain kinematic movements are presumed to place the shoulder at risk for subacromial impingement, including scapulothoracic internal rotation and anterior tilt as well as glenohumeral internal rotation. When the current study findings are evaluated according to these beliefs, the weight relief task placed the shoulder at greater risk for reduction in the subacromial space as it possessed peak values for scapulothoracic internal rotation and anterior tilt and glenohumeral internal rotation, and when comparing mean event data, it possessed greater anterior tilt (equal to propulsion) and glenohumeral internal rotation. Scapular plane abduction possessed the least at-risk kinematics, with the smallest event data across tasks for anterior tilt and glenohumeral internal rotation as well as for peak scapular internal rotation, anterior tilt, and glenohumeral internal rotation. Findings from the linear distance and risk analysis, however, did not support these findings. The weight relief task was clearly not implicated for reduction in the space, as it had no measurable risk of compression of the three tendons, while scapular plane abduction and propulsion caused substantial risk of impingement in this population. Further, while the regression analysis was under-powered and did not include the scapulothoracic rotations, it clearly implicated glenohumeral elevation as a primary predictor of linear distance changes. As subacromial impingement risk is defined based on glenohumeral motion changes (not incomplete shoulder kinematic descriptors including scapulothoracic rotations), it is imperative that future research focus on the glenohumeral articulation rather than on the scapula and humerus motions independently to attempt to define risk. Further, many of the studies which attempt to identify changes in kinematics associated with subacromial risk focus on the scapular plane abduction movement. These data clearly demonstrate that there are differences between tasks, and risk needs to be quantified for the tasks in question rather than translating findings from assessments of other movements.

E.7. Clinical implications

The current study clearly identified that weight relief maneuvers (even though they are weight bearing) do not subject individuals in manual wheelchairs to risk of impingement of rotator cuff tendons as defined in this study. Due to the necessity for offloading of the skin to reduce issues with pressure sores, these individuals perhaps could be encouraged to continue performing the maneuvers in the manner described in this study. However, other risks of loading are possible, such as higher bone compressive or shear forces that were not evaluated in this study. Further, the risk associated with propulsion and scapular plane abduction are cause for careful consideration for these individuals. Propulsion is a highly-repetitive and necessary movement that clearly places the tendons at risk for mechanical impingement. Given the current design of manual wheelchairs, modifications to the task are possible via changes in seating[118, 119] including raising the seat height (to place the glenohumeral joint in more adduction) as well as suggested movement changes to encourage less glenohumeral rotation. Clearly, novel wheelchair designs would enable many factors to be considered and altered; however, these designs would have to incorporate user feedback and would need to be less conspicuous than conventional manual wheelchair designs.

The linear distance measures, risk, and proximity maps in the current study bring us a step closer to clinically-relevant measures which are invariant to the kinematic coordinate systems and definitions. Distance and risk measures have implicated the infraspinatus and supraspinatus distances to the acromion during propulsion and scapular plane abduction as at-risk movements. Further, the proximity maps have identified the locations of contact between the footprints and overlying anatomy such that surgical intervention strategies for acromioplasty can be evaluated. In addition, the contact areas on the tendon footprints can be compared to imaging findings in this population to discern patterns of tendinopathy and rotator cuff tears consistent with the patterns of contact. These may lead to advances in clinical treatment strategies for these individuals.

Some research groups have focused on prescribing exercise and strengthening interventions in this population as a means of reducing pain thought to result from impingement of rotator cuff tendons. Further analysis of the measures obtained in this study can suggest evidence-based movement alterations, and thus muscle strengthening exercises and postural adjustments, which can potentially reduce the risk in this population. Data obtained for the sensitivity analysis can be further probed to discern which rotations changes resulted in increased distances to the coracoacromial arch, and if the distance changes occurred during specific movement phases.

E.8. Limitations of the current study

The current study had limitations in experimental techniques as well as in the assumptions made in the model-based calculations. Surface markers are known to have error as compared to bone-mounted sensors for recording shoulder kinematics. The effect of these errors on linear distance and risk values were determined in Aim 3, and overall, resulted in sub millimeter distance values, up to approximately 2.0 mm. Further, the humeral translation in the current model was fixed relative to the scapula. This assumption was based on literature reports and pilot data that quantified translation values in the 1.0 mm range for values of humeral elevation reported in this study. The range of distance values that resulted from the angular kinematics alone (5.0-25.0 mm, **Appendix 6**), especially during propulsion and scapular plane abduction, far exceeded these values, implying that the angular changes have the potential to have greater impact on the subacromial space than translations of the humeral head.

This study focused on reduction of the subacromial space while reduction in the space beneath the coracoid and between the humerus and glenoid may also be important measures to investigate. Additionally, the generic bone model from a single CT, the identification of tendon footprints from bony anatomy, and the planar representation of the coracoacromial ligament, limit the conclusions that can be drawn from the model.

Variability in bony geometry, as well as soft tissue changes with pathology, are known factors. Variations in scapular geometry, including the acromion, changes in coracoacromial thickness, as well as potential glenoid remodeling, are also known factors which were not incorporated into the model. Further, geometry of the tendon footprints and tendon thicknesses were not varied for each individual. Future studies are recommended to pursue the interplay between individual subject anatomic and kinematic factors. However, the intent of this investigation was to focus on the specific influence of angular kinematic changes across tasks.

E.9. Future implications of the current study

There are several logical methodological and clinical implications from the current study. An important methodological question is how subject-specific bone model and soft tissue geometries (including pathological changes) would impact the predictions of linear distance and risk values. Further, we can compare the subject-specific proximity maps to magnetic resonance imaging of subjects' shoulders to further validate and inform surgical and conservative intervention strategies. Finally, we can assess whether the humeral translations can be accurately quantified to incorporate any effect they have on the subacromial space. These ideas can be addressed more accurately using dynamic fluoroscopic imaging techniques which allow noninvasive, three-dimensional kinematics (rotations and translations) to be obtained during shoulder movements in vivo.

The study has clearly established that there are differences in mechanical impingement risk between and within different activities performed by users of wheelchairs. Of concern is the fact that it appears that both propulsion and arm raise activities place the joint at risk for reduction of the subacromial space. Both of these tasks are often performed by this population and both are necessary for independent living. Modifications to these individuals' seating configurations or posture need to be investigated to determine if changes will alleviate the risk to their shoulder health.

Further, this study has elucidated, through the sensitivity and regression analyses in Aim 3, that changes in the linear distances (space) can be accomplished in varying amounts by changing certain glenohumeral rotation values. Clearly, glenohumeral elevation was implicated as an important movement which has great impact on the linear distance values. Further investigation is needed to determine whether movement changes, and/or timing of movement changes, can be altered through interventions such as seating modifications or rehabilitation interventions to help increase the subacromial space during the critical phases of movement in which they are at most risk.

Other tasks which are often performed by manual wheelchair users should be assessed for risk as well. It was clearly demonstrated in this study that each task has unique kinematics and should be assessed independently. Other activities to consider include propelling up a ramp as well as placing the wheelchair in the backseat (using humeral elevation and extension) while seated in the front seat of a car; both have been anecdotally reported to cause pain and are concerning motions based on our previous findings.

Finally, this study has raised questions regarding the risk of open (scapular plane abduction) versus closed (propulsion) chain activities and our ability to prescribe interventions for the two. Modifications to the performance of an open chain task would seem to be easier to implement and users may or may not self-select movement patterns that are protective of the space. Modifications to a closed-chain task may or may not be achievable given the limited degrees of freedom of the arm when it is required to follow a prescribed movement trajectory. As it appears that the scapula tracks along the thorax surface during most movements, it is of interest to address the postural curvature and positioning to achieve greater changes in glenohumeral orientations for these closed-chain tasks.

E.10. Summary and Conclusion

Scapulothoracic (3 rotations), glenohumeral (3 rotations) and thorax flexion/extension angles were determined and analyzed between and within the tasks of weight relief, propulsion, and scapular plane abduction in fifteen users of manual wheelchairs. Further, each subject's glenohumeral rotation values were combined with CT-generated bone models of the scapula and humerus for all three tasks to quantify the proximity (distance) mapping and minimum distance from each of three tendon footprints (infraspinatus, supraspinatus, and subscapularis) to the acromion and coracoacromial ligament throughout the movements. Sensitivity of the linear distance values to errors in kinematic values were computed as well as an exploratory regression to predict linear distances from glenohumeral kinematics. Significant between-task and within task differences were observed in many of the kinematic variables. Further, significant between-task differences were seen in linear distance values and risk (area between linear distance curves and 5.0 mm threshold). In general linear distances were smaller and risks were higher between the tendon footprints and the acromion (versus the coracoacromial ligament). Further, linear distances were smaller and risks higher during propulsion and scapular plane abduction, than during weight relief. Sensitivity analysis of the linear distance values resulted in sub millimeter changes for ± 3 degree changes in glenohumeral rotations and less than 2.0 mm for ± 6 degree changes. Proximity maps (within 2.0 mm and 5.0 mm thresholds) depicted changes in location of the maps on the underlying anatomy as well as contact area between tasks and muscles. When the current study findings are evaluated according to currently-held beliefs about at-risk scapulothoracic kinematics, the weight relief task placed the shoulder at greater risk for reduction in the subacromial space. Findings from the linear distance and risk analysis, however, did not support these findings. Scapular plane abduction and propulsion were found to cause substantial risk of impingement using these measures. As subacromial impingement risk is defined based on glenohumeral motion changes; future research should focus on the glenohumeral articulation rather than on the scapula and humerus motions independently to attempt to define risk. Further, while the regression analysis was under-powered and did not include the scapulothoracic rotations, it clearly implicated glenohumeral elevation as a primary predictor of linear distance changes. Many of the studies which attempt to identify changes in kinematics associated with subacromial risk are defined during scapular plane abduction movements. The data from the current study clearly demonstrate that there are differences between tasks, and risk needs to be quantified for the tasks in question rather than translating findings from assessments of other movements. Further, measures which are invariant to coordinate system definitions need to be quantified (such as linear distance measures and areas of contact) to facilitate comparisons between study conclusions and improve upon the clinical relevance of the findings.

TABLES

Table B.1: Summary of shoulder kinematics studies comparing humeral elevation in subjects with impingement diagnosis to asymptomatic (differences rounded to whole numbers).

Study	Hardware	Analysis/conventions	Sample	Variables analyzed	Significant Results
Ludewig[16]	Electromagnetic surface sensors (acromial marker)	ISB C.S./ ISB for scapulothoracic	26 asymptomatic 26 impingement	Scapulothoracic	
				- upward	**↓ (4°)**
				- posterior tilt	**↓ (6°)**
				- internal	**↑ (5°)**
				Glenohumeral	
				- internal	**↑ (2°)**
Lukasiewicz[45]	Electromechanical digitizer (static)	Projection angles	20 asymptomatic 17 impingement	Scapulothoracic	
				- upward	**-**
				- posterior tilt	**↓ (9°)**
				- internal	**-**
				- position (elev.)	**↑ (2cm)**
Endo[41]	Plane AP xray (static)	2D calculations	27 unilateral impingement (comparison within subject)	Scapulothoracic	
				- upward	**↓ (4°)**
				- posterior tilt	**↓**
				- internal	**-**
Graichen[52]	Open MRI (static)	Principal components/internal angles	20 unilateral impingement 14 asymptomatic	Scapulothoracic	
				- upward	**-**
				Glenohumeral	
				- elevation	**-**
Hebert[42]	Optical digitizing (static)	Non-ISB coordinate systems/ Euler angles	41 impingement 10 asymptomatic	Scapulothoracic	
				- upward	**-**
				- posterior tilt	**-**
				- internal	**↑ (2°)**
Su[126]	Digital inclinometer (static)		20 impingement 20 asymptomatic, all swimmers	Scapulothoracic	
				- upward	**↓ (3-5°)**
McClure[83]	Electromagnetic surface sensors	ISB coordinate systems/ ISB Euler angles	45 impingement 45 asymptomatic	Scapulothoracic	
				- upward	**↑ (4°)**
				- posterior tilt	**↑ (3°)**
				- internal	**-**
Hallstrom[127]	Dynamic radiostereometry	Non-ISB coordinate systems/Euler angles	25 impingement 12 asymptomatic	Scapulothoracic	
				- upward	**-**
				- posterior tilt	**-**
				- internal	**-**
Lin[84]	Electromagnetic	**ISB coordinate systems/ ISB Euler angles**	14 impingement 7 asymptomatic	Scapulothoracic	
				- upward	**-**
				- posterior tilt	**↓ (7-14°)**

Table D.2: Study participant demographics.

Subject	Age (yrs)	Gender	Weight (kg)	Injury level	Years in chair
1	32	Male	104	T5	9
2	31	Male	79	T3-4	12
3	26	Female	98	T9	9
4	25	Male	77	T12	22
5	45	Male	72	T12	4
6	47	Male	75	T4	16
7	57	Male	98	T10	4
8	53	Male	96	T3-4	6
9	51	Male	111	T9 - L2	17
10	31	Male	74	C6-7	7
11	59	Male	59	Polio	23
12	35	Male	75	T12	34
13	28	Male	70	T7	8
14	33	Male	77	T10	19
15	31	Female	45	L2	23
Mean(SD)	39(12)		81(18)		14(9)

Table D.3: Passive ranges of motion (PROM) and tendon insertion palpation (+ positive; - negative).

Subject	PROM in neutral (external) (deg)	PROM in 90 deg abduction (external) (deg)	PROM in 90 deg abduction (internal) (deg)	Pec minor insertion palpation	Suprasp. insertion palpation	Infrasp. insertion palpation
1	90.0	95.0	45.0	-	-	-
2	77.5	92.5	65.0	-	-	-
3	80.0	100.0	72.5	-	+	-
4	72.5	95.0	45.0	-	+	+
5	72.5	95.0	60.0	-	-	+
6	67.5	85.0	60.0	-	-	-
7	69.0	93.5	27.5	not avail.	-	-
8	65.0	82.5	65.0	+	-	-
9	82.5	85.0	25.0	-	-	-
10	52.5	90.0	50.0	-	-	-
11	82.5	90.0	50.0	-	-	-
12	57.5	105.0	40.0	not avail.	-	-
13	52.0	77.0	43.5	-	-	-
14	67.5	95.0	67.5	-	-	-
15	90.0	107.5	67.5	-	-	-
Mean(SD)	71.9(12.0)	92.5(8.1)	52.2 (14.7)			

Table D.4: Special test results for all subjects (+ positive, - negative, o not attempted due to pain).

Subject	Speed's test	Neer test	Hawkins-Kennedy test	Empty can test (pain)	Empty can test (weakness)	Crank test	Sulcus	Load shift
1	-	-	+	-	+	+	-	-
2	-	-	-	-	-	-	-	-
3	+	+	+	-	-	-	-	-
4	+	-	+	+	-	-	-	-
5	-	+	-	+	-	+	-	-
6	+	-	+	+	-	-	-	-
7	-	-	+	-	-	-	-	-
8	-	+	+	+	-	-	-	+
9	+	o	o	o	-	o	-	-
10	-	-	-	-	+	-	-	-
11	+	-	+	-	-	-	-	-
12	-	-	-	-	-	-	-	+
13	-	-	-	-	-	-	-	-
14	-	-	-	+	-	-	-	-
15	+	-	+	+	+	-	-	-

Table D.5: Study participant seated posture and wheelchair configuration.

Subject	Hand Top Center Handrim (deg) GH elev.	horiz abd.	axial	Camber (deg)	Dump (deg)	Acromion distance to WC axis (ant/post) (cm)	Acromion position relative to WC axis
1	-6.8	-6.3	-19.4	10	5	7	Anterior
2	-13.3	-23.2	-26.8	5	0	2.5	Anterior
3	-25.9	-6.6	25.1	5	10	2	Posterior
4	-30.8	-23.9	-6.8	5	5	7	Posterior
5	-16.3	-25.7	-33.5	5	15	1.5	Posterior
6	-15.5	-28.3	-18.1	0	10	2	Posterior
7	-10.7	-31.4	-24.4	5	7	0	n/a
8	-22.4	-27.1	3.7	5	7	3.5	Posterior
9	9.9	-16.8	-55.1	5	5	10	Anterior
10	-7.3	-23.4	-43.8	5	15	1	Posterior
11	-14.6	-37.3	-27.7	5	5	2	Posterior
12	-13.2	-30.4	7.4	3	5	2	Anterior
13	0.9	-2.8	-50.1	5	7	3	Posterior
14	-6.3	-23.8	-15.5	5	7	8.5	Posterior
15	-10.7	-29.1	-24.3	not avail.	5	not avail.	not avail.
Mean(SD)	-12.2 (10.0)	-22.4(10.0)	-20.6(21.6)	4.9 (2.0)	7.2(3.9)	3.7(3.1)	

Table D.6: Questionnaire scores.

Subject	WUSPI	DASH	SRQ
1	19.0	11.7	86.2
2	28.7	44.2	36.2*
3	73.6	49.2	60.0
4	62.0	32.5	56.0
5	45.1	31.7	72.8
6	4.9	13.3	82.9
7	14.8	39.2	77.0
8	56.6	35.0	70.7
9	61.8	36.7	56.0
10	18.8	36.7	83.9
11	57.4	52.5	47.7
12	1.2	0.8	95.6
13	4.2	4.2	92.0
14	23.9	10.8	80.8
15	51.4	18.3	82.9
Mean (SD)	37.9(24.4)	27.8(16.6)	72.0(17.3)

* subject did not complete 15 points worth of survey

Table D.7: Mean (SD)/% proximity area within threshold of 2.0 mm.

	Supraspinatus	Infraspinatus
Propulsion	21mm^2 (17)/ 12%	10mm^2 (9)/ 7%
Scapular plane abduction	14mm^2 (17)/ 8%	2mm^2 (4)/ 1%

Table D.8: Mean (SD)/% proximity area within threshold of 5.0 mm.

	Supraspinatus	Infraspinatus
Propulsion	89mm^2 (36)/ 52%	67mm^2 (22)/ 48%
Scapular plane abduction	72mm^2 (41)/ 42%	13mm^2 (21)/ 9%

Table D.9: Multiple regression table for prediction of minimum distance from the supraspinatus to the acromion during weight relief.

Parameter	Estimate	Standard Error	95% confidence limits		Z	Pr > |Z|
Intercept	11.31	0.83	9.69	12.93	13.69	<.0001
Glenohumeral axial rotation	0.07	0.02	0.04	0.10	4.32	<.0001
Trunk flexion/extension	0.09	0.05	-0.01	0.18	1.79	0.0736

Table D.10: Multiple regression table for prediction of minimum distance from the infraspinatus to the acromion during weight relief.

Parameter	Estimate	Standard Error	95% confidence limits		Z	Pr > |Z|
Intercept	11.04	0.51	10.05	12.03	21.85	<.0001
Glenohumeral elevation	0.21	0.02	0.18	0.24	12.77	<.0001
Glenohumeral axial rotation	0.08	0.01	0.05	0.10	6.07	<.0001
Trunk flexion/extension	0.05	0.03	0.00	0.11	1.90	0.0572

Table D.11: Multiple regression table for prediction of minimum distance from the supraspinatus to the acromion during propulsion.

Parameter	Estimate	Standard Error	95% confidence limits		Z	Pr > |Z|
Intercept	10.72	0.83	9.08	12.35	12.86	<.0001
Glenohumeral elevation	0.17	0.02	0.13	0.22	7.29	<.0001
Glenohumeral horizontal abduction	-0.02	0.03	-0.08	0.04	-0.69	0.4927
Glenohumeral axial rotation	0.11	0.02	0.07	0.15	5.61	<.0001

Table D.12: Multiple regression table for prediction of minimum distance from the infraspinatus to the acromion during propulsion.

Parameter	Estimate	Standard Error	95% confidence limits		Z	Pr > |Z|
Intercept	5.98	0.62	4.77	7.19	9.68	<.0001
Glenohumeral elevation	0.11	0.02	0.06	0.15	4.70	<.0001

FIGURES

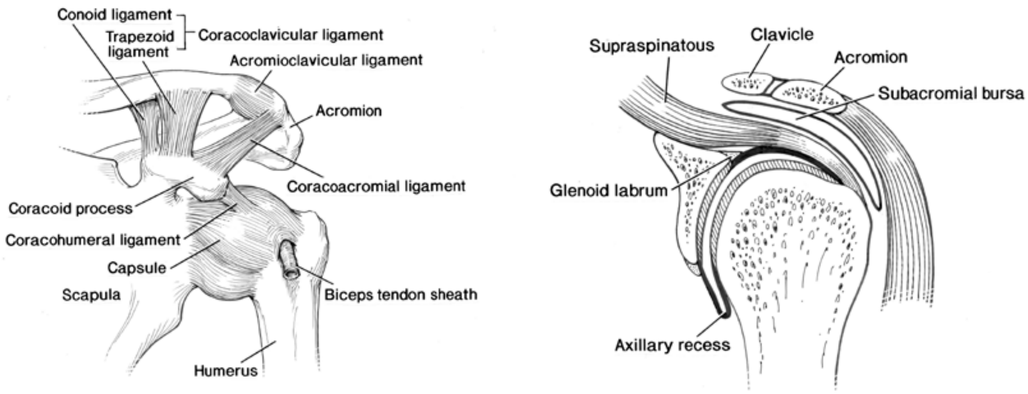


Figure A.1: Anterior views of anatomy of anterior shoulder. Important anatomical structures in the anterior shoulder include the coracoid process, acromion, subacromial bursa, supraspinatus tendon, biceps tendon coursing through the bicipital tendon sheath and the acromioclavicular joint.

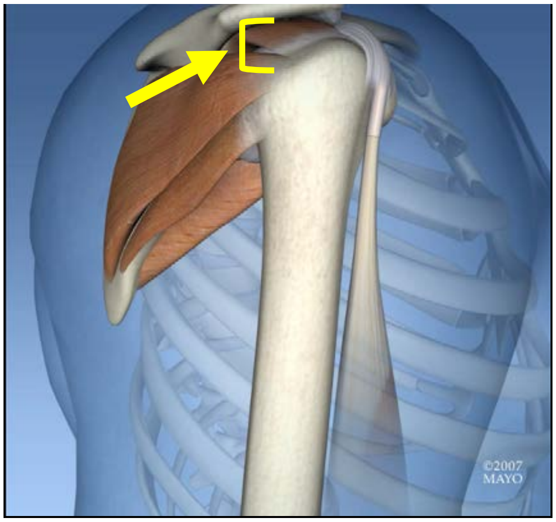


Figure A.2: The subacromial space is the space or void between the coracoacromial arch (acromion, coracoacromial ligament, coracoid, and acromioclavicular joint) superiorly, and humerus inferiorly. Copyright Mayo Foundation; used with permission.

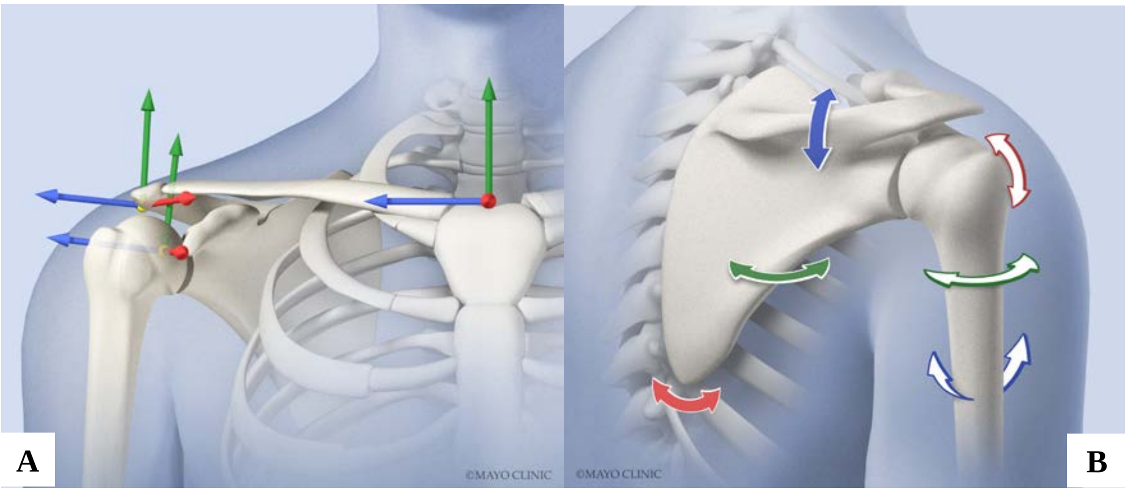


Figure A.3: A) Thorax, scapula, and humerus anatomical coordinate axes, B) Scapulothoracic (solid arrows) and glenohumeral (outlined arrows) motions. Scapulothoracic rotation is comprised of internal/external rotation about a superior/inferior axis (B, solid green), upward/downward rotation about an anterior posterior axis (B, solid red), and posterior/anterior tilting about a medial/lateral axis (B, solid blue). Glenohumeral motions of interest include elevation (B, outlined red), plane of elevation (B, outlined blue), and axial rotation (internal/external) about the humeral long axis (B, outlined green). Copyright Mayo Foundation; used with permission.

Figure A.4: Hand-on (left) and hand-off (right) phases of wheelchair propulsion.

Figure A.5: Initiation (left) and hold phase (right) of weight relief maneuver.

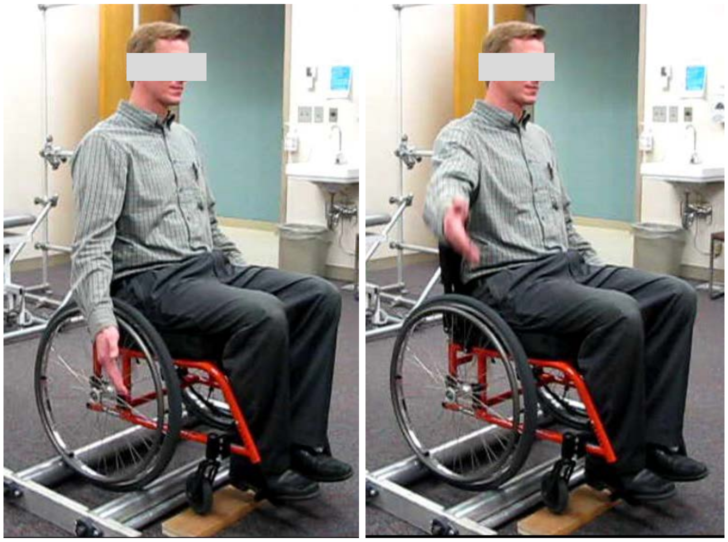


Figure A.6: Initiation (left) and end (right) of scapular plane abduction.

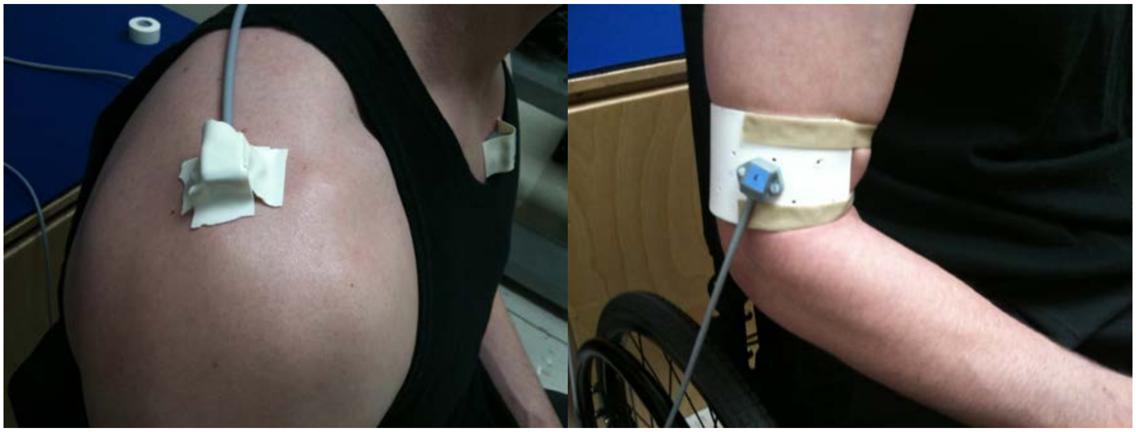


Figure C.7: Attachment of electromagnetic sensors.

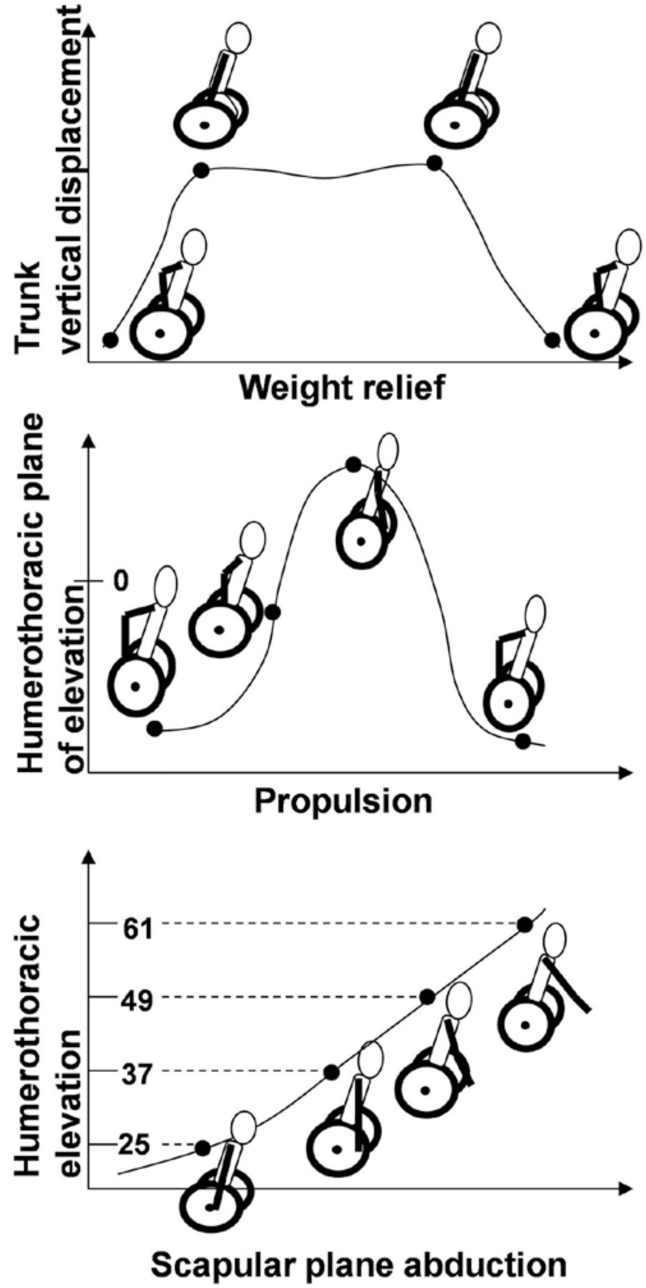


Figure C.8: Events for (TOP) weight relief include initiation of lift, beginning of hold, end of hold, and end of lowering phases; (MIDDLE) propulsion include beginning of push, mid-push, end of push, end of recovery phases; (BOTTOM) scapular plane abduction include 25, 37, 49, and 61 degrees of humerothoracic elevation.

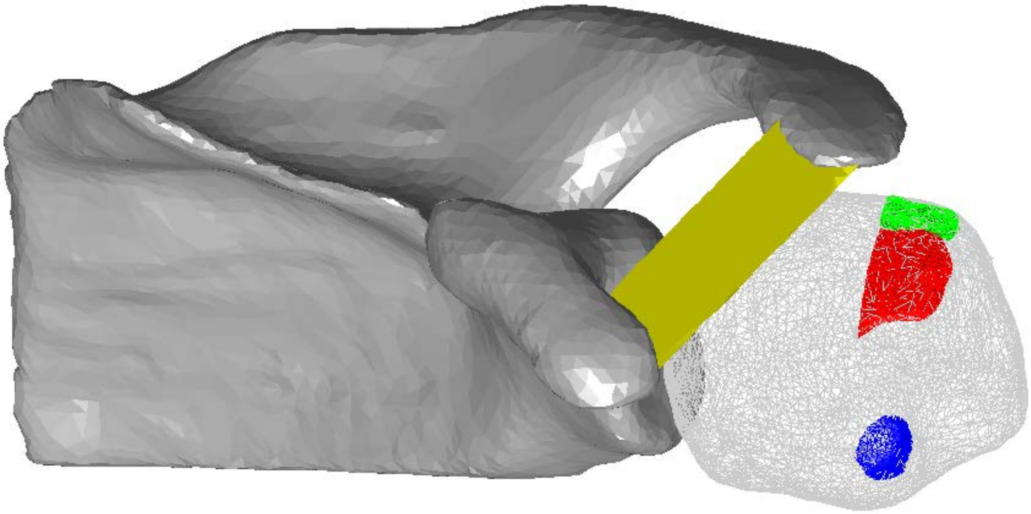


Figure C.9: Anatomical surface models of the scapula (solid gray) and humeral head (meshed gray) with the CA ligament (yellow), subscapularis tendon footprint (blue), supraspinatus tendon footprint (red), and infraspinatus tendon footprint (green).

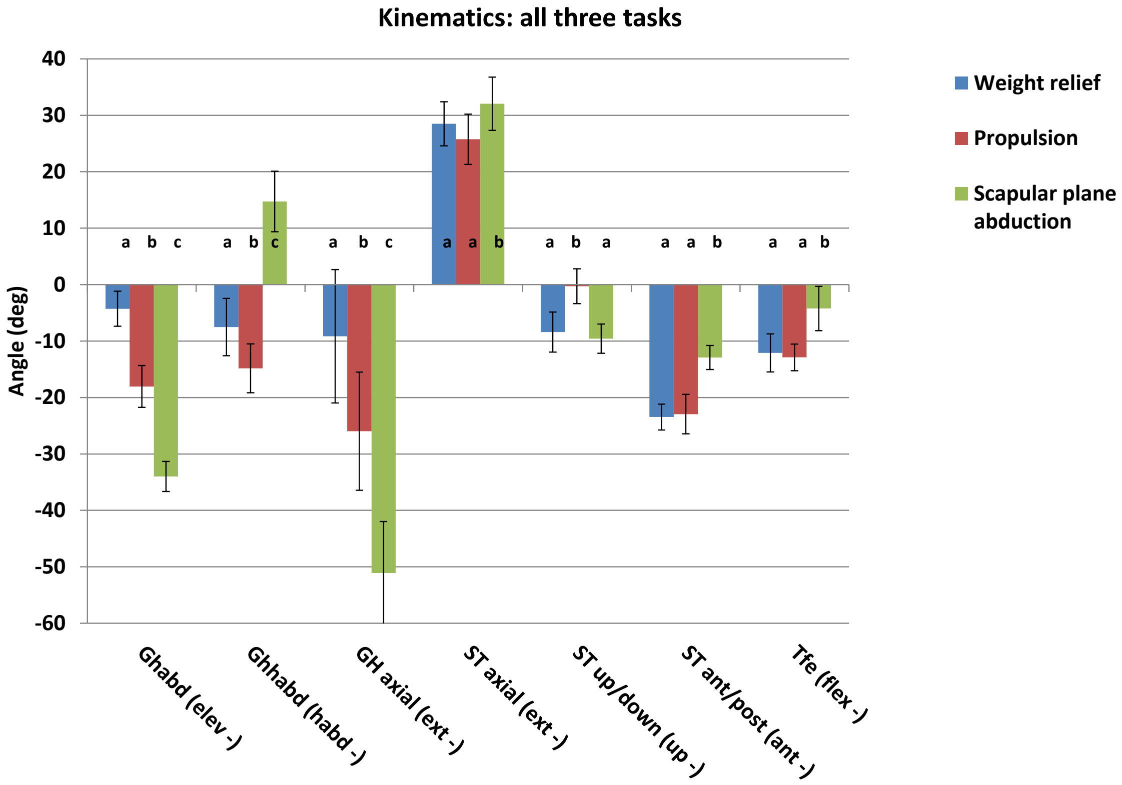


Figure D.10: Means and 95% confidence interval values for between-task comparison of the mean of all four events for all three tasks in degrees (deg). Letters indicate significance; the same letter indicates no significant difference between values (GHabd=glenohumeral elevation/lowering, GHhabd=glenohumeral horizontal abduction/adduction, GH axial= glenohumeral internal/external, ST axial=scapulothoracic internal/external, ST up=scapulothoracic upward/downward, ST ant/post=scapulothoracic anterior/posterior, and Tfe=trunk flexion/extension rotations).

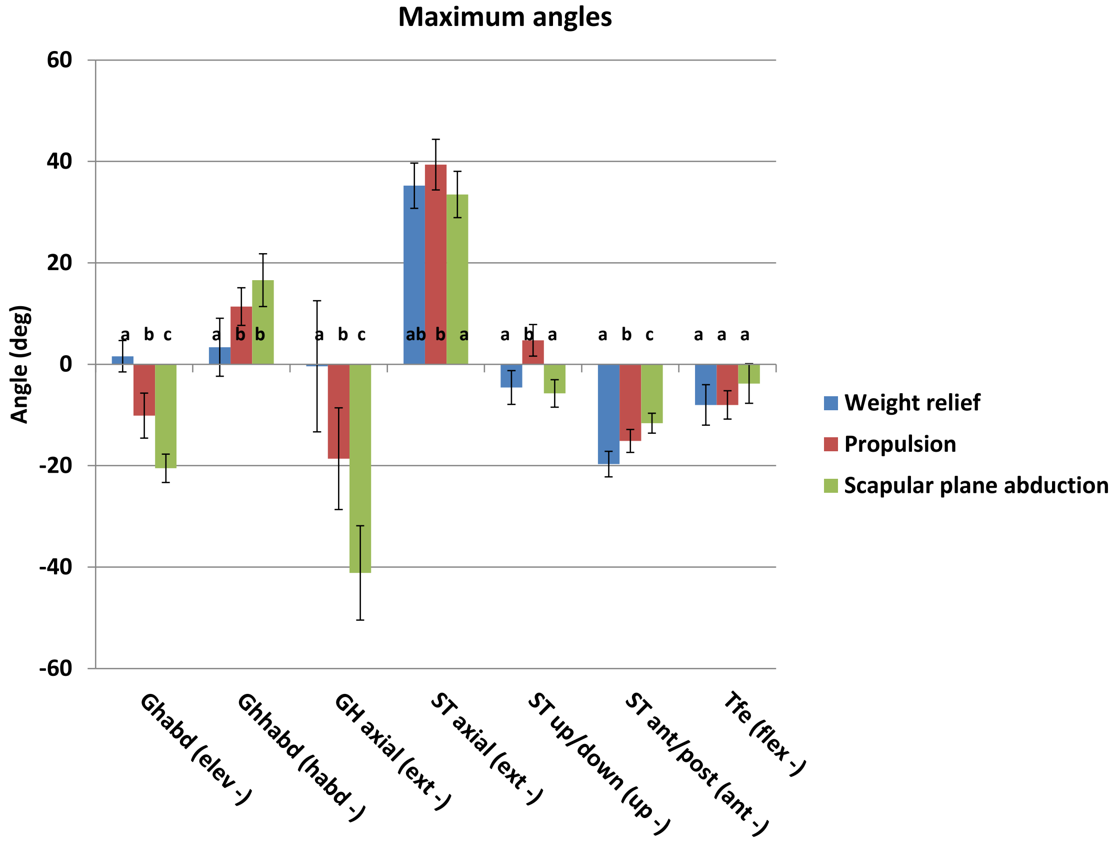


Figure D.11: Means and 95% confidence intervals for peak (positive) values for each angle for all three tasks in degrees (deg). Letters indicate significance; the same letter indicates no significant difference between values (GHabd=glenohumeral elevation/lowering, GHhabd=glenohumeral horizontal abduction/adduction, GH axial= glenohumeral internal/external, ST axial=scapulothoracic internal/external, ST up=scapulothoracic upward/downward, ST ant/post=scapulothoracic anterior/posterior, and Tfe=trunk flexion/extension rotations).

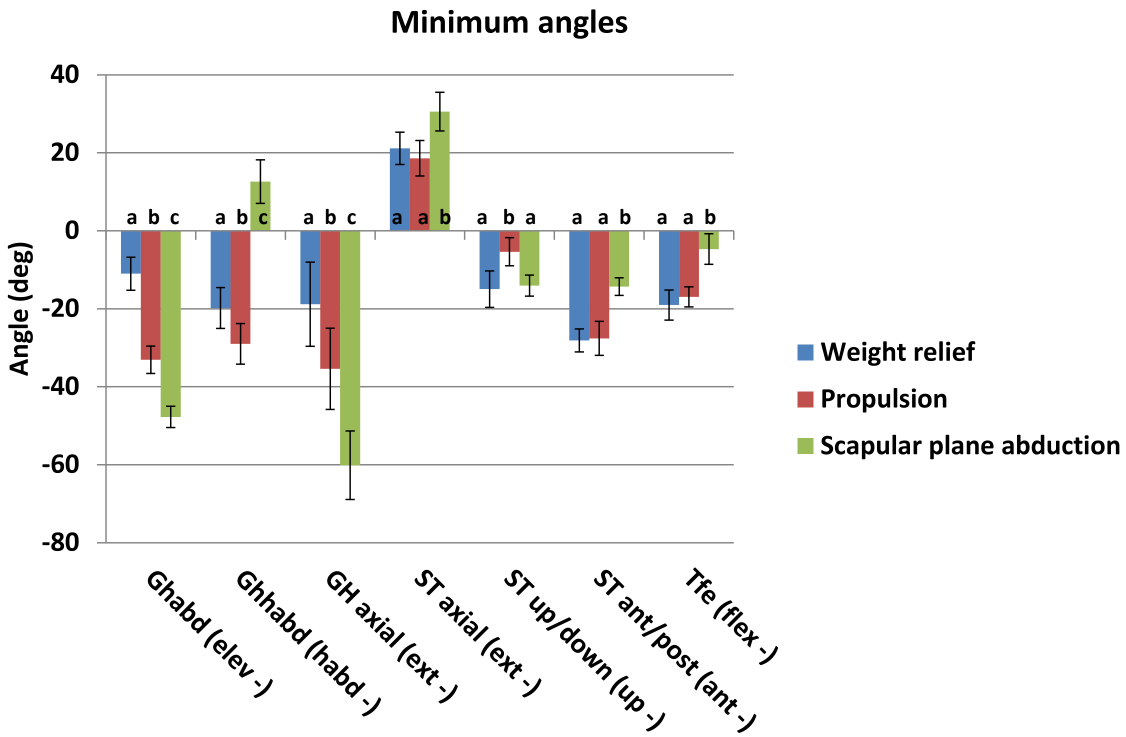


Figure D.12: Means and 95% confidence intervals for peak (negative) values for each angle for all three tasks in degrees (deg). Letters indicate significance; the same letter indicates no significant difference between values (GHabd=glenohumeral elevation/lowering, GHhabd=glenohumeral horizontal abduction/adduction, GH axial= glenohumeral internal/external, ST axial=scapulothoracic internal/external, ST up=scapulothoracic upward/downward, ST ant/post=scapulothoracic anterior/posterior, and Tfe=trunk flexion/extension rotations).

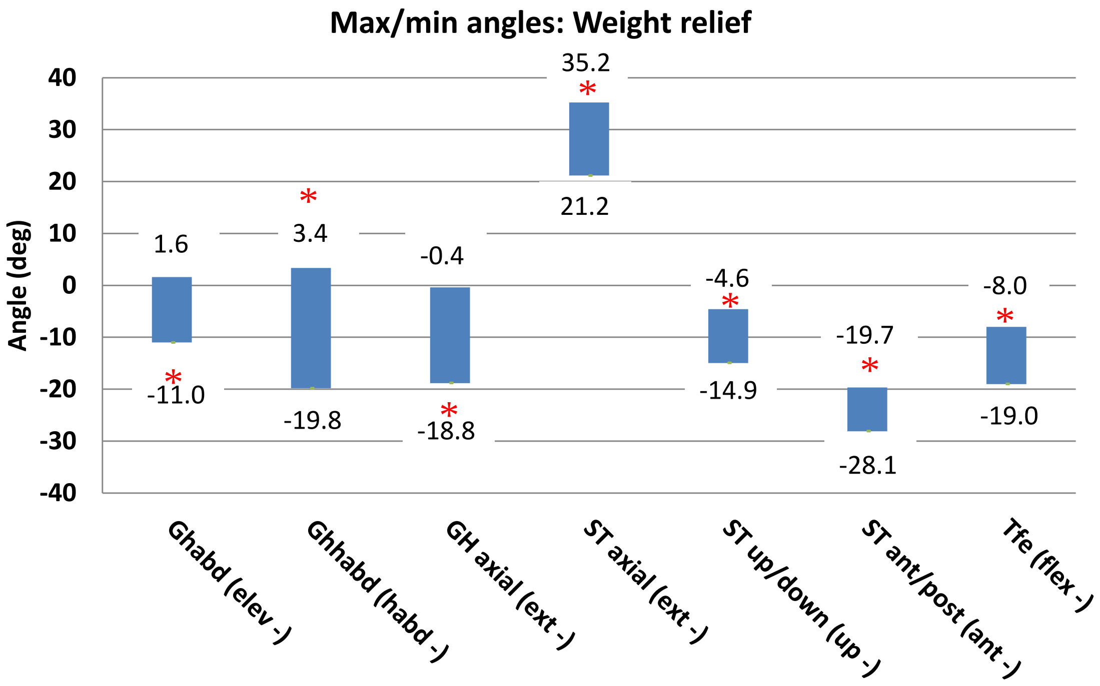


Figure D.13: Mean maximum and minimum angles (boxes) and static posture (red asterisks) in degrees (deg) for each angle during weight relief (GHabd=glenohumeral elevation/lowering, GHhabd=glenohumeral horizontal abduction/adduction, GH axial= glenohumeral internal/external, ST axial=scapulothoracic internal/external, ST up=scapulothoracic upward/downward, ST ant/post=scapulothoracic anterior/posterior, and Tfe=trunk flexion/extension rotations).

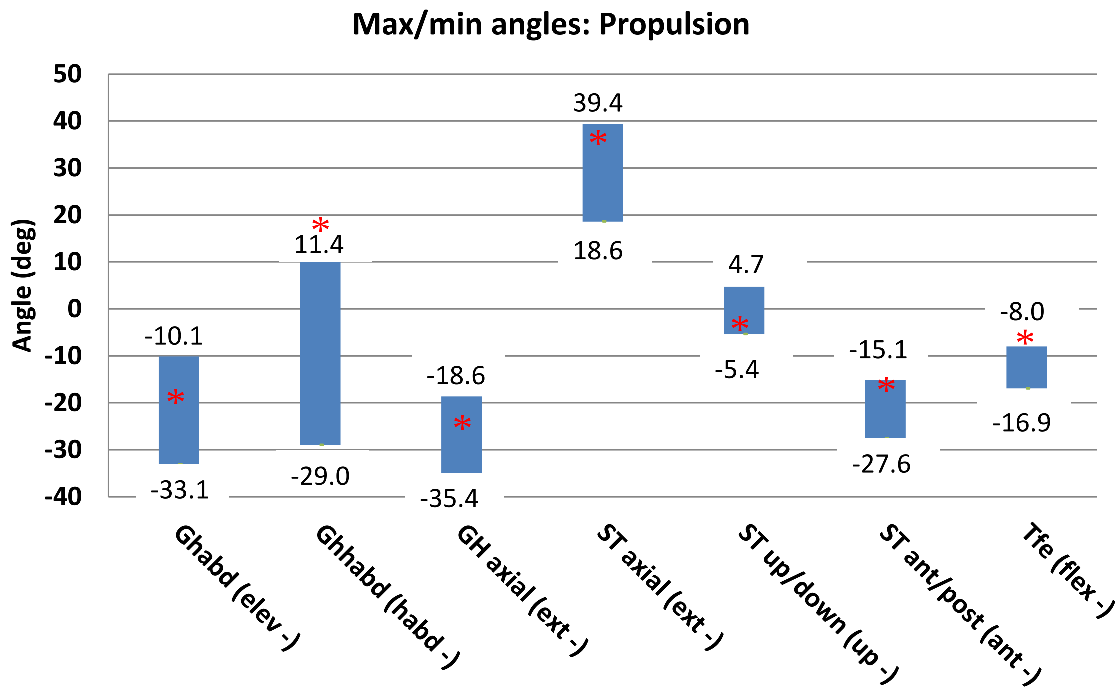


Figure D.14: Mean maximum and minimum angles (boxes) and static posture (red asterisks) in degrees (deg) for each angle during propulsion (GHabd=glenohumeral elevation/lowering, GHhabd=glenohumeral horizontal abduction/adduction, GH axial= glenohumeral internal/external, ST axial=scapulothoracic internal/external, ST up=scapulothoracic upward/downward, ST ant/post=scapulothoracic anterior/posterior, and Tfe=trunk flexion/extension rotations).

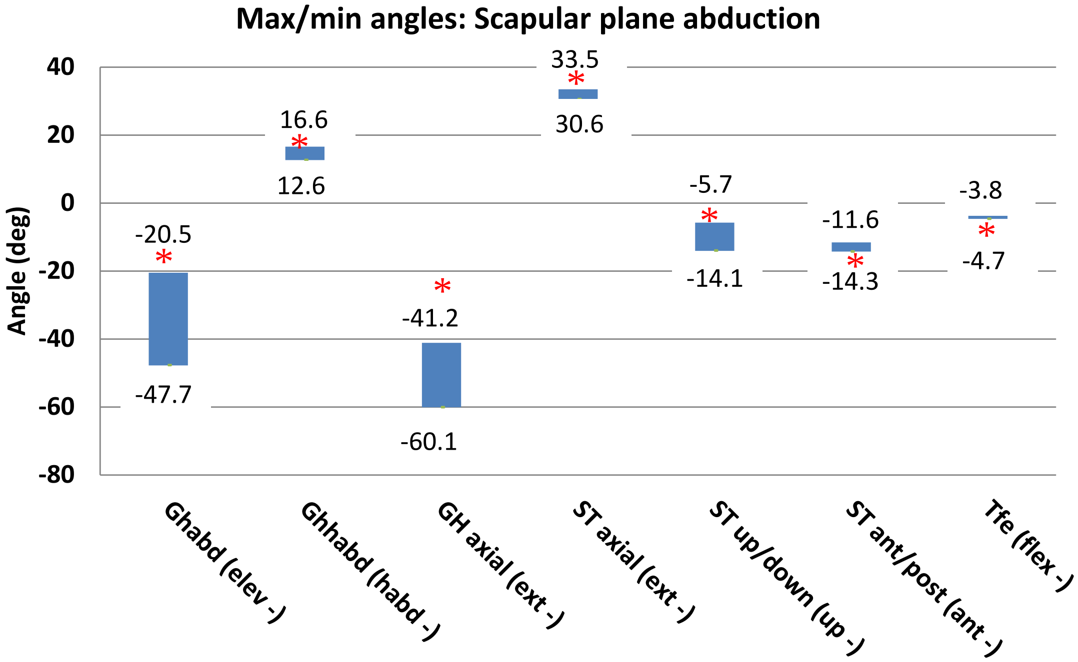


Figure D.15: Mean maximum and minimum angles (boxes) and static posture (red asterisks) in degrees (deg) for each angle during scapular plane abduction (GHabd=glenohumeral elevation/lowering, GHhabd=glenohumeral horizontal abduction/adduction, GH axial= glenohumeral internal/external, ST axial=scapulothoracic internal/external, ST up=scapulothoracic upward/downward, ST ant/post=scapulothoracic anterior/posterior, and Tfe=trunk flexion/extension rotations).

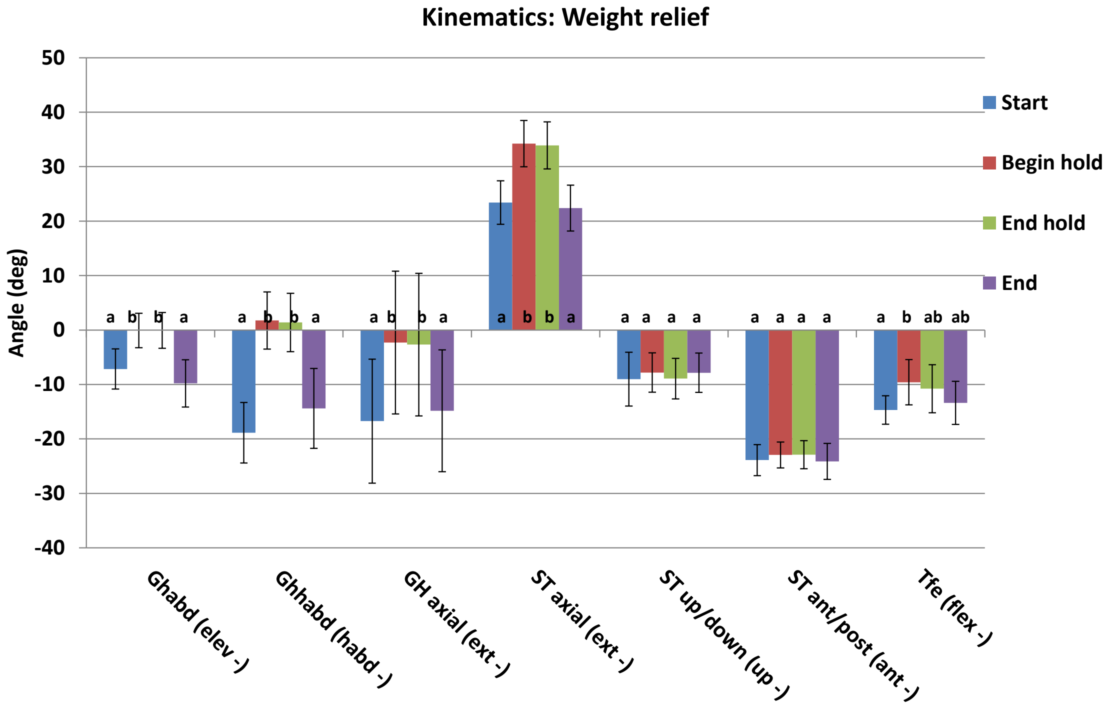


Figure D.16: Means and 95% confidence intervals for the four events (start, begin hold, end hold, end) during weight relief in degrees (deg). Letters indicate significance; the same letter indicates lack of significant difference between values (GHabd=glenohumeral elevation/lowering, GHhabd=glenohumeral horizontal abduction/adduction, GH axial= glenohumeral internal/external, ST axial=scapulothoracic internal/external, ST up=scapulothoracic upward/downward, ST ant/post=scapulothoracic anterior/posterior, and Tfe=trunk flexion/extension rotations).

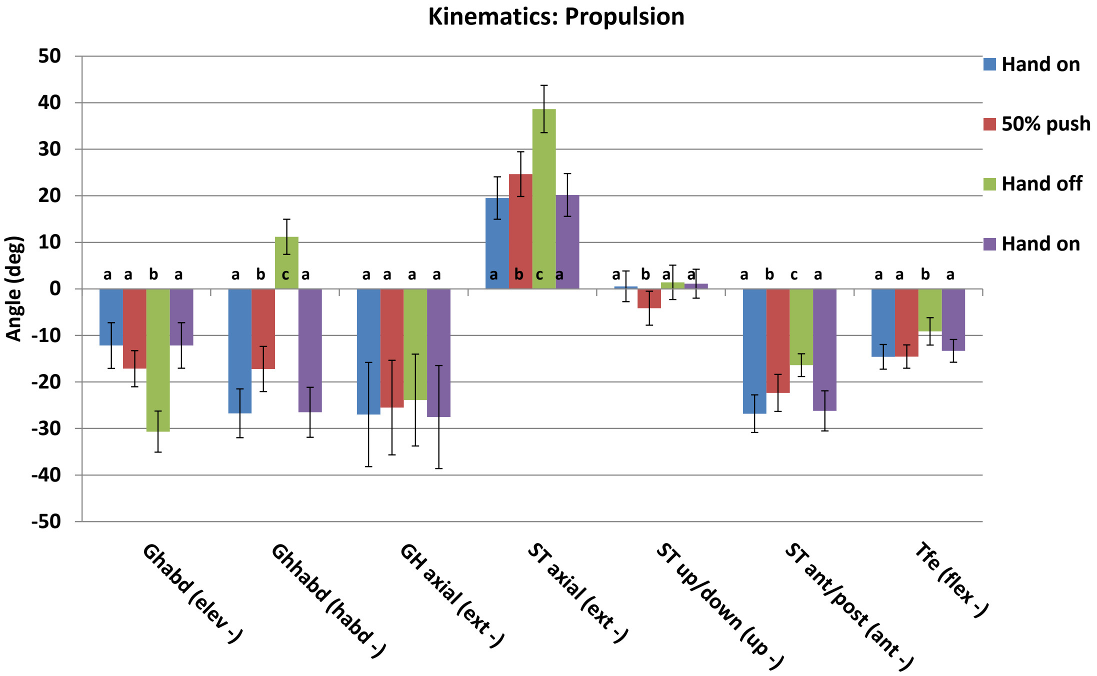


Figure D.17: Means and 95% confidence intervals for the four events (hand on, 50% push, hand off, hand on) during propulsion in degrees (deg). Letters indicate significance; the same letter indicates lack of significant difference between values (GHabd=glenohumeral elevation/lowering, GHhabd=glenohumeral horizontal abduction/adduction, GH axial= glenohumeral internal/external, ST axial=scapulothoracic internal/external, ST up=scapulothoracic upward/downward, ST ant/post=scapulothoracic anterior/posterior, and Tfe=trunk flexion/extension rotations).

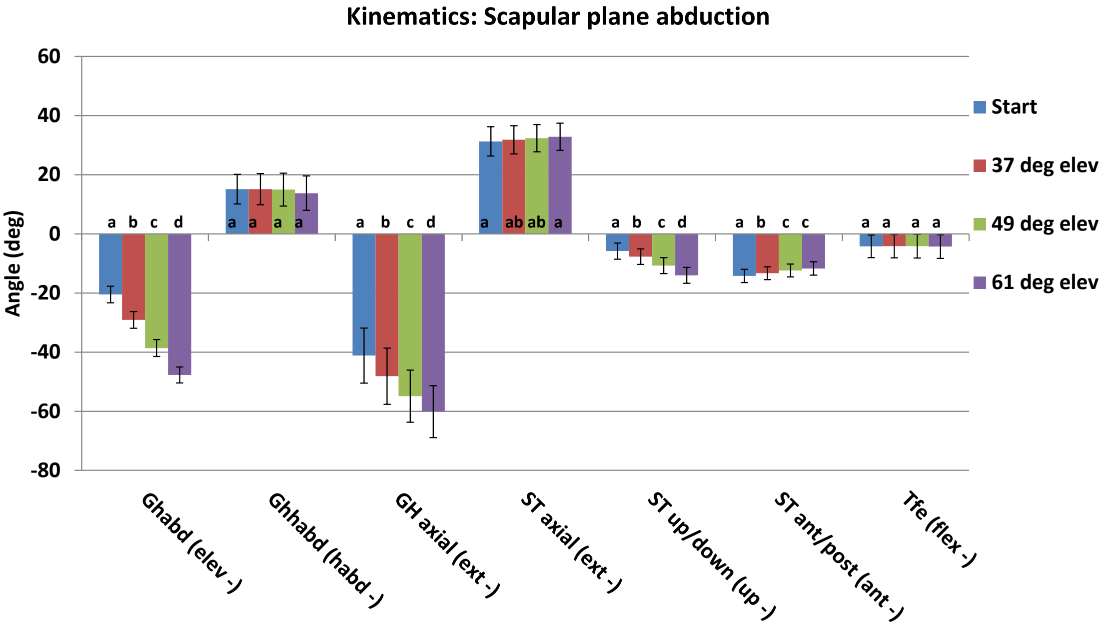


Figure D.18: Means and 95% confidence intervals for the four events (start, 37 deg elev, 49 deg elev, 61 deg elev) during scapular plane abduction in degrees (deg). Letters indicate significance; the same letter indicates lack of significant difference between values (GHabd=glenohumeral elevation/lowering, GHhabd=glenohumeral horizontal abduction/adduction, GH axial= glenohumeral internal/external, ST axial=scapulothoracic internal/external, ST up=scapulothoracic upward/downward, ST ant/post=scapulothoracic anterior/posterior, and Tfe=trunk flexion/extension rotations).

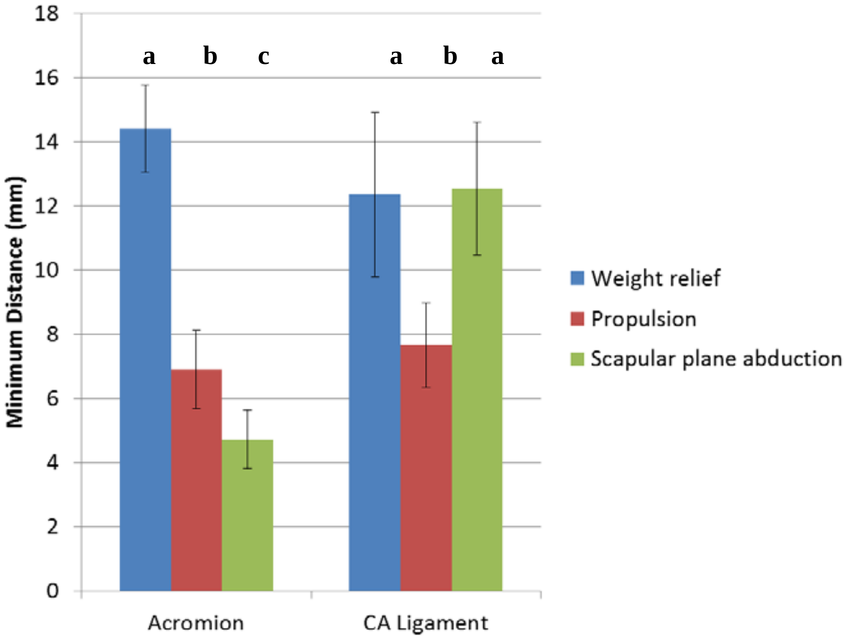


Figure D.19: Means and 95% confidence interval values for between-task comparison of mean minimum linear distances (in mm) to the acromion and coracoacromial ligament (CA ligament) for all three tendons (subscapularis, supraspinatus, infraspinatus). Letters indicate significance; the same letter indicates lack of significant difference between values.

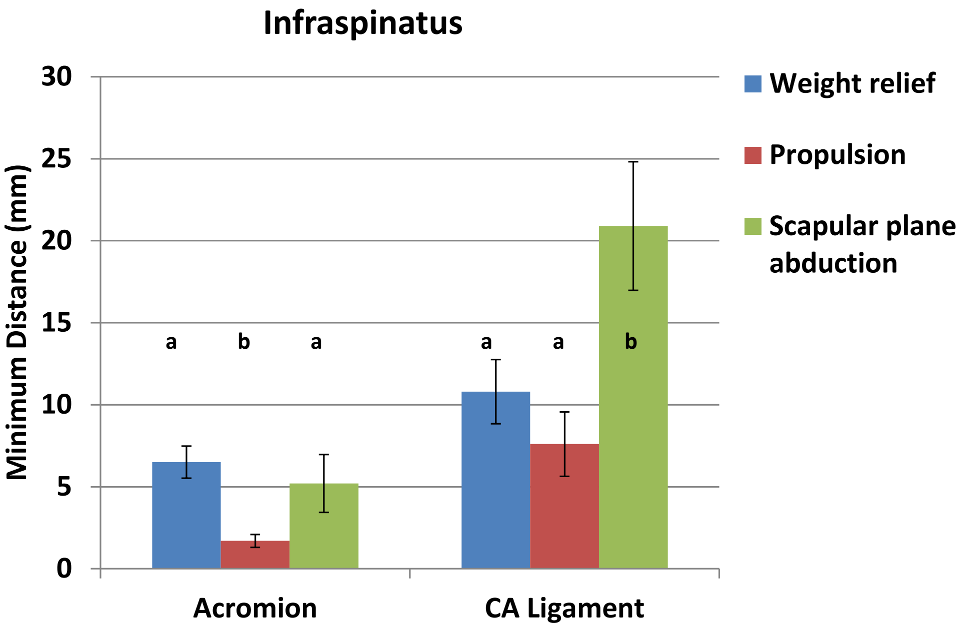


Figure D.20: Means and 95% confidence interval values for between-task comparison of minimum linear distances (in mm) to the acromion and coracoacromial ligament (CA ligament) for the infraspinatus tendon. Letters indicate significance; the same letter indicates lack of significant difference between values.

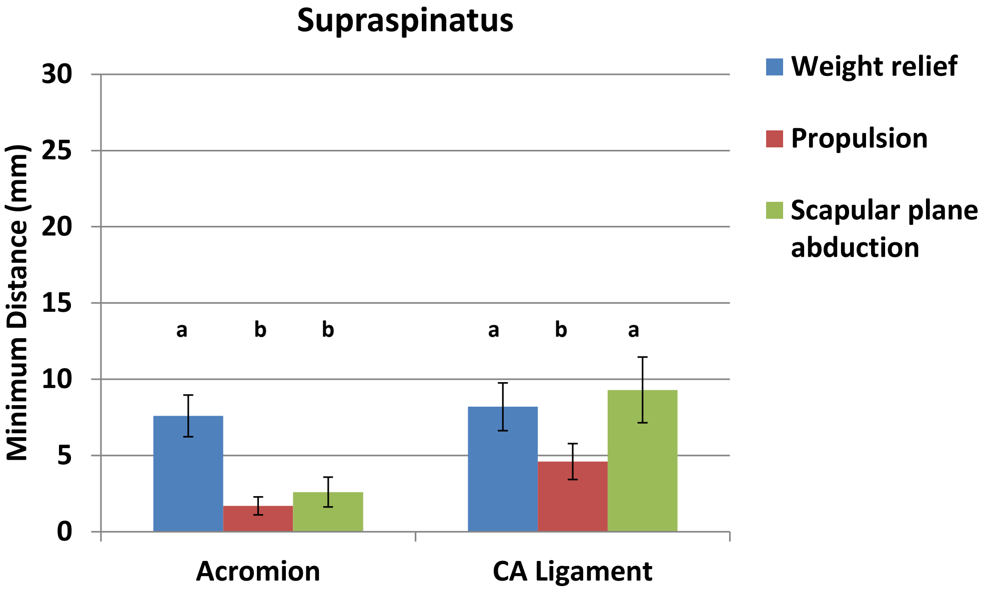


Figure D.21: Means and 95% confidence interval values for between-task comparison of minimum linear distances (in mm) to the acromion and coracoacromial ligament (CA ligament) for the supraspinatus tendon. Letters indicate significance; the same letter indicates lack of significant difference between values.

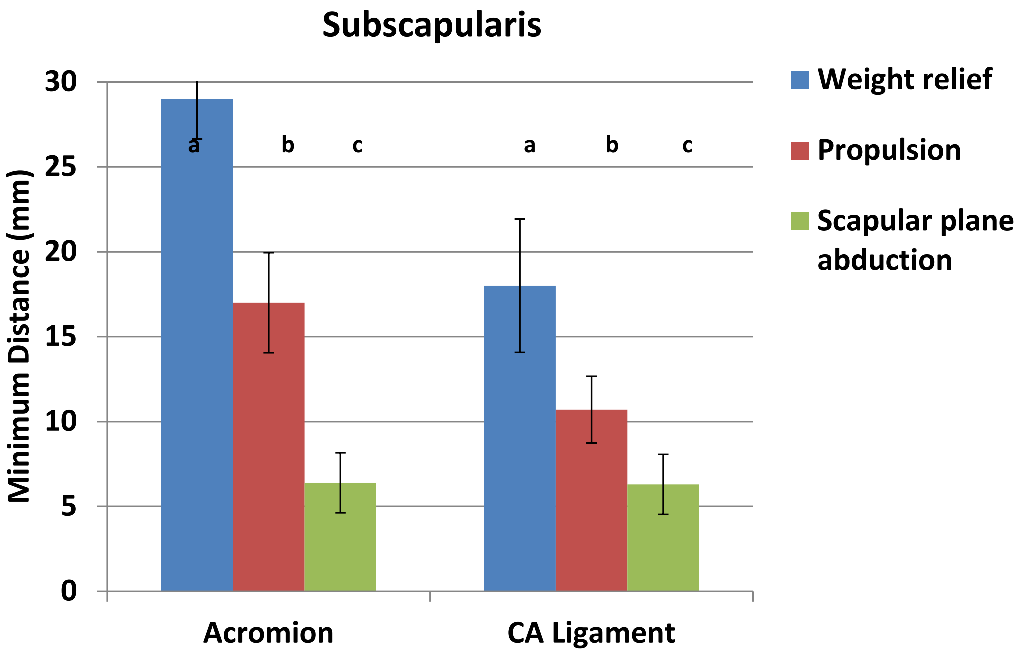


Figure D.22: Means and 95% confidence interval values for between-task comparison of minimum linear distances (in mm) to the acromion and coracoacromial ligament (CA ligament) for the subscapularis tendon. Letters indicate significance; the same letter indicates lack of significant difference between values.

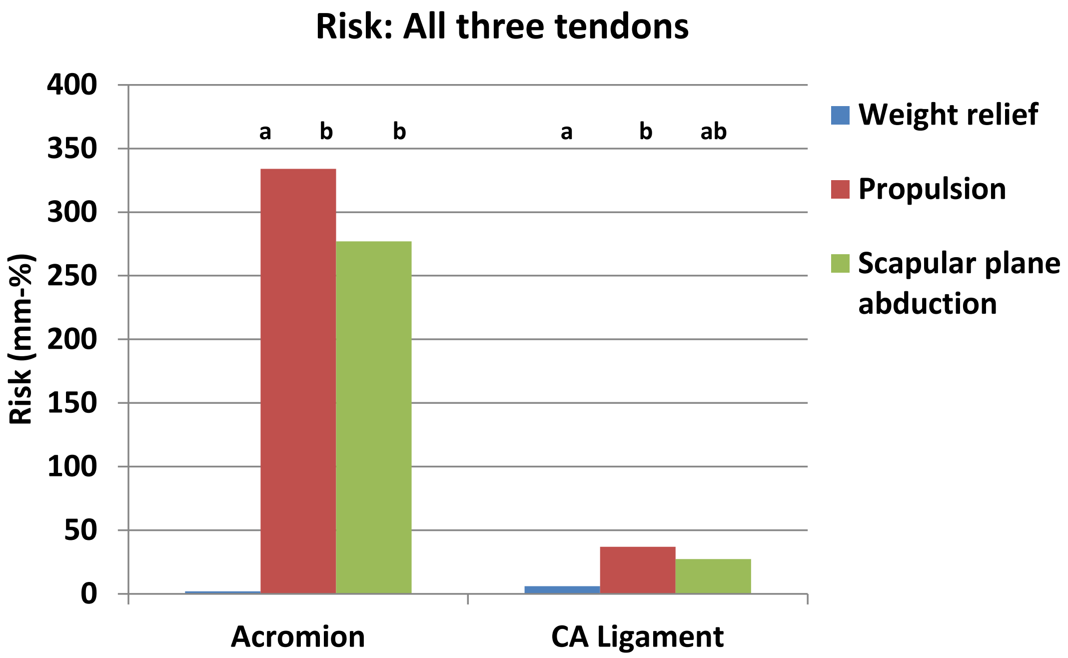


Figure D.23: Mean values for between-task comparison of risk (in mm-%) relative to the acromion and coracoacromial ligament (CA ligament) for all three tendons (subscapularis, supraspinatus, and infraspinatus). Letters indicate significance; the same letter indicates lack of significant difference between values.

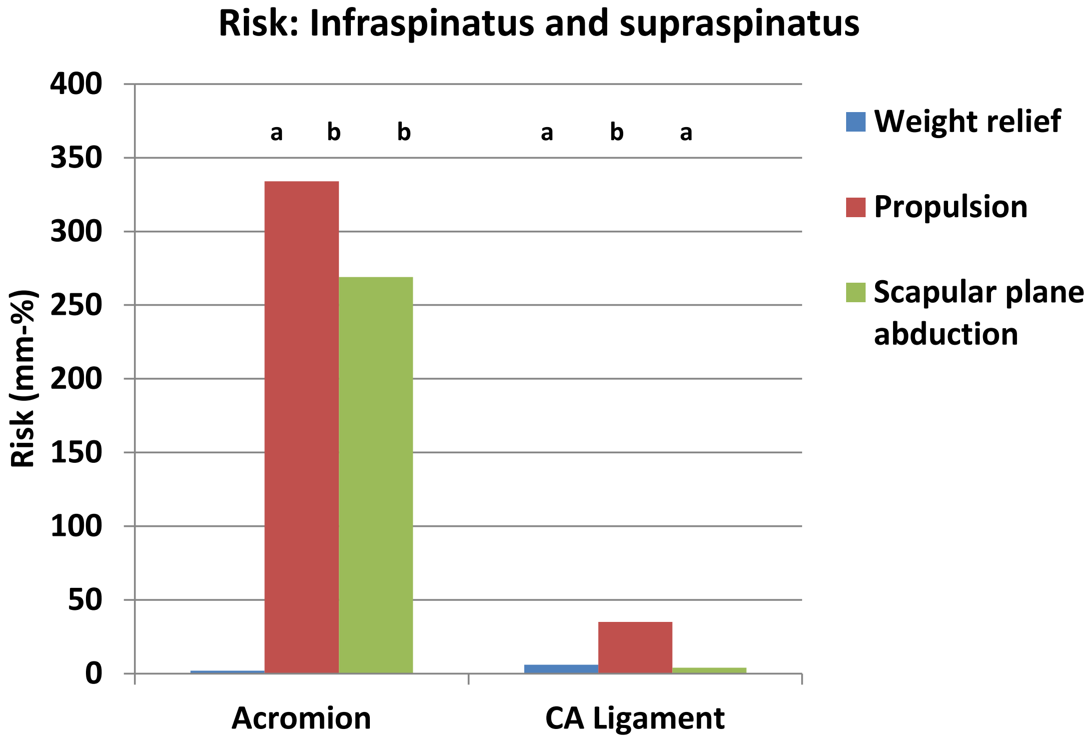
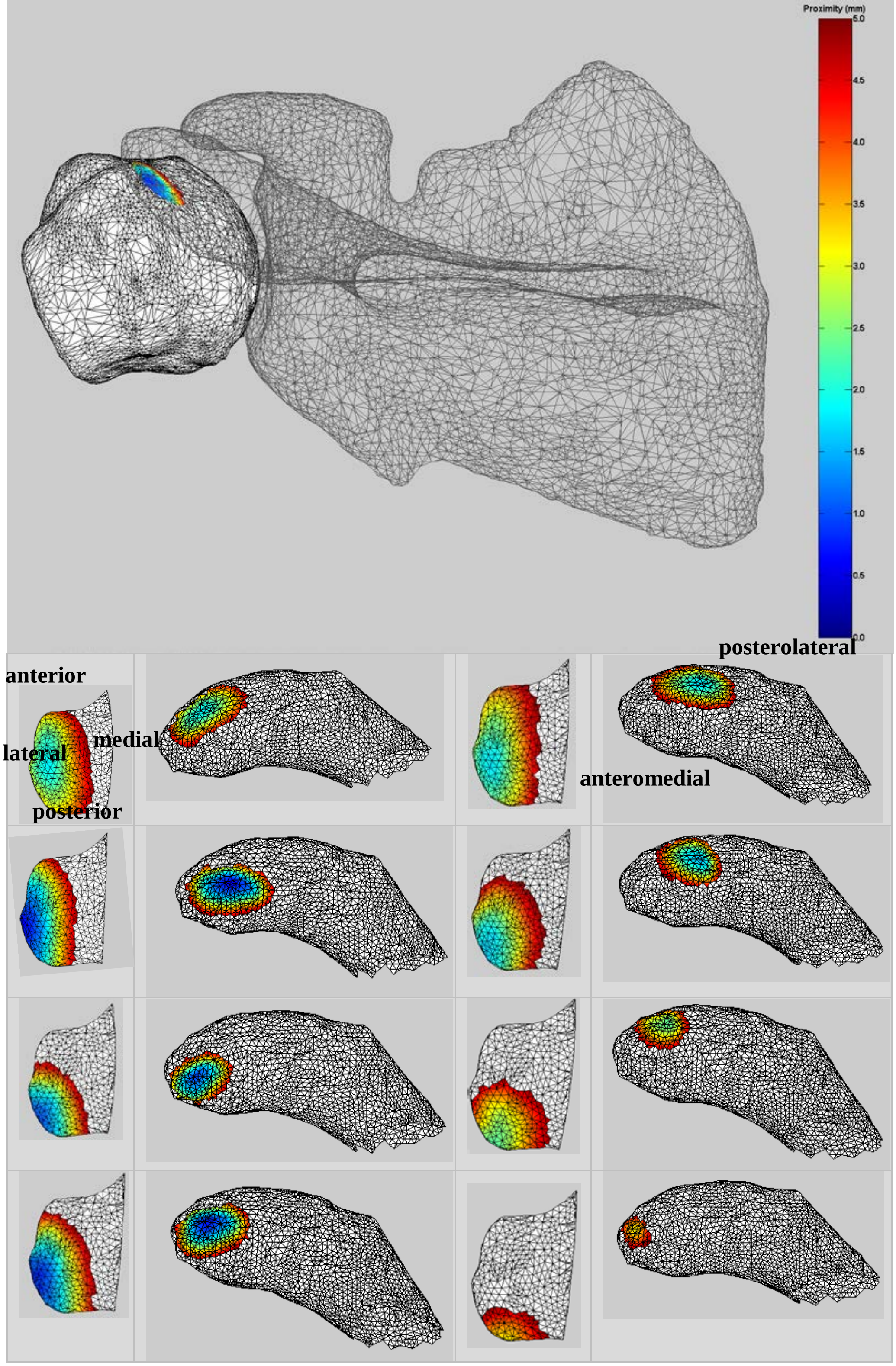
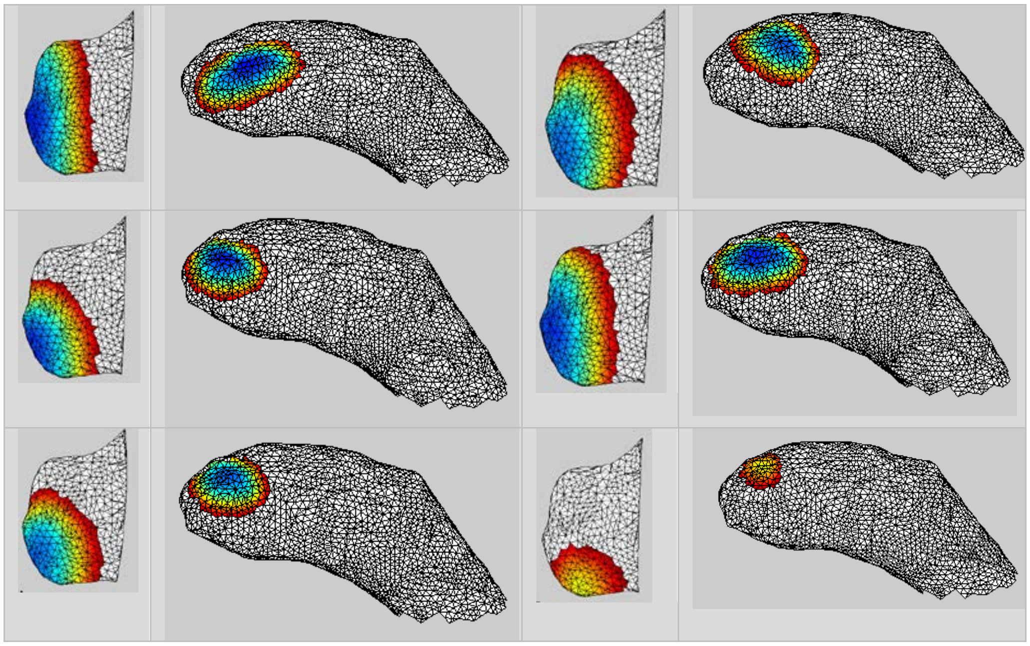


Figure D.24: Mean values for between-task comparison of risk (in mm-%) relative to the acromion and coracoacromial ligament (CA ligament) for the infraspinatus and supraspinatus tendons. Letters indicate significance; the same letter indicates lack of significant difference between values.

Supraspinatus to acromion (Propulsion)

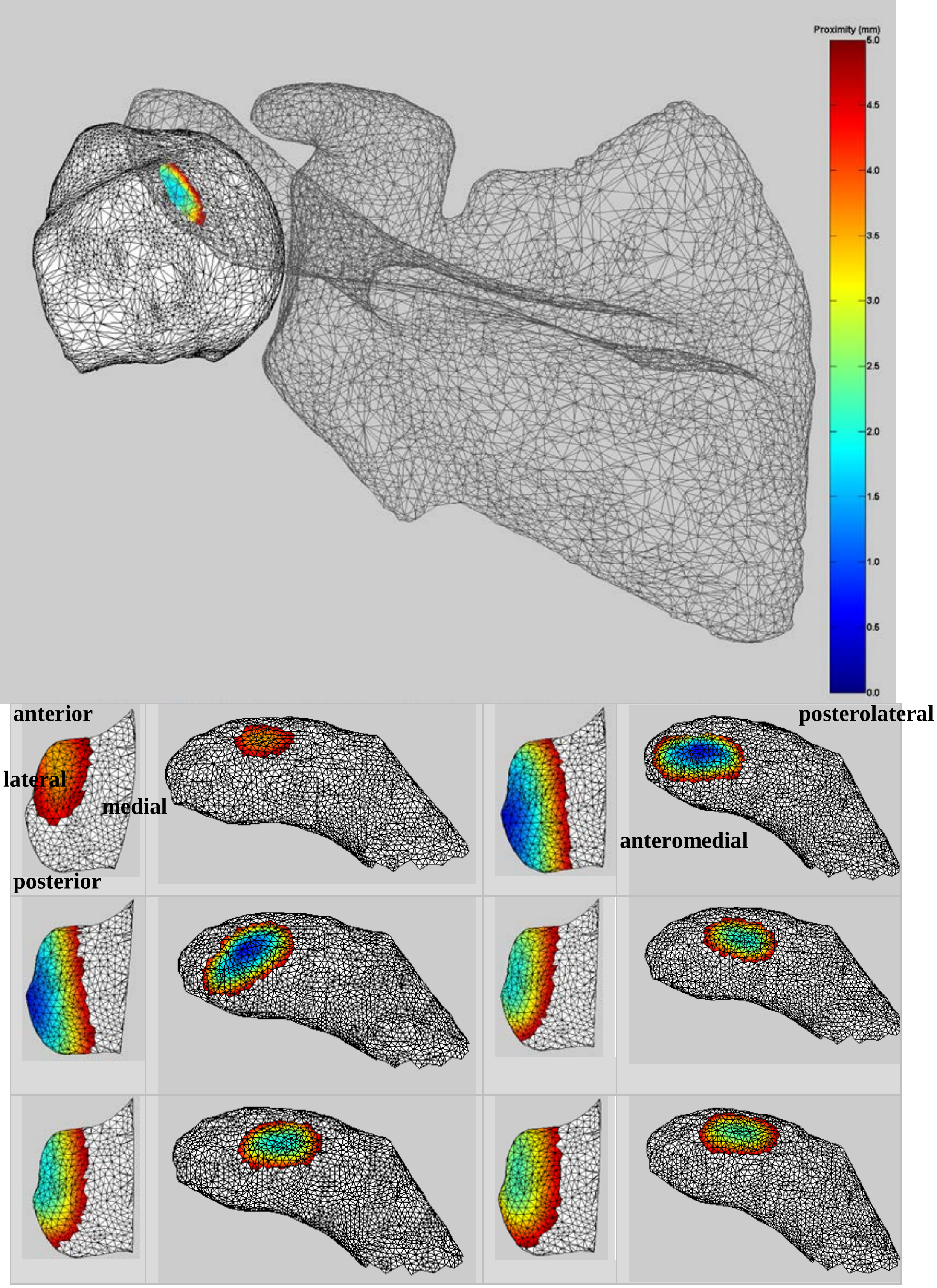


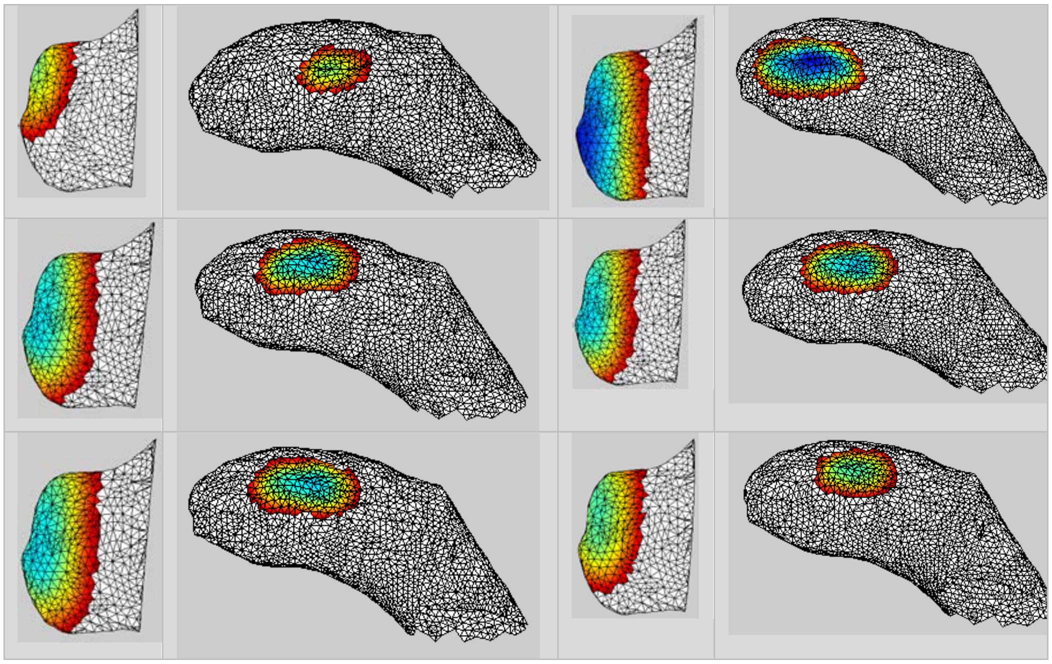


(*subject 8, no proximity less than 5mm)

Figure D.25: Glenohumeral position at the point of the least linear distance from the supraspinatus to the acromion during propulsion for a representative subject. Proximity maps (color range, blue = 0.0 mm and red = 5.0 mm) for each subject represented on the supraspinatus footprint and underside of the acromion.

Supraspinatus to acromion (scapular plane abduction)

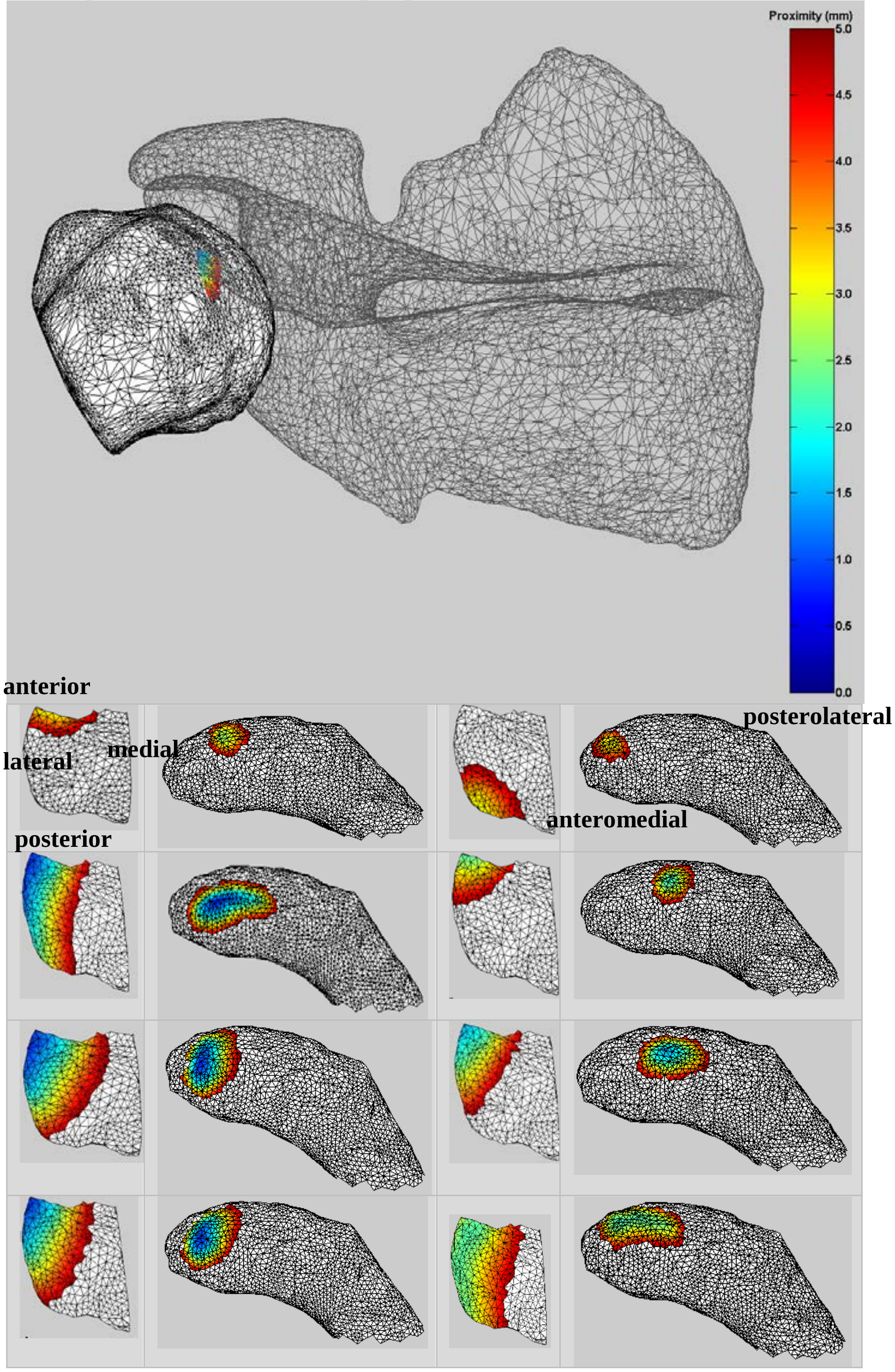




(*subject 2, 10, 13, no proximity less than 5mm)

Figure D.26: Glenohumeral position at the point of the least linear distance from the supraspinatus to the acromion during scapular plane abduction for a representative subject. Proximity maps (color range, blue = 0.0 mm and red = 5.0 mm) for each subject represented on the supraspinatus footprint and underside of the acromion.

Infraspinatus to acromion (propulsion)



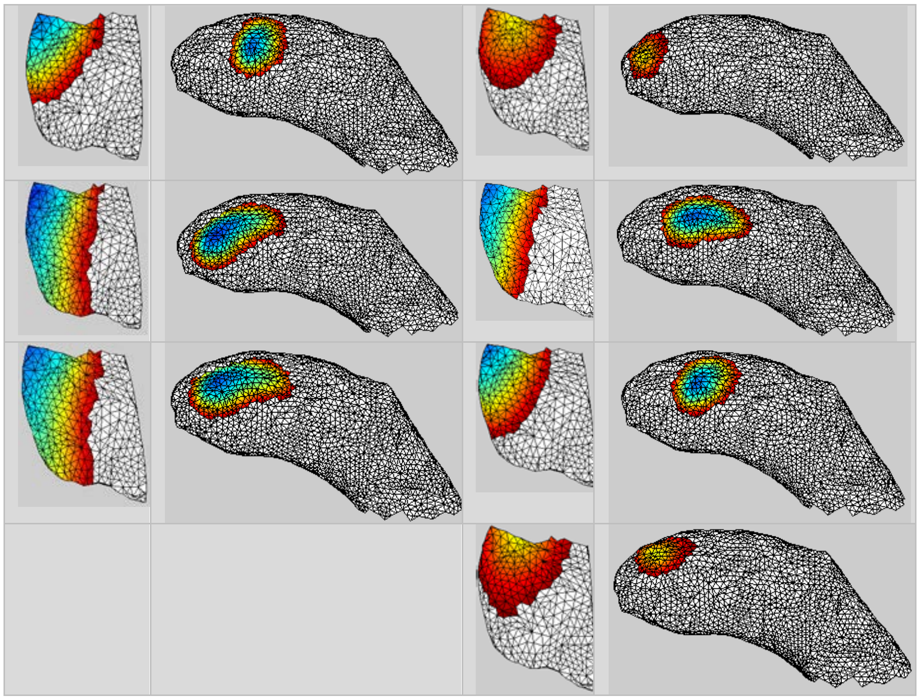
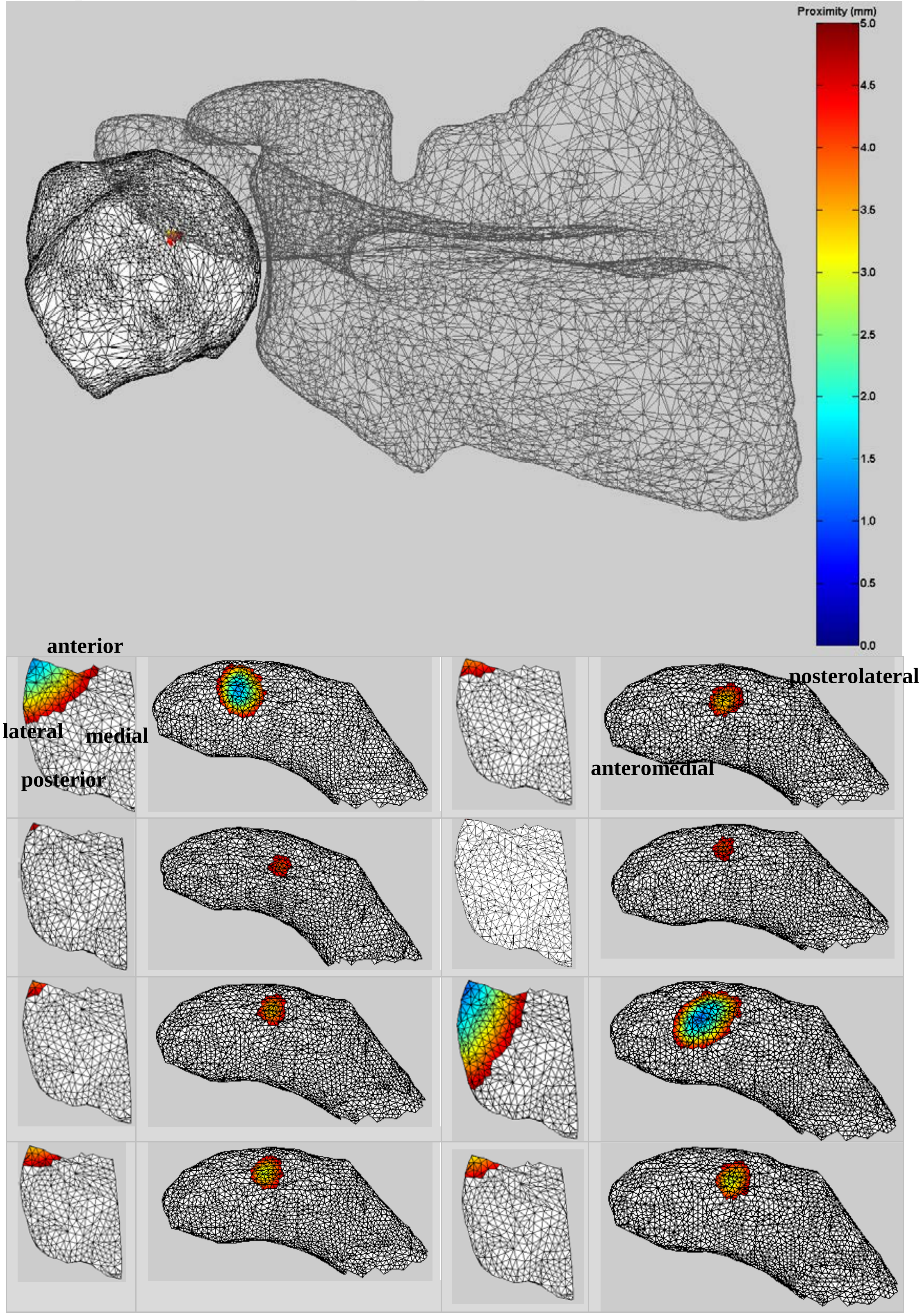
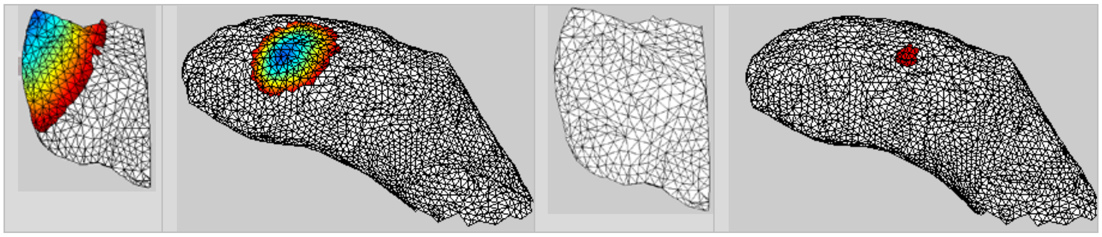


Figure D.27: Glenohumeral position at the point of the least linear distance from the infraspinatus to the acromion during propulsion for a representative subject. Proximity maps (color range, blue = 0.0 mm and red = 5.0 mm) for each subject represented on the infraspinatus footprint and underside of the acromion.

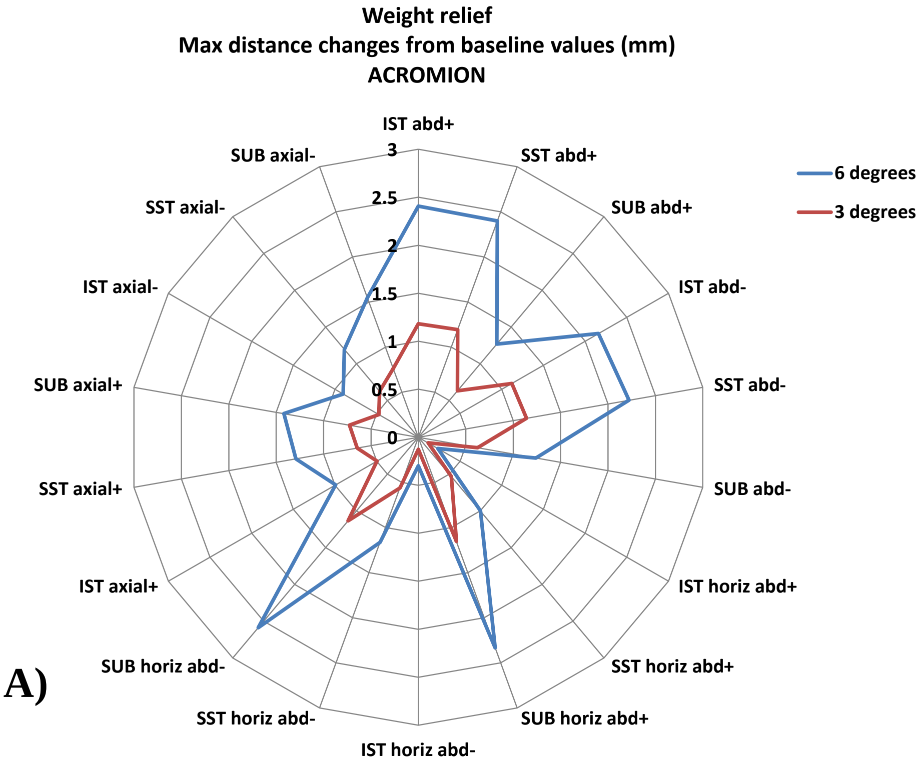
Infraspinatus to acromion (scapular plane abduction)



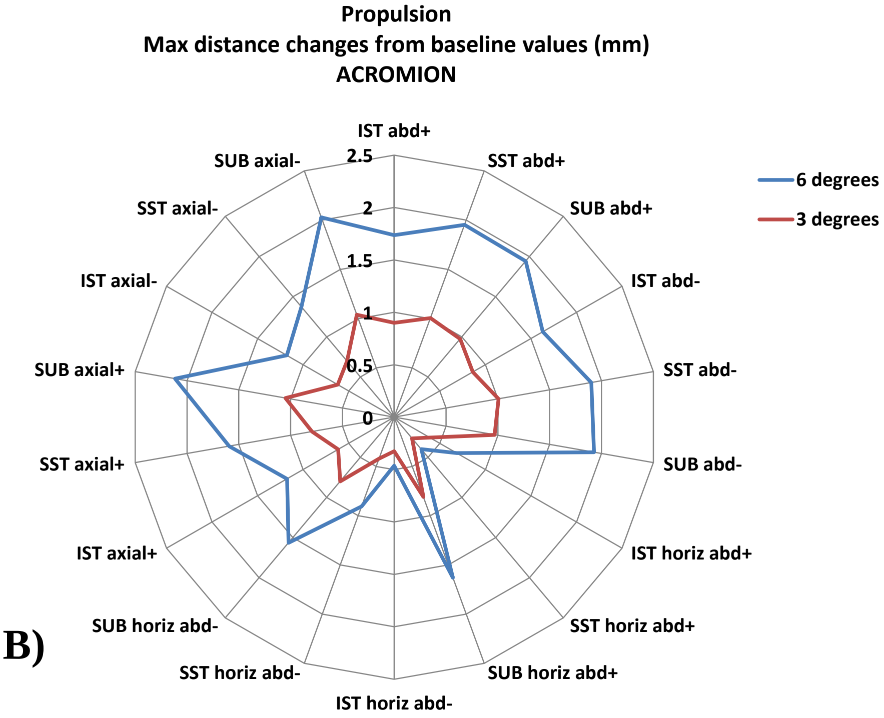


(*subjects 1,2,5,10,13 no proximity less than 5mm)

Figure D.28: Glenohumeral position at the point of the least linear distance from the infraspinatus to the acromion during scapular plane abduction for a representative subject. Proximity maps (color range, blue = 0.0 mm and red = 5.0 mm) for each subject represented on the infraspinatus footprint and underside of the acromion.


Weight relief
Max distance changes from baseline values (mm)
ACROMION
IST abd+
SST abd+
SUB abd+
IST abd-
SST abd-
SUB abd-
IST horiz abd+
SST horiz abd+
SUB horiz abd+
IST horiz abd-
SST horiz abd-
SUB horiz abd-
IST axial+
SST axial+
SUB axial+
IST axial-
SST axial-
SUB axial-
3
2.5
2
1.5
1
0.5
0
6 degrees
3 degrees

A)


Propulsion
Max distance changes from baseline values (mm)
ACROMION
IST abd+
SST abd+
SUB abd+
IST abd-
SST abd-
SUB abd-
IST horiz abd+
SST horiz abd+
SUB horiz abd+
IST horiz abd-
SST horiz abd-
SUB horiz abd-
IST axial+
SST axial+
SUB axial+
IST axial-
SST axial-
SUB axial-
2.5
2
1.5
1
0.5
0
6 degrees
3 degrees

B)

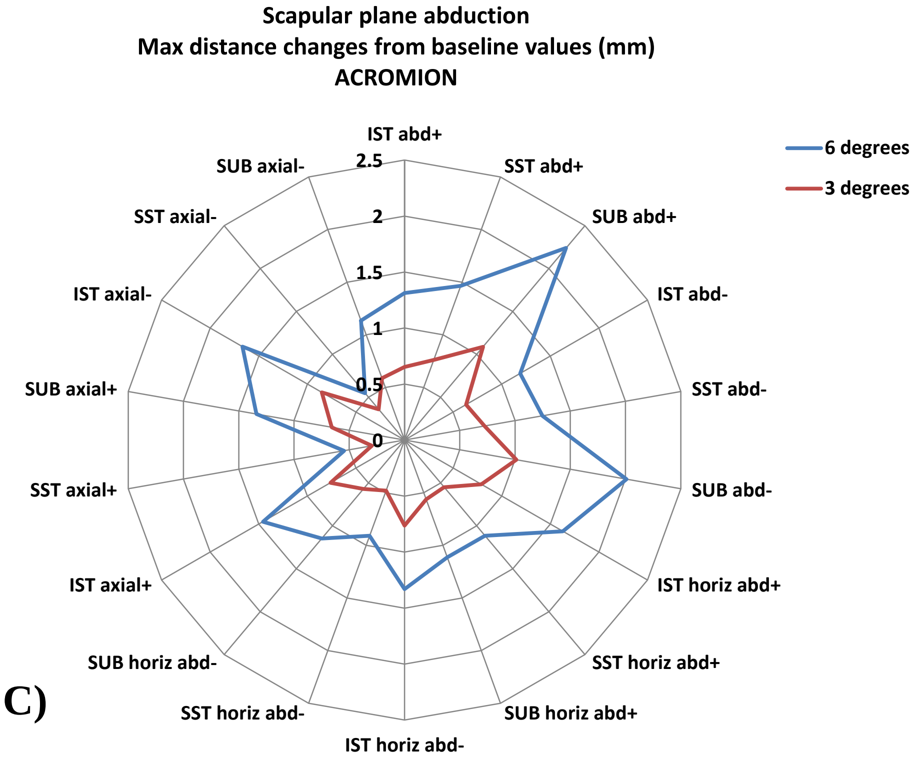
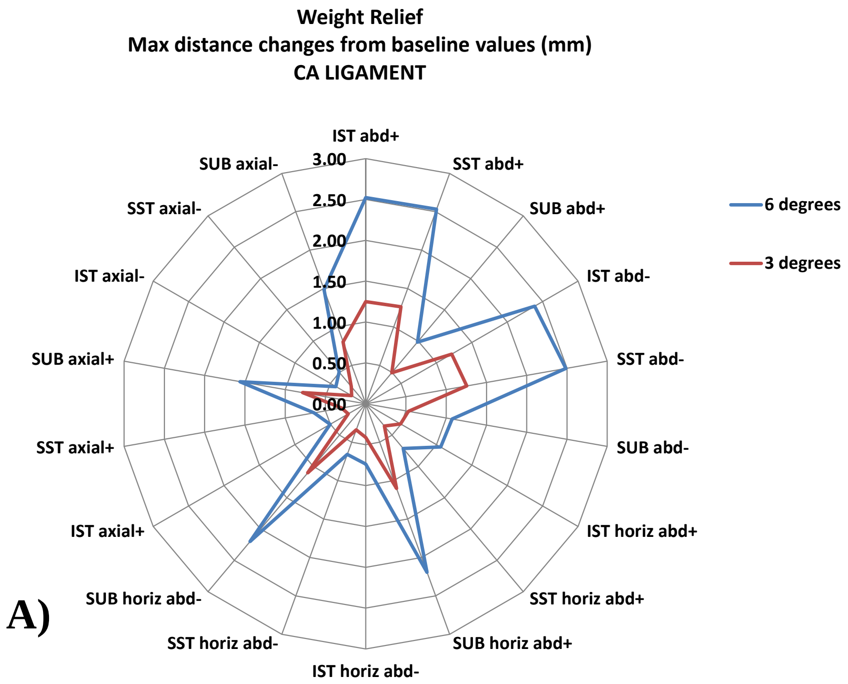
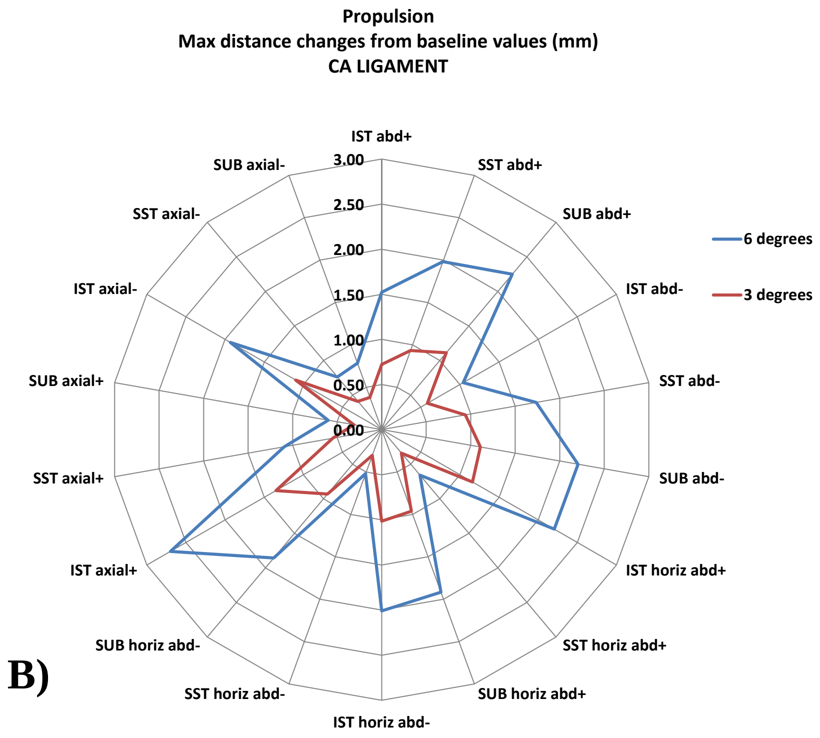


Figure D.29: Maximum absolute distance changes (in mm) from baseline for each angle/muscle as a result of ± 3 and ± 6 deg permutations in each rotation value across the movement cycle (+ indicates adding 3 or 6 deg, - indicates subtracting 3 or 6 degrees). Distances to the acromion during A) weight relief, B) propulsion, and C) scapular plane abduction are presented for each muscle (SUB=subscapularis, SST=supraspinatus, IST=infraspinatus) and each glenohumeral rotation (axial=axial rotation, abd=elevation/lowering, horiz abd=horizontal abduction/adduction).


Weight Relief
Max distance changes from baseline values (mm)
CA LIGAMENT
A)
IST abd+
SST abd+
SUB abd+
IST abd-
SST abd-
SUB abd-
IST horiz abd+
SST horiz abd+
SUB horiz abd+
IST horiz abd-
SST horiz abd-
SUB horiz abd-
IST axial+
SST axial+
SUB axial+
IST axial-
SST axial-
SUB axial-
3.00
2.50
2.00
1.50
1.00
0.50
0.00
6 degrees
3 degrees


Propulsion
Max distance changes from baseline values (mm)
CA LIGAMENT
B)
IST abd+
SST abd+
SUB abd+
IST abd-
SST abd-
SUB abd-
IST horiz abd+
SST horiz abd+
SUB horiz abd+
IST horiz abd-
SST horiz abd-
SUB horiz abd-
IST axial+
SST axial+
SUB axial+
IST axial-
SST axial-
SUB axial-
3.00
2.50
2.00
1.50
1.00
0.50
0.00
6 degrees
3 degrees

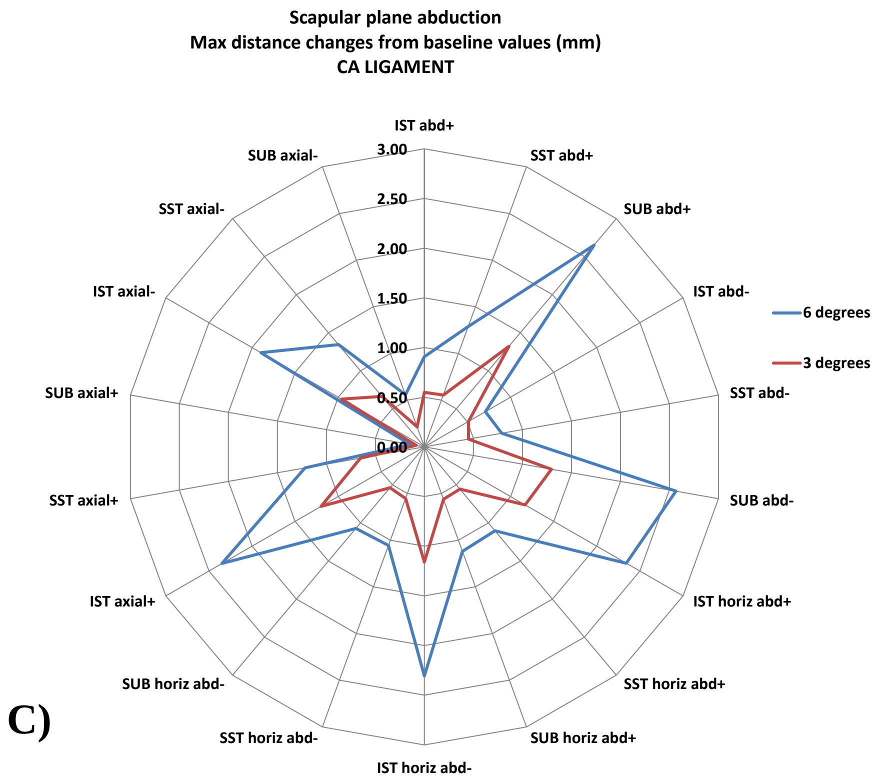


Figure D.30: Maximum absolute distance changes (in mm) from baseline for each angle/muscle as a result of ± 3 and ± 6 deg permutations in each rotation value across the movement cycle (+ indicates adding 3 or 6 deg, - indicates subtracting 3 or 6 degrees). Distances to the coracoacromial ligament (CA Ligament) during A) weight relief, B) propulsion, and C) scapular plane abduction are presented for each muscle (SUB=subscapularis, SST=supraspinatus, IST=infraspinatus) and each glenohumeral rotation (axial=axial rotation, abd=elevation/lowering, horiz abd=horizontal abduction/adduction).

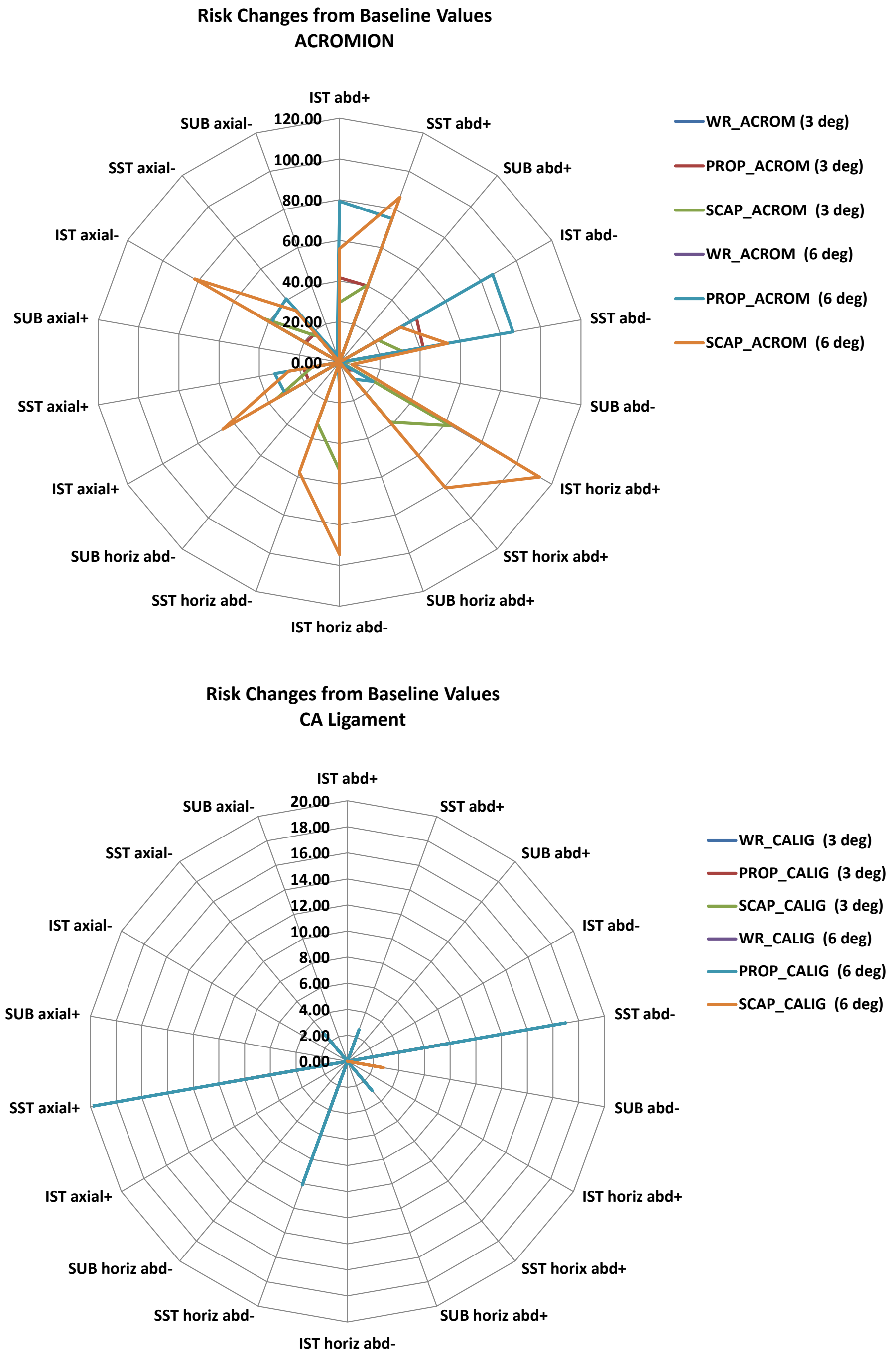
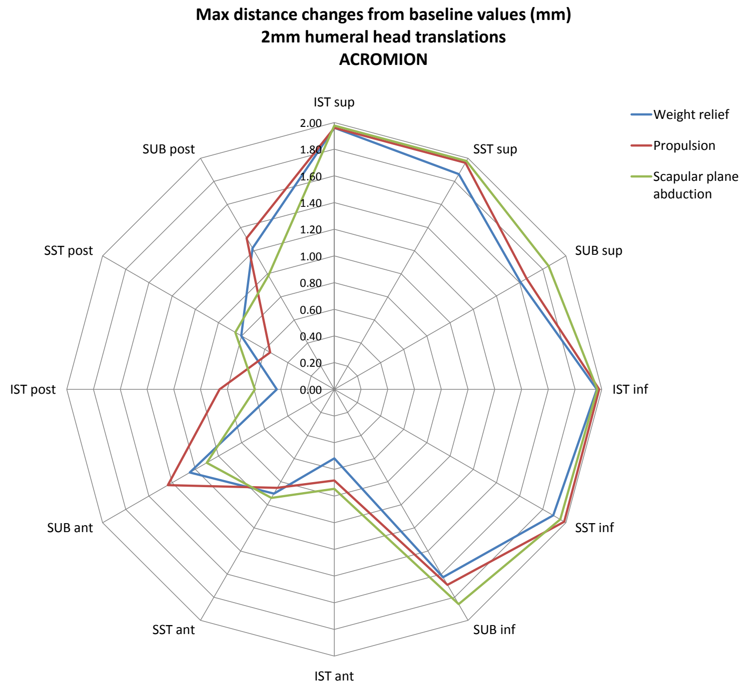


Figure D.31: Risk changes (in mm-%) from baseline for each angle/muscle as a result of ± 3 and ± 6 deg permutations in each rotation value across the movement cycle (+ indicates adding 3 or 6 deg, - indicates subtracting 3 or 6 degrees). Risk relative to the acromion and coracoacromial ligament (CA ligament) are presented (SUB=subscapularis, SST=supraspinatus, IST=infraspinatus, WR=weight relief, PROP=propulsion, SCAP=scapular plane abduction).



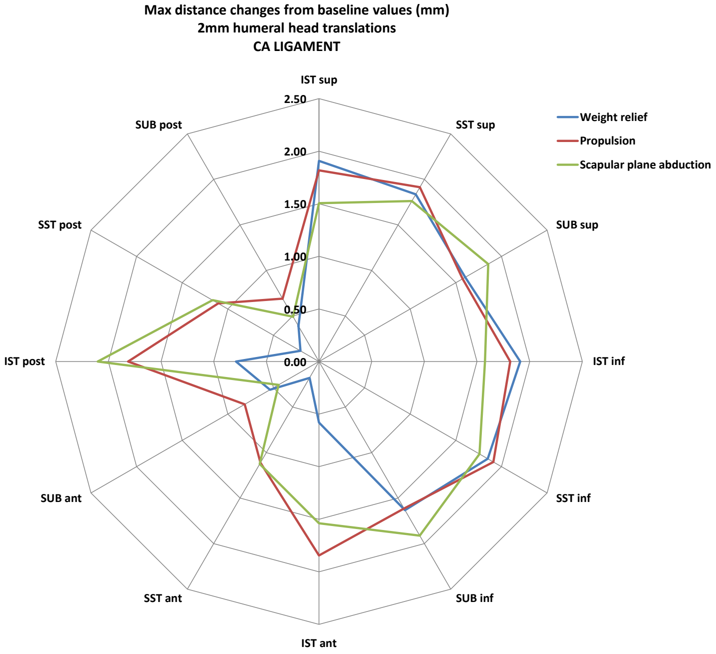


Figure D.32: Maximum absolute distance changes (in mm) from baseline for each angle/muscle as a result of 2mm translations of the humeral head across the movement cycle in the anterior, posterior, superior, and inferior directions. Distances to the acromion and CA ligament during all three tasks are presented (SUB=subscapularis, SST=supraspinatus, IST=infraspinatus, sup=superior, inf=inferior, ant=anterior, post=posterior, WR=weight relief, PROP=propulsion, SCAP=scapular plane abduction).

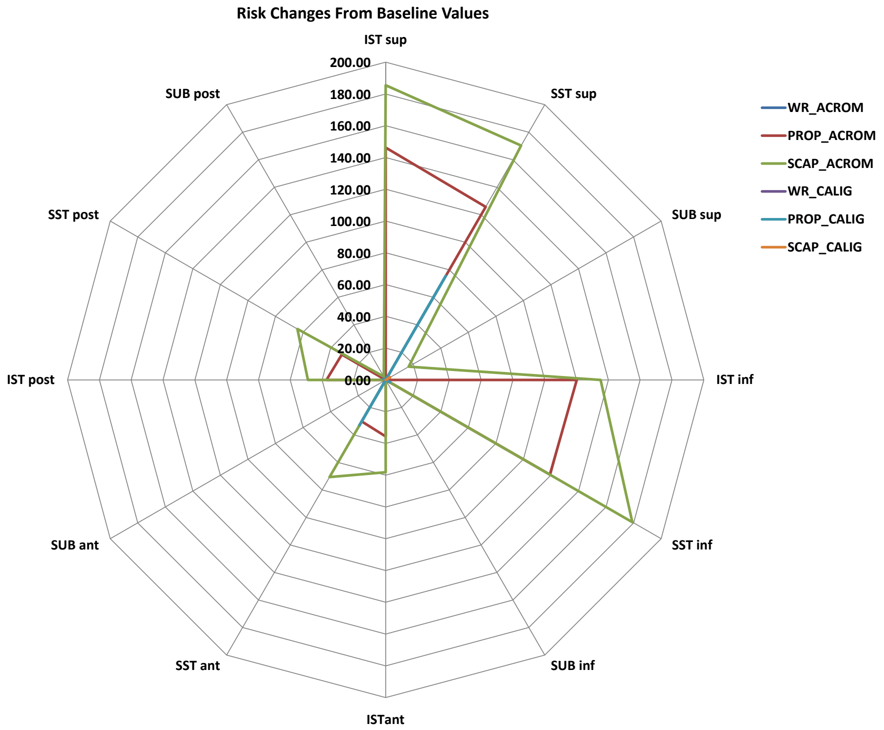


Figure D.33: Risk value changes (in mm-%) from baseline for each angle/muscle as a result of 2mm translations of the humeral head across the movement cycle in the superior, inferior, anterior, posterior directions. Risk relative to the acromion and coracoacromial ligament during all three tasks are presented (SUB=subscapularis, SST=supraspinatus, IST=infraspinatus, sup=superior, inf=inferior, ant=anterior, post=posterior, WR=weight relief, PROP=propulsion, SCAP=scapular plane abduction).

Figure E.34: Glenohumeral (GH) rotations calculated using two rotation sequences, XZ'Y'' and YX'Y'' in a representative subject during the weight relief task. The XZ'Y'' rotation sequence results in: GH abd(X) = glenohumeral elevation/lowering, GH horiz abd(Z') = glenohumeral horizontal abduction/adduction, and GH axial(Y'') =glenohumeral internal/external rotation. The YX'Y'' rotation sequence results in: GH plane (Y)= glenohumeral plane of elevation, GH elev(X')= glenohumeral elevation, and GH rot(Y'') = glenohumeral axial rotation. The sum of GH plane and GH rot (Y' and Y'') is also represented and is nearly coincident with GH axial.

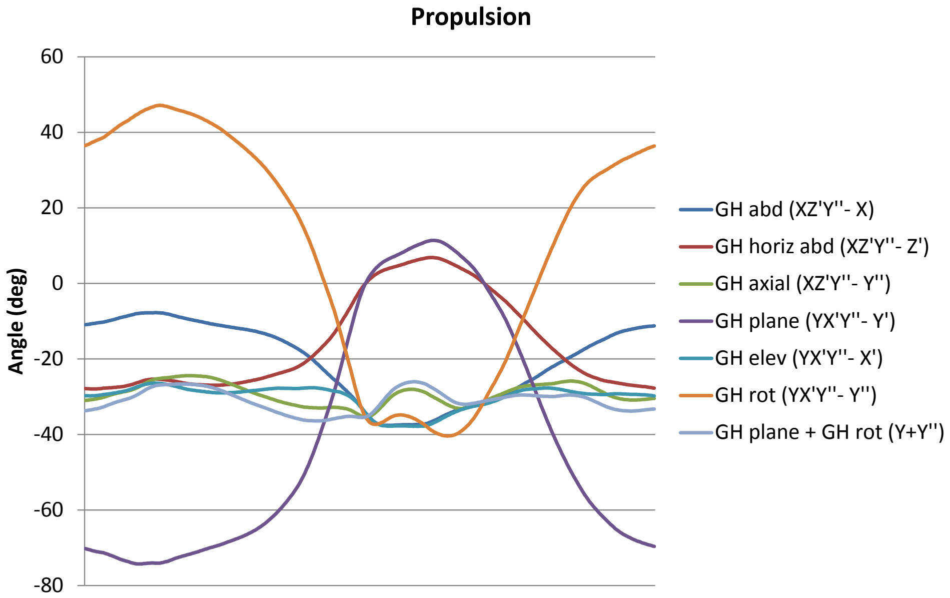


Figure E.35: Glenohumeral (GH) rotations calculated using two rotation sequences, XZ'Y'' and YX'Y'' in a representative subject during the propulsion task. The XZ'Y'' rotation sequence results in: GH abd(X) = glenohumeral elevation/lowering, GH horiz abd(Z') = glenohumeral horizontal abduction/adduction, and GH axial(Y'') =glenohumeral internal/external rotation. The YX'Y'' rotation sequence results in: GH plane (Y) = glenohumeral plane of elevation, GH elev(X') = glenohumeral elevation, and GH rot(Y'') = glenohumeral axial rotation. The sum of GH plane and GH rot (Y' and Y'') is also represented.

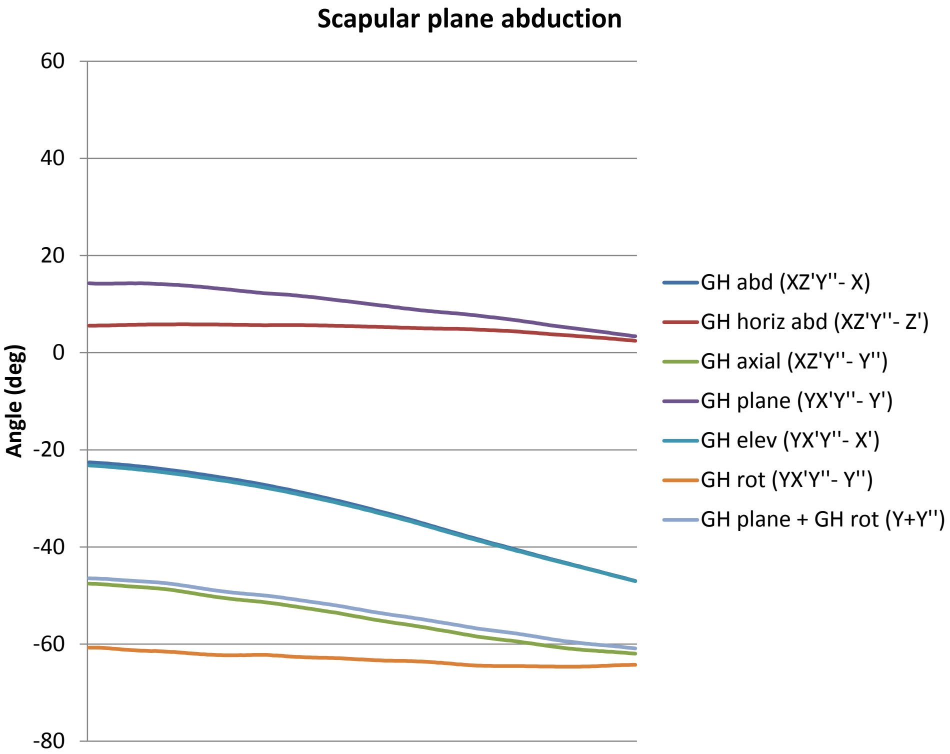


Figure E.36: Glenohumeral (GH) rotations calculated using two rotation sequences, XZ'Y'' and YX'Y'' in a representative subject during the scapular plane abduction task. The XZ'Y'' rotation sequence results in: GH abd(X) = glenohumeral elevation/lowering, GH horiz abd(Z') = glenohumeral horizontal abduction/adduction, and GH axial(Y'') = glenohumeral internal/external rotation. The YX'Y'' rotation sequence results in: GH plane (Y) = glenohumeral plane of elevation, GH elev(X') = glenohumeral elevation, and GH rot(Y'') = glenohumeral axial rotation. The sum of GH plane and GH rot (Y' and Y'') is also represented.

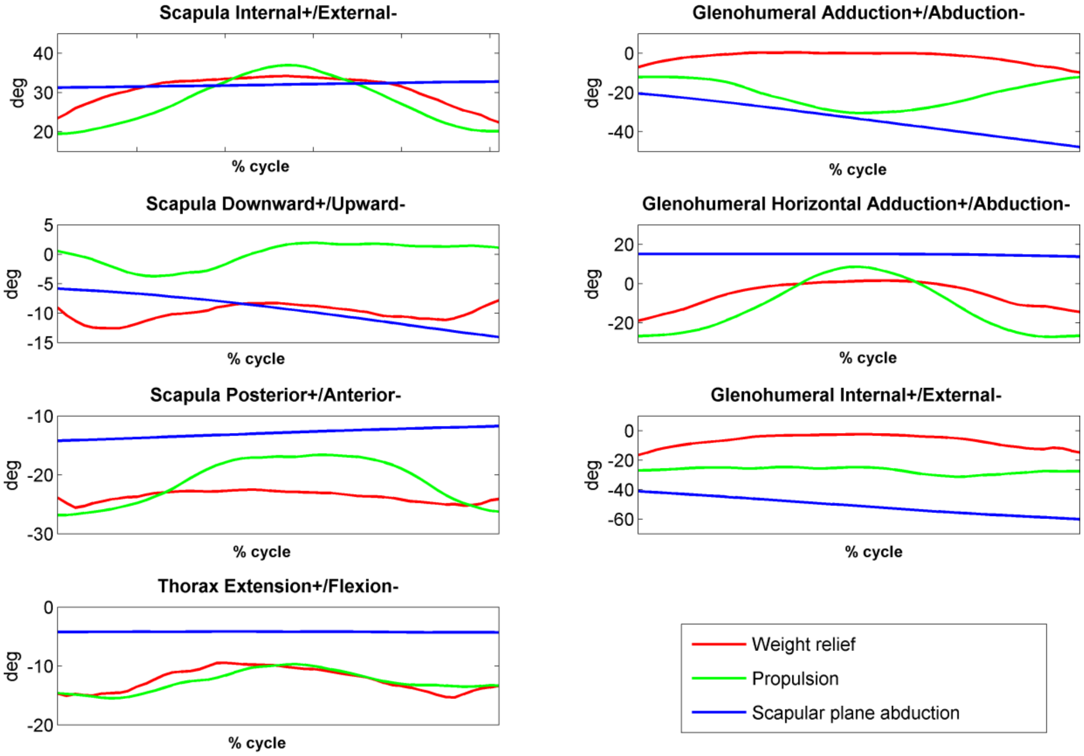


Figure E.37: Subjects' scapulothoracic (scapula internal+/external-, scapula downward+/upward-, scapula posterior+/anterior-), glenohumeral (glenohumeral lowering+/elevation-, glenohumeral horizontal adduction+/abduction-, glenohumeral internal+/external-, and thorax (thorax extension+/flexion-) rotations averaged across the cycles of weight relief, propulsion, and scapular plane abduction.

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APPENDICES

Appendix 1: Consent form

Name and Clinic Number

IRB # **11-000900 00**
Consent form approved **April 12, 2012**;
This consent valid through **March 21, 2013**;

1. General Information About This Research Study

Study Title: A Rehabilitation Program for Manual Wheelchair Users with Shoulder Pain

Name of Principal Investigator on this Study: Kristin D. Zhao, and Colleagues

A. Study Eligibility and Purpose

You are being asked to take part in this research study because you use a manual wheelchair and are currently experiencing shoulder pain. We are studying whether a home-based exercise program can help reduce your shoulder pain.

As you read this form describing the study, ask any questions you have. Take your time to decide. Feel free to discuss the study with your family, friends, and healthcare provider before you decide. If you decide to participate, you may stop participating at any time during the study. You may decide not to participate. If you decide not to participate, none of your current benefits or normal health care will be affected in any way. When you feel comfortable that all your questions have been answered, and you wish to take part in this study, sign this form in order to begin your participation. Your signature means you have been told about the study and what the risks are. Your signature on this form also means that you want to take part in this study.

B. Number of Participants

20 people will be enrolled to take part in this study at Mayo Clinic.

C. Additional Information You Should Know

The Paralyzed Veterans of America is funding the study. They will pay for the study personnel and the institution to cover costs related to running the study.

2. What Will Happen To You While You Are In This Research Study?

If you agree to be in the study, you will be asked to participate in the following:
You will first be asked to undergo an exam of your shoulder to ensure that you meet the inclusion/exclusion criteria for the study. If you are included, you will be asked to visit the Motion Analysis Laboratory on at least 1 additional occasions after your first visit (12 weeks after beginning the study). A six week visit will either be conducted in the laboratory or via teleconference.

We may review your medical record to obtain information about your spinal cord injury, your wheelchair and any injury you may have had or have to your muscles, ligaments, bones or nerves.

At your first visit (0 weeks), you will have various measurements taken including height, weight, muscle strength and the amount of motion in your shoulder. During this time, you will have sensors attached to your skin so that precise measurement of the bones and muscles in your shoulder can be measured. Your muscle activity and motion will be measured while you perform activities of daily living including propelling your wheelchair on a wheelchair treadmill, performing a weight relief task and arm raises.. These activities may be photographed or videotaped. You will also be asked to fill out a few surveys about your shoulder. Finally, you will be instructed by a physical therapist about the exercises that you will perform at home. If necessary, the exercise program will be introduced at a subsequent visit.

At your second visit (approximately 6 weeks), you will be asked to fill out surveys and you will have a training session with the therapist to help you with your exercises or give you new exercises. Your shoulders' range of motion will be measured.

At your third visit (approximately 12 weeks), you will fill out surveys, have your shoulders' range of motion and strength measured and record your muscle activity and motion during the activities of daily living. Further, you may be asked to use an abdominal support strap during the movements to see if it facilitates shoulder pain relief. Your movements may be photographed or videotaped.

During one of your visits, you will receive an MRI of your shoulder.

In between visits, you will be instructed to perform your exercises on a regular basis several times per week. On some of these occasions you will be asked to communicate with the therapist via internet conferencing software so that you can ask questions and receive instruction while you perform the exercises. If needed, you will be provided with a webcam for your computer. These public internet video communications may be recorded.

At 24 weeks, we will be following up with you. You will receive the surveys by mail or email to complete and return.

3. How Long Will You Be in This Research Study?

You will be in the study for 24 weeks.

4. Why You Might Want To Take Part In This Research Study

You may experience a reduction in shoulder pain after completing this study.

5. What Are the Risks Of This Research Study?

Risk summary
Some individuals may experience increased skin sensitivity or allergy to the hypoallergenic adhesive used to secure the sensors to their skin during the study. These reactions could include redness, rash, itching or dryness of the skin. If you are pregnant you may not participate in this study. We will exclude pregnancy by asking you if you are pregnant, no pregnancy testing will be done.

Some individuals may experience temporary muscle soreness following the strength testing or after advancing to a more difficult level of the strengthening program.

MRI scans do not emit ionizing radiation therefore not associated with radiation risk. If you suffer from claustrophobia then this may not be a study you wish to participate in. We will make sure that there are no contraindications to your undergoing an MRI scan: no pacemaker or automated internal coronary defibrillator (AICD), cochlear implants, cerebral aneurysm clips, any metallic pumps or indwelling catheters will be checked for, as also any history of metallic foreign bodies.

If you feel too confined in the MRI scanner you can inform the technologist and the MRI scan will be stopped. The MRI machine makes loud knocking sounds when it is scanning. Because of this you will be asked to wear earplugs while getting your MRI scan. The earplugs minimize discomfort from noise and keep the MRI noise within the safety range.

The photos and movie files recorded during this research study are immediately transferred to secure and password-protected servers from which authorized research personnel can conduct evaluations. There is a chance that someone reviewing a movie file at a later date would recognize you.

The risks of this research study are minimal, which means that we do not believe that they will be any different than what you would experience at a routine clinical visit or during your daily life.

6. What Other Choices Do You Have If You Don't Take Part In This Research Study?

You do not have to be in this study to receive treatment for your condition. Your other choices may include visiting a physical therapist or physician to receive alternative therapies. You should talk to the researcher and your regular physician about each of your choices before you decide if you will take part in this study.

7. Are There Reasons You Might Leave This Research Study Early?

Taking part in this research study is voluntary. You may decide to stop at any time. You should tell the researcher if you decide to stop and you will be advised whether any additional tests may need to be done for your safety.

In addition, the researchers or Mayo may stop you from taking part in this study at any time:

- if it is in your best clinical interest,
- if you do not follow the study procedures,
- if the study is stopped.

8. Will You Need To Pay For Any Of The Tests And Procedures?

You will not need to pay for tests and procedures which are done just for this research study. These tests and procedures are

- MR imaging of the shoulder
- Physical examination of the shoulders
- Motion and strength measurements
- Supervised therapeutic exercise program

However, you and/or your health plan will need to pay for all other tests and procedures that you would normally have as part of your regular clinical care.

If you have study related questions regarding billing, insurance or reimbursement, stop by or call:

Admission and Business Services office, or call Patient Account Services at (507) 266-5670

9. Will You Be Paid For Participating In This Research Study?

If you finish the study, you will receive $100. This money is for the time you spend in this study. If you start the study but stop before finishing the study, you will receive part of this money.

10. What Happens If You Are Injured Or Ill Because You Were In This Research Study?

If you have side effects from the study treatment, you need to report them to the researcher and your regular physician, and you will be treated as needed. If you receive this care at Mayo Clinic, Mayo Clinic will bill you or your insurer for these services at the usual charge. Mayo will not offer free medical care or payment for any bad side effects from taking part in this study.

11. What Are Your Rights If You Are In This Research Study?

Taking part in this research study will not change your rights and benefits. Taking part in this research study does not give you any special privileges. If you decide to not participate in this study, or stop in the middle of the study, no benefits are taken away from you. You do not have to be in this research study to receive or continue to receive medical care from Mayo Clinic.

You will be told of important new findings or any changes in the study or procedures that may affect you or your willingness to continue in the study.

12. What About Your Privacy?

Authorization To Use And Disclose Protected Health Information
Your privacy is important to us, and we want to protect it as much as possible. By signing this form, you authorize Mayo Clinic and the investigators to use and disclose any information created or collected in the course of your participation in this research protocol. This information might be in different places, including your original medical record, but we will only disclose information that is related to this research protocol for the purposes listed below.

This information will be given out for the proper monitoring of the study, checking the accuracy of study data, analyzing the study data, and other purposes necessary for the proper conduct and reporting of this study. If some of the information is reported in published medical journals or scientific discussions, it will be done in a way that does not directly identify you.

This information may be given to other researchers in this study, or private, state or federal government parties or regulatory authorities in the USA and other countries responsible for overseeing this research. These may include the Food and Drug Administration, the Office for Human Research Protections, or other offices within the Department of Health and Human Services, and the Mayo Clinic Office for Human Research Protections or other Mayo groups involved in protecting research subjects.

Information Disclosed to Study Sponsor
If this information is given out to anyone outside of Mayo, the information may no longer be protected by federal privacy regulations and may be given out by the person or entity that receives the information. However, Mayo will take steps to help other parties understand the need to keep this information confidential.

This authorization lasts until the end of the study. The study does not end until all data has been collected, checked (or audited) and analyzed. Sometimes this can be years after your study visits have ended. For example, this could happen if the results of the study are filed with a regulatory agency like the Food and Drug Administration.

You may stop this authorization at any time by writing to the following address:

Mayo Clinic
Office for Human Research Protection
ATTN: Notice of Revocation of Authorization
200 1st Street SW
Rochester, MN 55905

If you stop authorization, Mayo may continue to use your information already collected as part of this study, but will not collect any new information.

If you do not sign this authorization, or later stop authorization, you may not be able to receive study treatment.

13. What Will Happen to Your Samples?

No biological samples will be collected as part of this research study.

14. Who Can Answer Your Questions?

You can call …	**At …**	**If you have questions or concerns about …**
Principal Investigator: **Kristin Zhao**	**Phone:** **507-284-8942 (ofc)** **507-538-1717 (sec)** **507-538-8920 (pgr)**	**Questions about the study tests and procedures** **Research-related injuries or emergencies**
Other Study Contact: **Meegan Van Straaten**	**507-284-2262**	**Any research-related concerns or complaints**
Mayo Clinic IRB	**Phone:** **507-266-4000**	**Rights of a research subject**
Research Subject Advocate	**Toll-Free:** **866-273-4681**	**Use of Protected Health Information** **or any research-related concerns or complaints**
Research Billing	**Rochester:** **507-266-5670**	**Billing / Insurance Questions**

15. Summary and Enrollment Signatures

You have been asked to take part in a research study, at Mayo Clinic. The information about this study has been provided to you to inform you about this study.

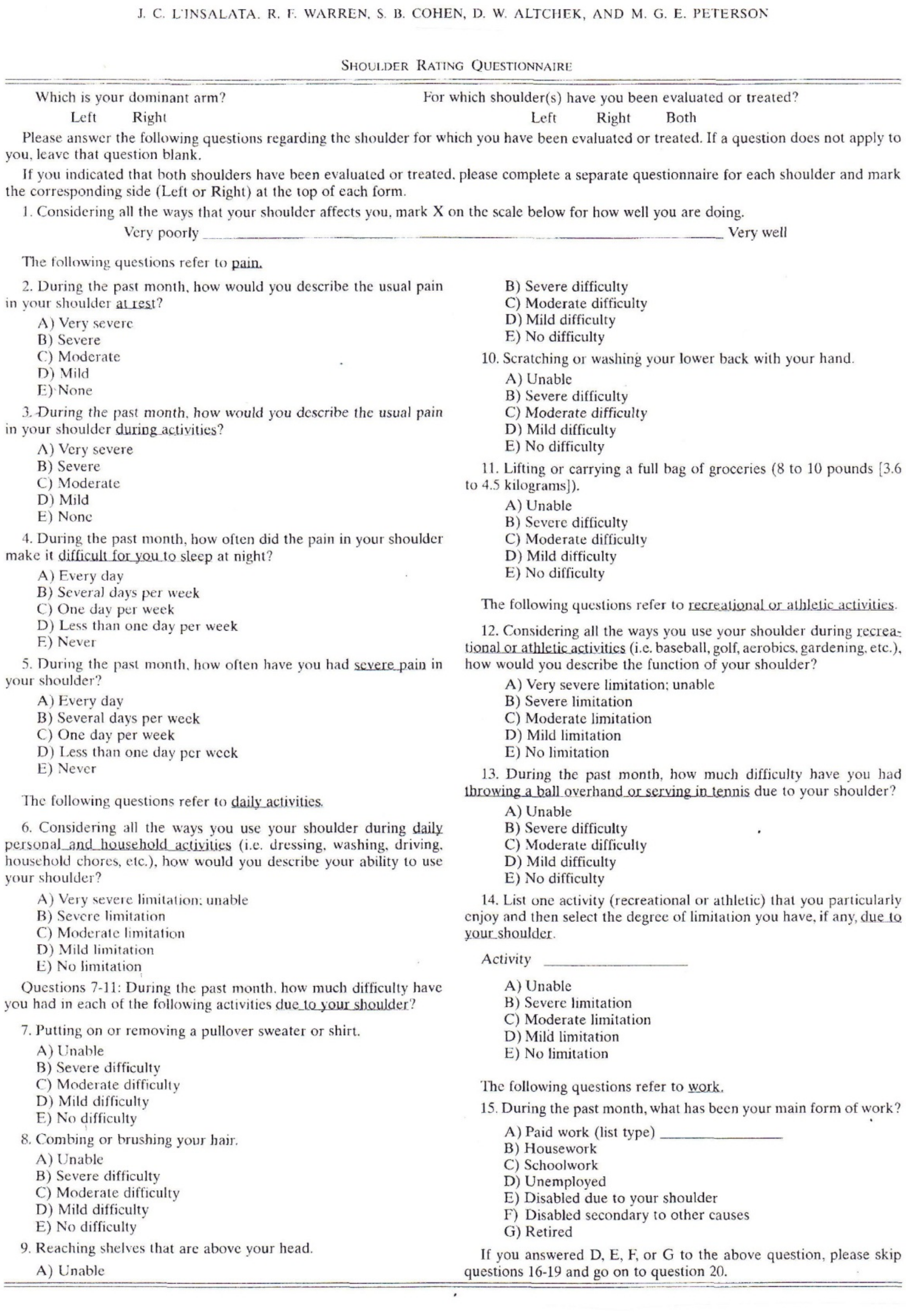
- I have read the whole consent form, and all of my questions have been answered to my satisfaction.
- I am satisfied that I have been given enough information about the purpose, methods, risks, and possible benefits of the study to decide if I want to join.
- I know that joining the study is voluntary and I agree to join the study.
- I know that I can call the investigator and research staff at any time with any questions or to tell them about side effects.
- I know that I may withdraw from the study at any time.
- I will be given a copy of this completed form.

Please sign and date to show that you have read all of the above guidelines. Please do not sign unless you have read this entire consent form. If you do not want to sign, you don't have to, but if you don't you cannot participate in this research study.

(Date / Time)	(Printed Name of Participant)	(Clinic Number)
	(Signature of Participant)	
(Date / Time)	(Printed Name of Individual Obtaining Consent)	
	(Signature of Individual Obtaining Consent)	

Appendix 2: SRQ, DASH

From: L'Insalata et al., A self-administered questionnaire for assessment of symptoms and function of the shoulder. J Bone Joint Surg Am 79(5):738-748, 1997.



SHOULDER RATING QUESTIONNAIRE

Which is your dominant arm?

Left Right

For which shoulder(s) have you been evaluated or treated?

Left Right Both

Please answer the following questions regarding the shoulder for which you have been evaluated or treated. If a question does not apply to you, leave that question blank.

If you indicated that both shoulders have been evaluated or treated, please complete a separate questionnaire for each shoulder and mark the corresponding side (Left or Right) at the top of each form.

1. Considering all the ways that your shoulder affects you, mark X on the scale below for how well you are doing.

Very poorly ____ Very well

The following questions refer to pain.

2. During the past month, how would you describe the usual pain in your shoulder at rest?
   - A) Very severe
   - B) Severe
   - C) Moderate
   - D) Mild
   - E) None

3. During the past month, how would you describe the usual pain in your shoulder during activities?
   - A) Very severe
   - B) Severe
   - C) Moderate
   - D) Mild
   - E) None

4. During the past month, how often did the pain in your shoulder make it difficult for you to sleep at night?
   - A) Every day
   - B) Several days per week
   - C) One day per week
   - D) Less than one day per week
   - E) Never

5. During the past month, how often have you had severe pain in your shoulder?
   - A) Every day
   - B) Several days per week
   - C) One day per week
   - D) Less than one day per week
   - E) Never

The following questions refer to daily activities.

6. Considering all the ways you use your shoulder during daily personal and household activities (i.e. dressing, washing, driving, household chores, etc.), how would you describe your ability to use your shoulder?
   - A) Very severe limitation; unable
   - B) Severe limitation
   - C) Moderate limitation
   - D) Mild limitation
   - E) No limitation

Questions 7-11: During the past month, how much difficulty have you had in each of the following activities due to your shoulder?

7. Putting on or removing a pullover sweater or shirt.
   - A) Unable
   - B) Severe difficulty
   - C) Moderate difficulty
   - D) Mild difficulty
   - E) No difficulty

8. Combing or brushing your hair.
   - A) Unable
   - B) Severe difficulty
   - C) Moderate difficulty
   - D) Mild difficulty
   - E) No difficulty

9. Reaching shelves that are above your head.
   - A) Unable
   - B) Severe difficulty
   - C) Moderate difficulty
   - D) Mild difficulty
   - E) No difficulty

10. Scratching or washing your lower back with your hand.
    - A) Unable
    - B) Severe difficulty
    - C) Moderate difficulty
    - D) Mild difficulty
    - E) No difficulty

11. Lifting or carrying a full bag of groceries (8 to 10 pounds [3.6 to 4.5 kilograms]).
    - A) Unable
    - B) Severe difficulty
    - C) Moderate difficulty
    - D) Mild difficulty
    - E) No difficulty

The following questions refer to recreational or athletic activities.

12. Considering all the ways you use your shoulder during recreational or athletic activities (i.e. baseball, golf, aerobics, gardening, etc.), how would you describe the function of your shoulder?
    - A) Very severe limitation; unable
    - B) Severe limitation
    - C) Moderate limitation
    - D) Mild limitation
    - E) No limitation

13. During the past month, how much difficulty have you had throwing a ball overhand or serving in tennis due to your shoulder?
    - A) Unable
    - B) Severe difficulty
    - C) Moderate difficulty
    - D) Mild difficulty
    - E) No difficulty

14. List one activity (recreational or athletic) that you particularly enjoy and then select the degree of limitation you have, if any, due to your shoulder.

Activity ____________________
   - A) Unable
   - B) Severe limitation
   - C) Moderate limitation
   - D) Mild limitation
   - E) No limitation

The following questions refer to work.

15. During the past month, what has been your main form of work?
    - A) Paid work (list type) ________________
    - B) Housework
    - C) Schoolwork
    - D) Unemployed
    - E) Disabled due to your shoulder
    - F) Disabled secondary to other causes
    - G) Retired

If you answered D, E, F, or G to the above question, please skip questions 16-19 and go on to question 20.

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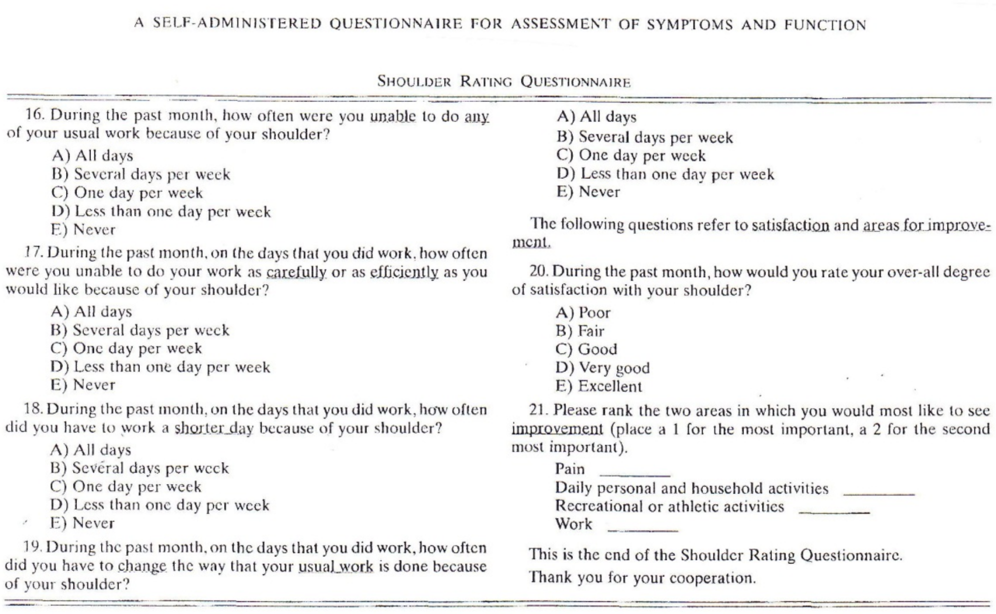


A SELF-ADMINISTERED QUESTIONNAIRE FOR ASSESSMENT OF SYMPTOMS AND FUNCTION

SHOULDER RATING QUESTIONNAIRE

16. During the past month, how often were you unable to do any of your usual work because of your shoulder?

A) All days
B) Several days per week
C) One day per week
D) Less than one day per week
E) Never

17. During the past month, on the days that you did work, how often were you unable to do your work as carefully or as efficiently as you would like because of your shoulder?

A) All days
B) Several days per week
C) One day per week
D) Less than one day per week
E) Never

18. During the past month, on the days that you did work, how often did you have to work a shorter day because of your shoulder?

A) All days
B) Several days per week
C) One day per week
D) Less than one day per week
E) Never

19. During the past month, on the days that you did work, how often did you have to change the way that your usual work is done because of your shoulder?

A) All days
B) Several days per week
C) One day per week
D) Less than one day per week
E) Never

The following questions refer to satisfaction and areas for improvement.

20. During the past month, how would you rate your over-all degree of satisfaction with your shoulder?

A) Poor
B) Fair
C) Good
D) Very good
E) Excellent

21. Please rank the two areas in which you would most like to see improvement (place a 1 for the most important, a 2 for the second most important).

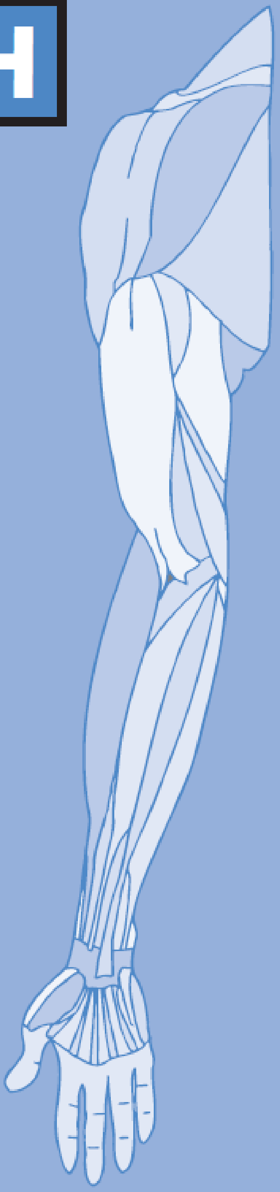
Pain ________
Daily personal and household activities ________
Recreational or athletic activities ________
Work ________

This is the end of the Shoulder Rating Questionnaire.

Thank you for your cooperation.

DISABILITIES OF THE ARM, SHOULDER AND HAND

THE DASH



INSTRUCTIONS

This questionnaire asks about your symptoms as well as your ability to perform certain activities.

Please answer *every question*, based on your condition in the last week, by circling the appropriate number.

If you did not have the opportunity to perform an activity in the past week, please make your *best estimate* on which response would be the most accurate.

It doesn't matter which hand or arm you use to perform the activity; please answer based on your ability regardless of how you perform the task.

DISABILITIES OF THE ARM, SHOULDER AND HAND

Please rate your ability to do the following activities in the last week by circling the number below the appropriate response.

	NO DIFFICULTY	MILD DIFFICULTY	MODERATE DIFFICULTY	SEVERE DIFFICULTY	UNABLE
1. Open a tight or new jar.	1	2	3	4	5
2. Write.	1	2	3	4	5
3. Turn a key.	1	2	3	4	5
4. Prepare a meal.	1	2	3	4	5
5. Push open a heavy door.	1	2	3	4	5
6. Place an object on a shelf above your head.	1	2	3	4	5
7. Do heavy household chores (e.g., wash walls, wash floors).	1	2	3	4	5
8. Garden or do yard work.	1	2	3	4	5
9. Make a bed.	1	2	3	4	5
10. Carry a shopping bag or briefcase.	1	2	3	4	5
11. Carry a heavy object (over 10 lbs).	1	2	3	4	5
12. Change a lightbulb overhead.	1	2	3	4	5
13. Wash or blow dry your hair.	1	2	3	4	5
14. Wash your back.	1	2	3	4	5
15. Put on a pullover sweater.	1	2	3	4	5
16. Use a knife to cut food.	1	2	3	4	5
17. Recreational activities which require little effort (e.g., cardplaying, knitting, etc.).	1	2	3	4	5
18. Recreational activities in which you take some force or impact through your arm, shoulder or hand (e.g., golf, hammering, tennis, etc.).	1	2	3	4	5
19. Recreational activities in which you move your arm freely (e.g., playing frisbee, badminton, etc.).	1	2	3	4	5
20. Manage transportation needs (getting from one place to another).	1	2	3	4	5
21. Sexual activities.	1	2	3	4	5

DISABILITIES OF THE ARM, SHOULDER AND HAND

	NOT AT ALL	SLIGHTLY	MODERATELY	QUITE A BIT	EXTREMELY
22. During the past week, *to what extent* has your arm, shoulder or hand problem interfered with your normal social activities with family, friends, neighbours or groups? *(circle number)*	1	2	3	4	5

	NOT LIMITED AT ALL	SLIGHTLY LIMITED	MODERATELY LIMITED	VERY LIMITED	UNABLE
23. During the past week, were you limited in your work or other regular daily activities as a result of your arm, shoulder or hand problem? *(circle number)*	1	2	3	4	5

Please rate the severity of the following symptoms in the last week. *(circle number)*

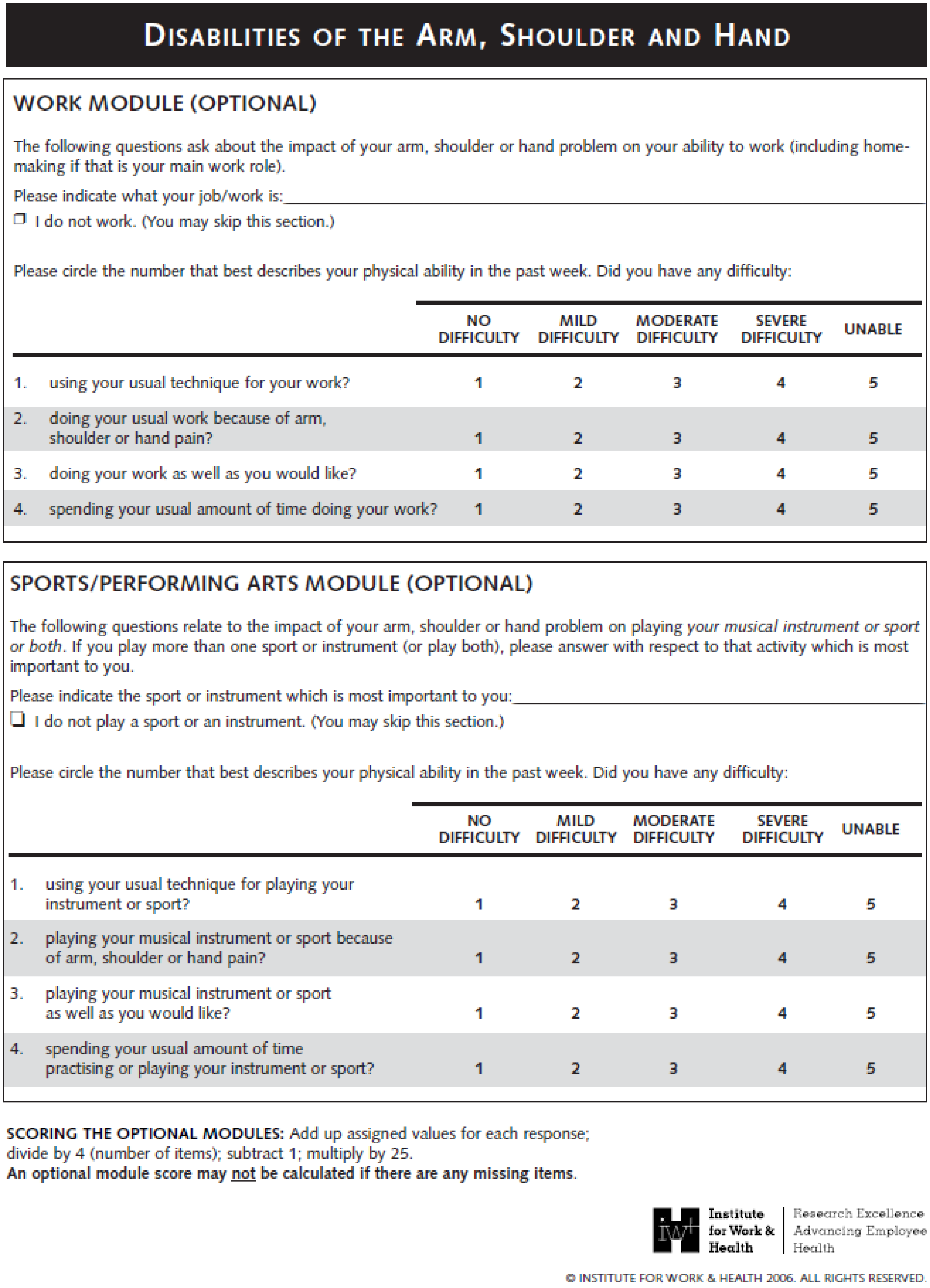
	NONE	MILD	MODERATE	SEVERE	EXTREME
24. Arm, shoulder or hand pain.	1	2	3	4	5
25. Arm, shoulder or hand pain when you performed any specific activity.	1	2	3	4	5
26. Tingling (pins and needles) in your arm, shoulder or hand.	1	2	3	4	5
27. Weakness in your arm, shoulder or hand.	1	2	3	4	5
28. Stiffness in your arm, shoulder or hand.	1	2	3	4	5

	NO DIFFICULTY	MILD DIFFICULTY	MODERATE DIFFICULTY	SEVERE DIFFICULTY	SO MUCH DIFFICULTY THAT I CAN'T SLEEP
29. During the past week, how much difficulty have you had sleeping because of the pain in your arm, shoulder or hand? *(circle number)*	1	2	3	4	5

	STRONGLY DISAGREE	DISAGREE	NEITHER AGREE NOR DISAGREE	AGREE	STRONGLY AGREE
30. I feel less capable, less confident or less useful because of my arm, shoulder or hand problem. *(circle number)*	1	2	3	4	5

DASH DISABILITY/SYMPTOM SCORE = $\left[\left(\frac{\text{sum of n responses}}{n}\right) - 1\right] \times 25$, where n is equal to the number of completed responses.

A DASH score may <u>not</u> be calculated if there are greater than 3 missing items.



DISABILITIES OF THE ARM, SHOULDER AND HAND

WORK MODULE (OPTIONAL)

The following questions ask about the impact of your arm, shoulder or hand problem on your ability to work (including homemaking if that is your main work role).

Please indicate what your job/work is:________________________________

☐ I do not work. (You may skip this section.)

Please circle the number that best describes your physical ability in the past week. Did you have any difficulty:

	NO DIFFICULTY	MILD DIFFICULTY	MODERATE DIFFICULTY	SEVERE DIFFICULTY	UNABLE
1. using your usual technique for your work?	1	2	3	4	5
2. doing your usual work because of arm, shoulder or hand pain?	1	2	3	4	5
3. doing your work as well as you would like?	1	2	3	4	5
4. spending your usual amount of time doing your work?	1	2	3	4	5

SPORTS/PERFORMING ARTS MODULE (OPTIONAL)

The following questions relate to the impact of your arm, shoulder or hand problem on playing *your musical instrument or sport or both*. If you play more than one sport or instrument (or play both), please answer with respect to that activity which is most important to you.

Please indicate the sport or instrument which is most important to you:________________________________

☐ I do not play a sport or an instrument. (You may skip this section.)

Please circle the number that best describes your physical ability in the past week. Did you have any difficulty:

	NO DIFFICULTY	MILD DIFFICULTY	MODERATE DIFFICULTY	SEVERE DIFFICULTY	UNABLE
1. using your usual technique for playing your instrument or sport?	1	2	3	4	5
2. playing your musical instrument or sport because of arm, shoulder or hand pain?	1	2	3	4	5
3. playing your musical instrument or sport as well as you would like?	1	2	3	4	5
4. spending your usual amount of time practising or playing your instrument or sport?	1	2	3	4	5

SCORING THE OPTIONAL MODULES: Add up assigned values for each response; divide by 4 (number of items); subtract 1; multiply by 25.
An optional module score may <u>not</u> be calculated if there are any missing items.

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Appendix 3: Selection of propulsion events

Consideration was given to the method for selecting wheelchair propulsion events that would differentiate the phases of pushing the wheel (hand in contact with the hand rim) and recovery. Instrumented hand rims have been developed and are commercially available that are capable of recording the forces and moments applied to the hand rim and therefore have been used extensively in studies interested in assessing the kinetics of propulsion, including joint moments and efficiency of propulsion. Simultaneously, they are able to define the event markers during the movement cycle with the kinetic data. There are some limitations to the use of instrumented hand rims, including: the increased weight to the wheelchair, potentially changing the subject's normal movement patterns; the additional time required to replace the subject's wheelchair wheel with the instrumented one; and finally, the potential for interference with electromagnetic data acquisition systems. While these factors prohibited the use of the instrumented wheel in our investigation, assessment of previously-acquired kinematics (using an optical system) and hand rim data in our laboratory[122] revealed a synchronous relationship between hand rim forces and humerothoracic plane of elevation data during over-ground propulsion. Data were subsequently acquired at 240Hz on a single subject during propulsion using the same protocol and experimental setup as the current study while incorporating the instrumented wheel (SmartWheel, Three Rivers Holdings Inc)(**Figure App3.1**). Special attention was placed on digitization and transmitter placement so as to reduce the effects of electromagnetic interference as much as possible. While synchronization of kinematic and kinetic data was manual, timing of the peaks in humerothoracic horizontal abduction aligned well with the force onset and offset times. Given the roller system used for the current study (not over ground propulsion), the close relationship between shoulder motion and events during propulsion was anticipated.

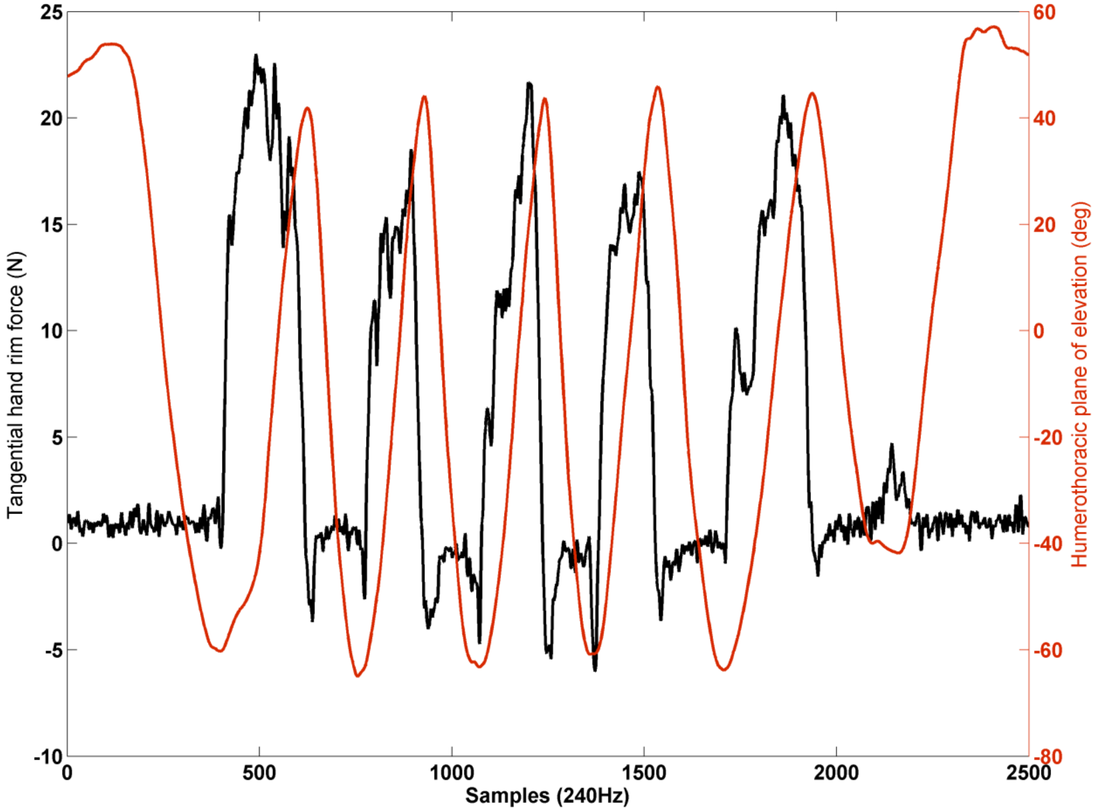

Figure App3.1: Tangential hand rim force in Newtons (black) and humerothoracic plane of elevation in degrees during multiple cycles of wheelchair propulsion. Hand on and hand off positions, corresponding to the minimum and maximum humerothoracic elevation values, respectively, align well with the onset and offset of tangential hand rim forces.

Appendix 4: Preliminary analysis to evaluate humeral translations during movement

For the current project, angular but not translatory glenohumeral positions were quantified and used in combination with the CT bone surface models to simulate movements and assess linear distances and risk values. This is based on a literature reports[35, 128] and preliminary data obtained during wheelchair propulsion, weight relief, and arm elevation, which report minimal glenohumeral translation during these tasks. As part of a larger study[30], shoulder motion data were obtained during a weight relief maneuver, scapular plane abduction, shoulder extension, and shoulder flexion on the same subject. Sensors were mounted to the subject's clavicle, scapula, and humerus using transcortical pins. Flexion was controlled by having the subject move the arm forward and parallel to the sagittal plane of the trunk; extension was achieved by having the subject move the arm backward and parallel to the sagittal plane. Scapular plane abduction was performed in a plane 40˚ anterior to the coronal plane of the trunk. Following data collection, the helical axis translations of the humerus pin sensor data relative to the scapular pin sensor data were computed during: the lift phase of the weight relief (-0.3 mm), three phases of scapular plane abduction (-0.5, -0.9, -0.9, -0.7 mm), shoulder extension (0.5 mm) and four phases of flexion (0.7, -0.9, 0.04, 0.9 mm) (**Table App4.1**). All translation values were less than 1 mm and the largest magnitude of translation occurred during scapular plane abduction and flexion (.9 mm).

Table App4.1: Helical axis translations of the humerus relative to the scapula, as obtained from transcortical bone pins during various tasks.

TASK	TRANSLATIONS (in range of humerothoracic elevation in parentheses)			
Weight relief	**- 0.3mm** **(lift phase)**			
Scapular plane abduction	**- 0.5mm** **(15-45° hum elev.)**	**- 0.9mm** **(45-75° hum elev.)**	**- 0.9mm** **(75-105° hum elev.)**	**-0.7mm** **(25-60° hum elev.)**
Extension	**0.5mm** **(15-50° hum elev.)**			
Flexion	**0.7mm** **(15-45° hum elev.)**	**- 0.9mm** **(45-75° hum elev.)**	**0.04mm** **(75-105° hum elev.)**	**0.9mm** **(25-60° hum elev.)**

Appendix 5: Data from a representative subject (subject 14)

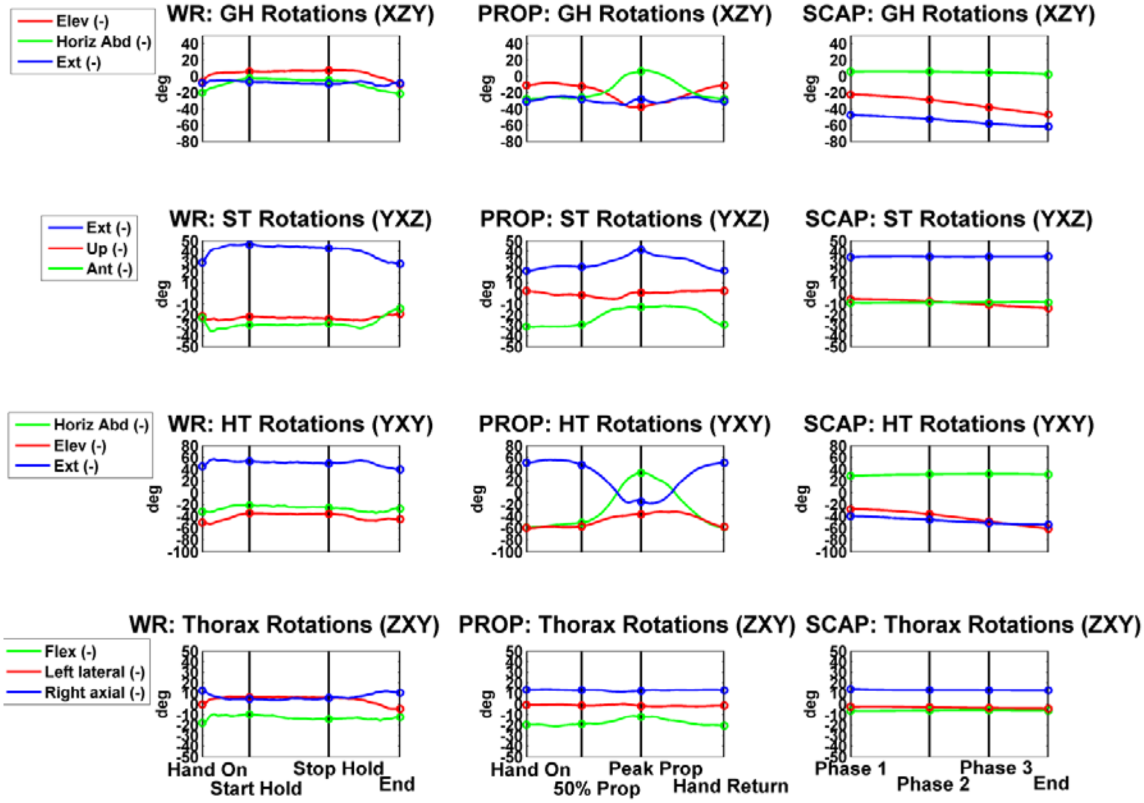

Figure App5.1: Glenohumeral (GH), scapulothoracic (ST), humerothoracic (HT), and thorax rotations (relative to the global coordinate system) during weight relief (WR), propulsion (PROP), and scapular plane abduction (SCAP) for a representative subject. Glenohumeral elevation (Elev), horizontal abduction (Horiz abd), and external rotation (Ext) are negative. Scapulothoracic external rotation (Ext), upward rotation (Up) , and anterior tilt (Ant) are negative. Humerothoracic horizontal abduction (Horiz abd), elevation (Elev), and external rotation (Ext) are negative. Thorax (relative to the global coordinate system) flexion (Flex), left lateral rotation (Left lateral), and right axial rotation (Right axial) are negative. The four events for each movement are indicated by vertical lines.

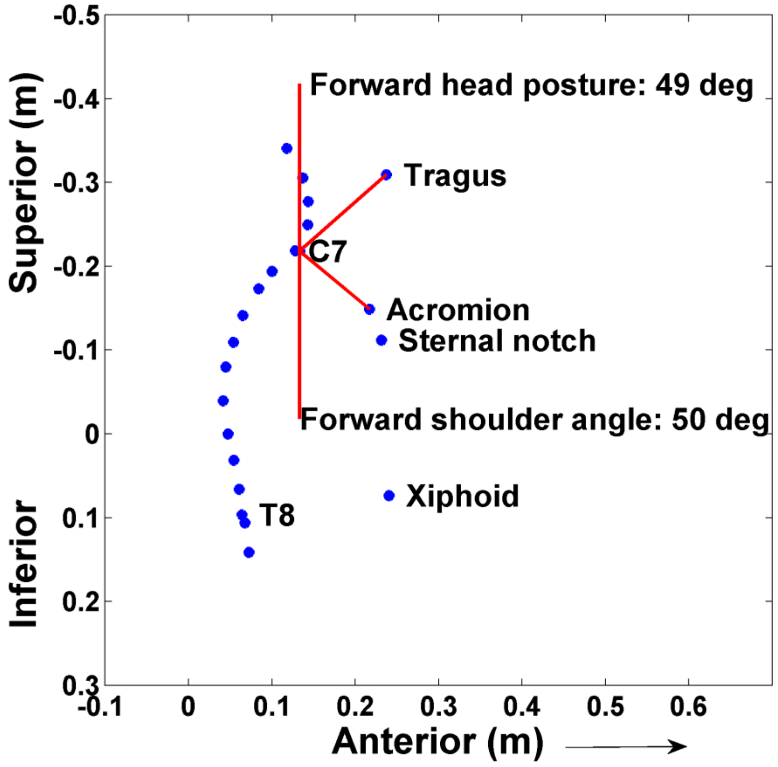

Figure App5.2: Sagittal plane image of postural curvature for a representative subject with anatomical landmarks indicated (tragus, 7th cervical vertebrae (C7), 8th thoracic vertebrae (T8), acromion, sternal notch, and xiphoid) as well as the forward shoulder angle calculated as the angle between the line connecting the acromion and C7, and the vertical line through C7, and the forward head angle calculated as the angle between the line connecting the tragus and C7, and the vertical line through C7.

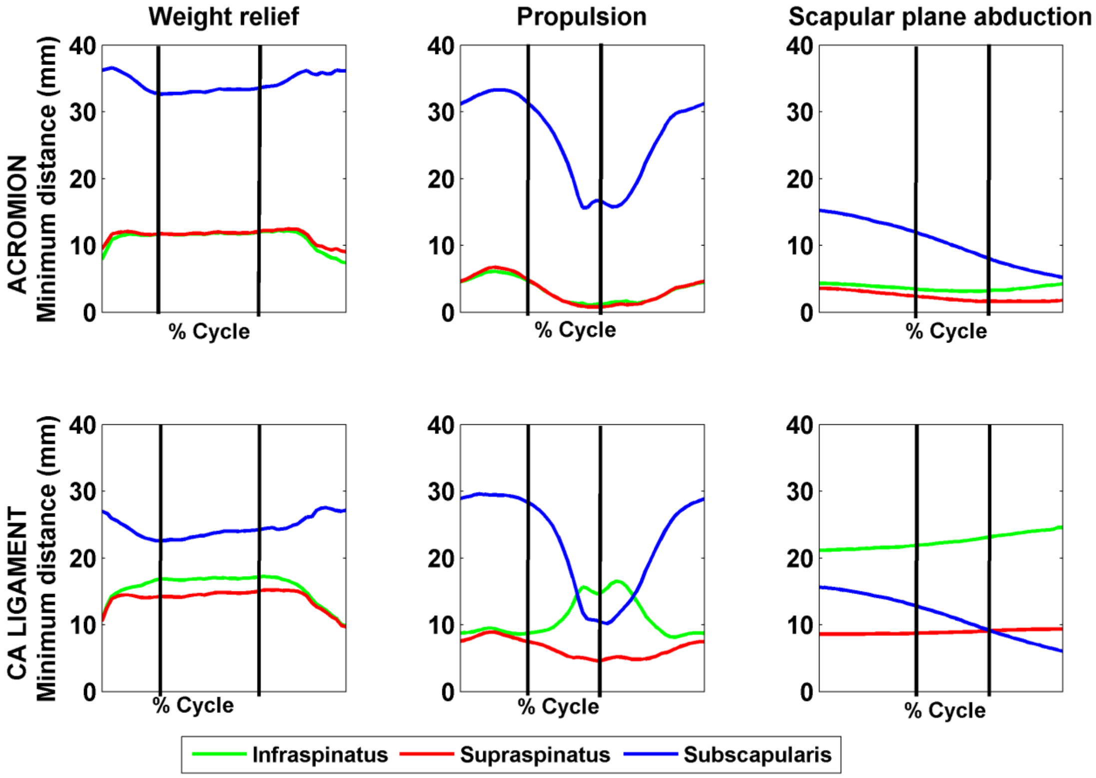

Figure App5.3: Minimum distance data across the weight relief, propulsion, and scapular plane abduction cycles for infraspinatus, supraspinatus, and subscapularis, in a representative subject.

Appendix 6: Linear distances

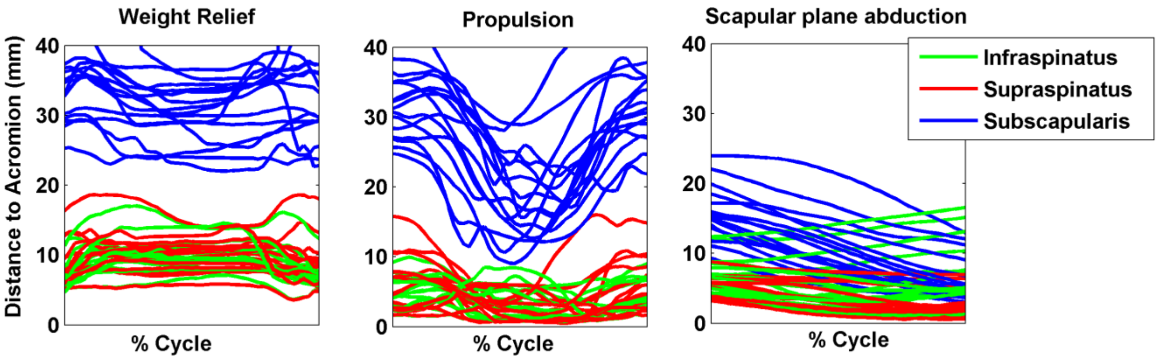

Figure App6.1: Linear distances to the acromion during weight relief, propulsion and scapular plane abduction for the infraspinatus, supraspinatus, and subscapularis for all 15 subjects.

Location of minimum distances:

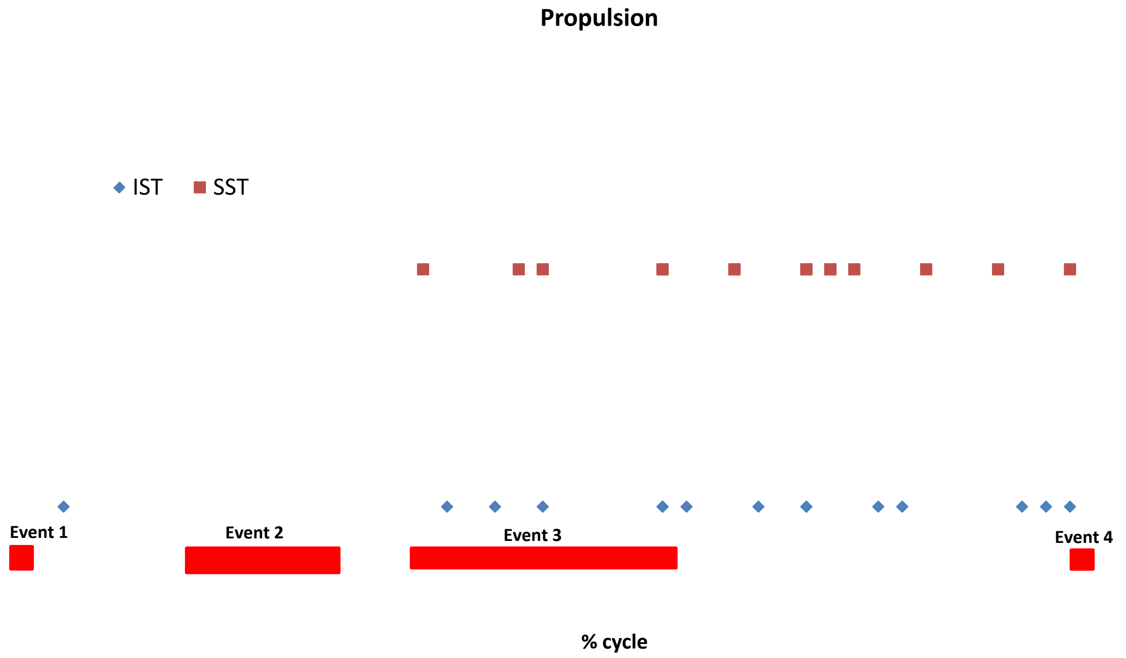

Figure App6.2: Location of minimum distances during the propulsion cycle for the infraspinatus (IST) and supraspinatus (SST) for all subjects. The range of events for all subjects are indicated by horizontal red bars.

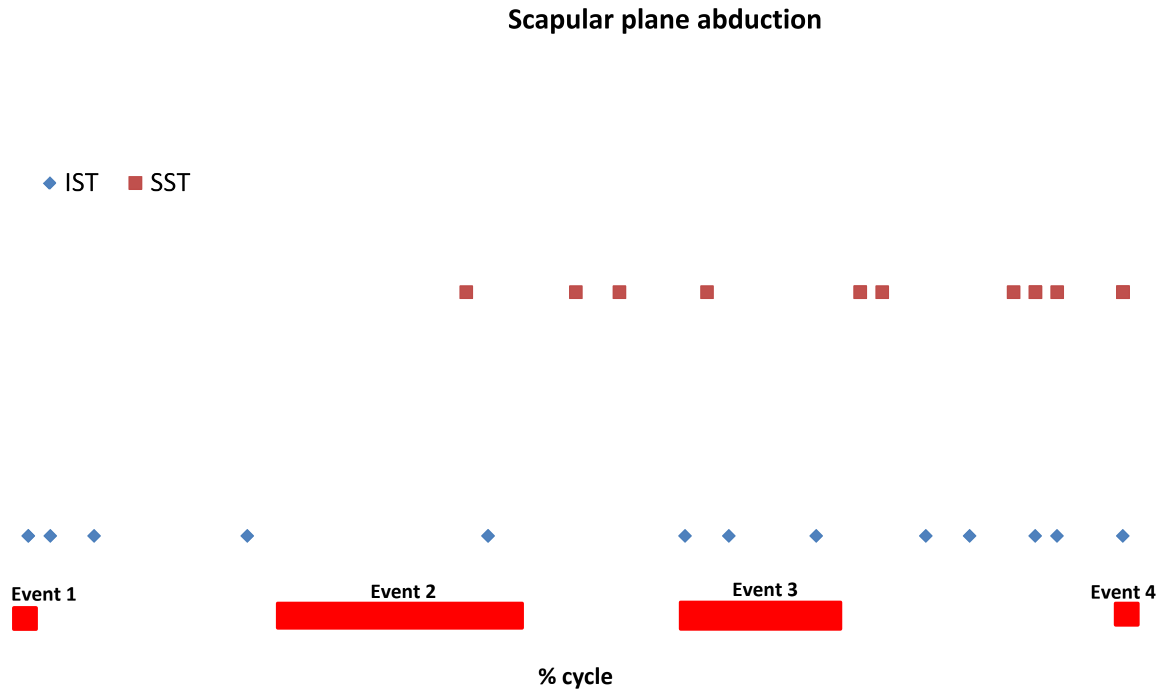

Figure App6.3: Location of minimum distances during the scapular plane abduction cycle for the infraspinatus (IST) and supraspinatus (SST) for all subjects. The range of events for all subjects are indicated by horizontal red bars.

Appendix 7: Sensitivity data re-visited

For the purposes of the current study, the sensitivity data was used to understand how error in surface sensor measurements affected the outcome variables of linear distance and risk. However, these data can also help us understand how angular movement changes may be prescribed as an intervention for increasing distances to impinging structures (indicated as a positive distance in the following graphs). Linear distances are depicted for the 3 and 6 degree permutations in rotation for each movement for the acromion and CA ligament (**Figures App7.1 –App7.6**).

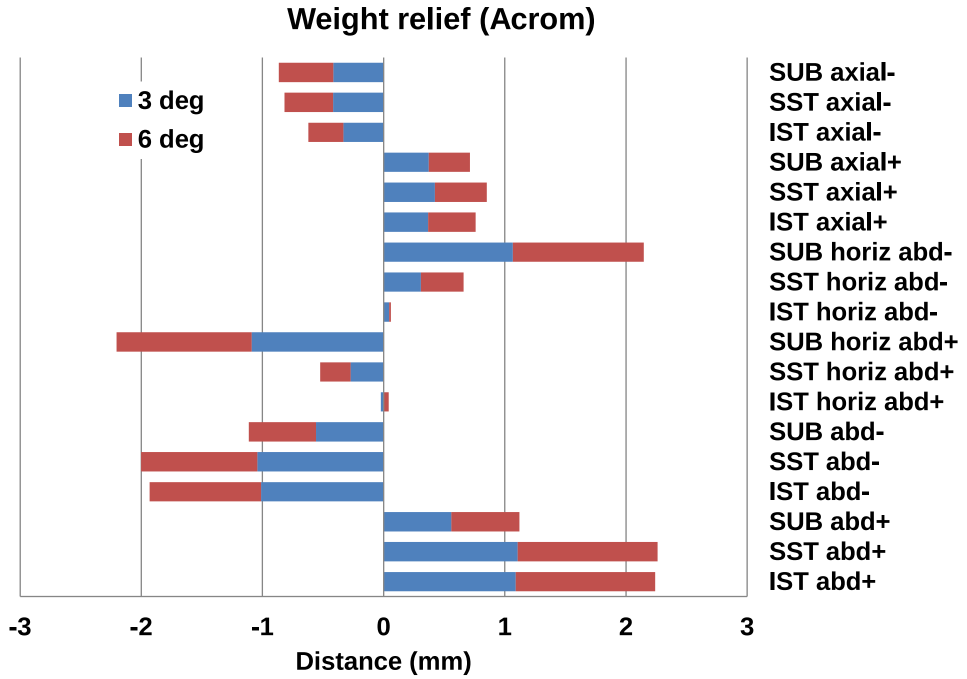

Figure App7.1: Mean distance changes (in mm) from baseline for each angle/muscle as a result of ± 3 and ± 6 deg permutations in each rotation value across the movement cycle (+ indicates adding 3 or 6 deg, - indicates subtracting 3 or 6 degrees). Distances to the acromion during weight relief are presented for each muscle (SUB=subscapularis, SST=supraspinatus, IST=infraspinatus) and each glenohumeral rotation (axial=axial rotation, abd=elevation/lowering, horiz abd=horizontal abduction/adduction).

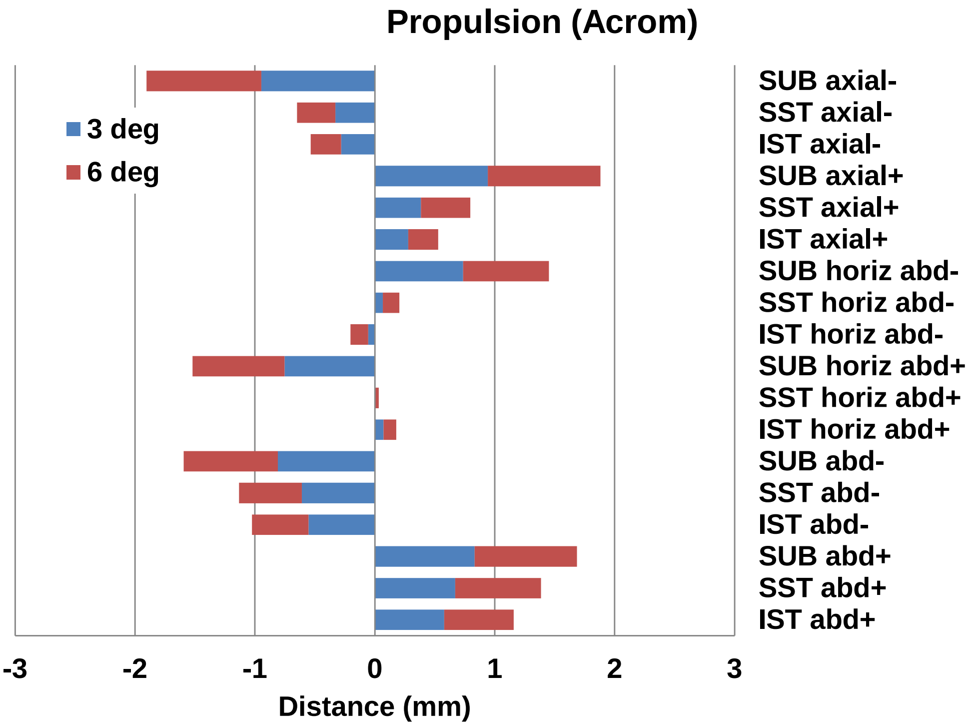

Figure App7.2: Mean distance changes (in mm) from baseline for each angle/muscle as a result of ± 3 and ± 6 deg permutations in each rotation value across the movement cycle (+ indicates adding 3 or 6 deg, - indicates subtracting 3 or 6 degrees). Distances to the acromion during propulsion are presented for each muscle (SUB=subscapularis, SST=supraspinatus, IST=infraspinatus) and each glenohumeral rotation (axial=axial rotation, abd=elevation/lowering, horiz abd=horizontal abduction/adduction).

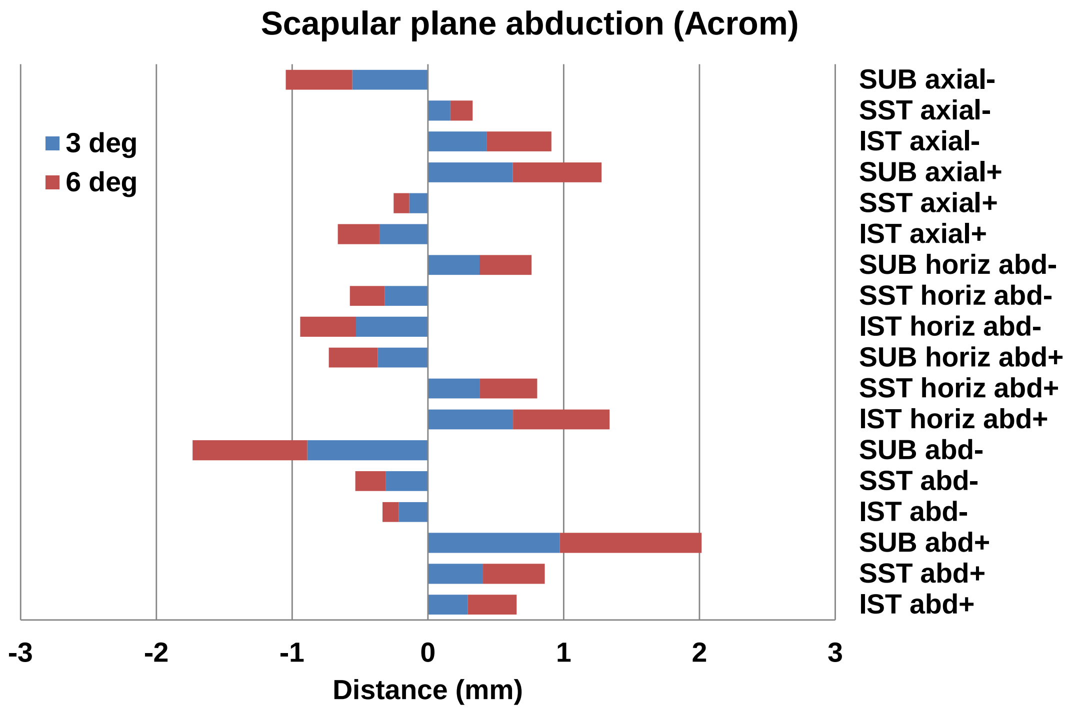

Figure App7.3: Mean distance changes (in mm) from baseline for each angle/muscle as a result of ± 3 and ± 6 deg permutations in each rotation value across the movement cycle (+ indicates adding 3 or 6 deg, - indicates subtracting 3 or 6 degrees). Distances to the acromion during scapular plane abduction are presented for each muscle (SUB=subscapularis, SST=supraspinatus, IST=infraspinatus) and each glenohumeral rotation (axial=axial rotation, abd=elevation/lowering, horiz abd=horizontal abduction/adduction).

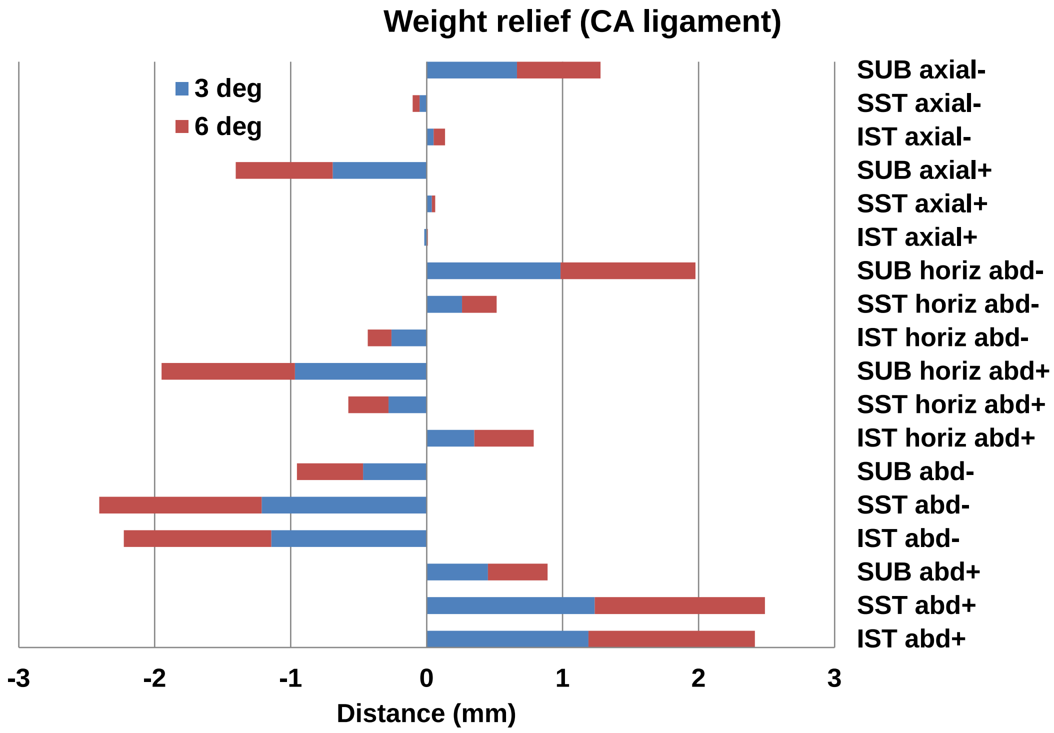

Figure App7.4: Mean distance changes (in mm) from baseline for each angle/muscle as a result of ± 3 and ± 6 deg permutations in each rotation value across the movement cycle (+ indicates adding 3 or 6 deg, - indicates subtracting 3 or 6 degrees). Distances to the CA ligament during weight relief are presented for each muscle (SUB=subscapularis, SST=supraspinatus, IST=infraspinatus) and each glenohumeral rotation (axial=axial rotation, abd=elevation/lowering, horiz abd=horizontal abduction/adduction).

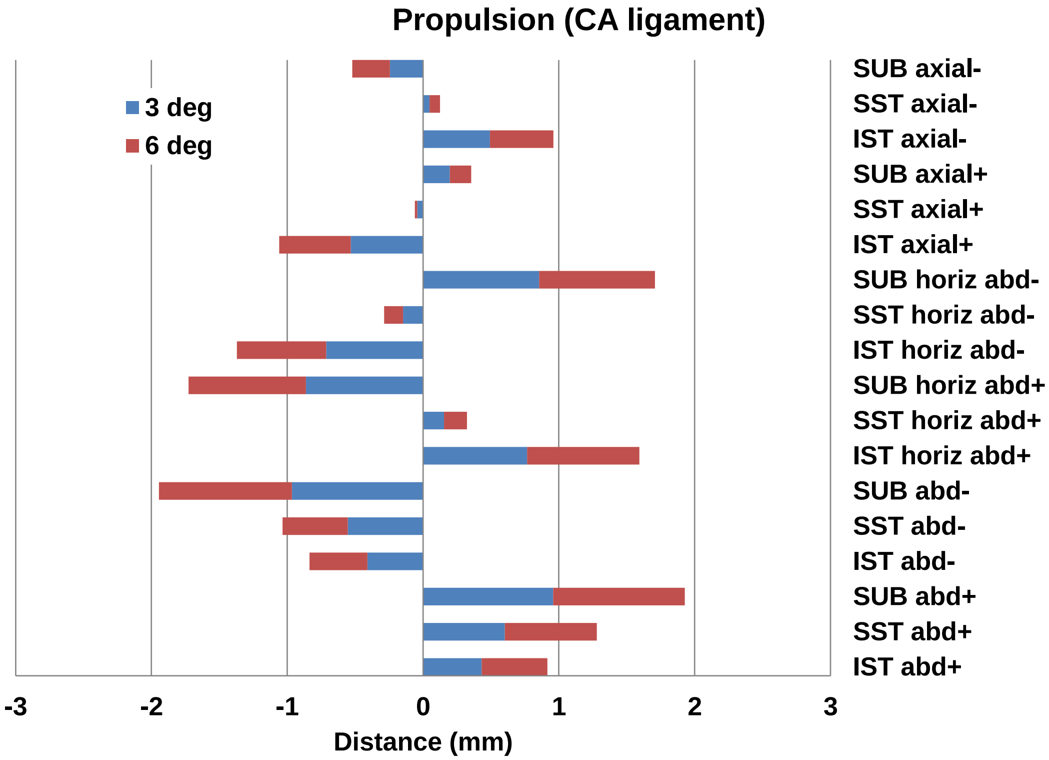

Figure App7.5: Mean distance changes (in mm) from baseline for each angle/muscle as a result of ± 3 and ± 6 deg permutations in each rotation value across the movement cycle (+ indicates adding 3 or 6 deg, - indicates subtracting 3 or 6 degrees). Distances to the CA ligament during propulsion are presented for each muscle (SUB=subscapularis, SST=supraspinatus, IST=infraspinatus) and each glenohumeral rotation (axial=axial rotation, abd=elevation/lowering, horiz abd=horizontal abduction/adduction).

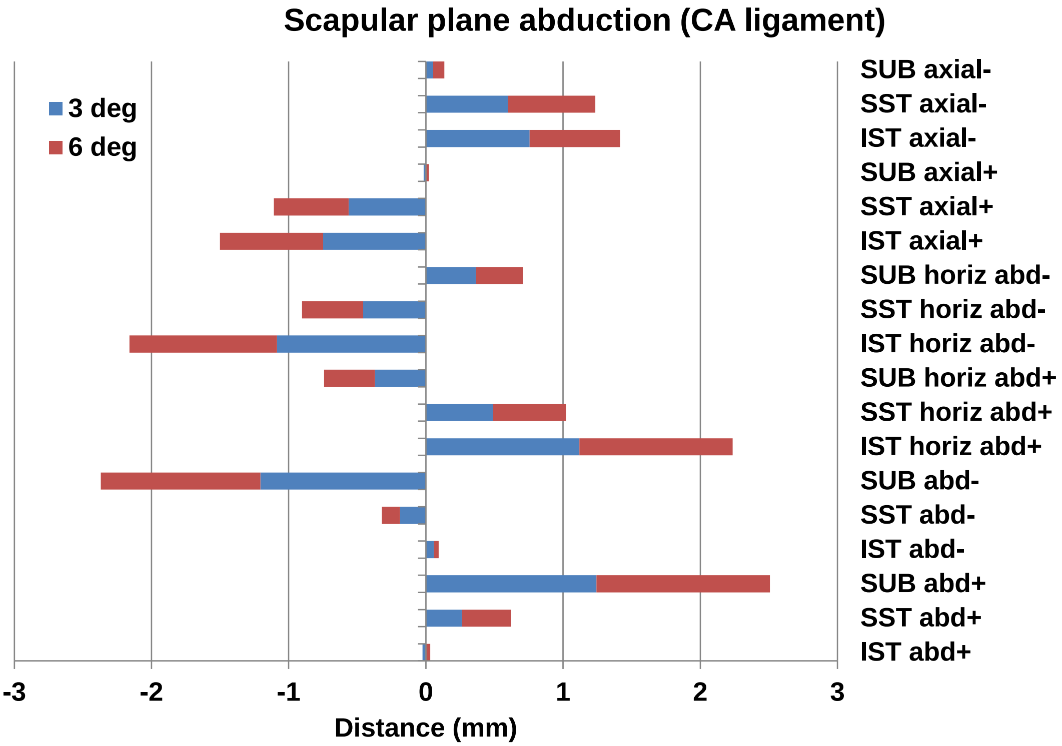

Figure App7.6: Mean distance changes (in mm) from baseline for each angle/muscle as a result of ± 3 and ± 6 deg permutations in each rotation value across the movement cycle (+ indicates adding 3 or 6 deg, - indicates subtracting 3 or 6 degrees). Distances to the CA ligament during scapular plane abduction are presented for each muscle (SUB=subscapularis, SST=supraspinatus, IST=infraspinatus) and each glenohumeral rotation (axial=axial rotation, abd=elevation/lowering, horiz abd=horizontal abduction/adduction).