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ULTRASONOGRAPHIC MEASUREMENT OF ACROMIOHUMERAL DISTANCE IN MANUAL WHEELCHAIR USERS

by

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Subacromial impingement syndrome is one of the most common problems among manual wheelchair users (MWUs). While the mechanism of impingement is associated with the encroachment of subacromial space, few studies have investigated the relationship between space narrowing and intense repetitive wheelchair activities. Ultrasound offers a non-invasive, radiation free, portable, and relatively cost-effective modality to identify acromiohumeral distance (AHD) between acromion and humeral head. We established moderate to excellent intra- and inter-rater reliability and intra- and inter-video reproducibility of the ultrasonographic AHD measurement in 10 MWUs with spinal cord injury and 10 able-bodied individuals in Chapter 2. AHD was significantly impacted while the shoulder was in overhead positions with or without muscle contraction. The effects of repetitive shoulder external rotations between two groups revealed that MWUs group had greater AHD decreases between 45° arm elevation and neutral. In Chapter 3, twenty-three MWUs performed two shoulder muscle-fatiguing protocols. AHD narrowing was detected in holding a weight relief raise compared to a neutral position. AHD was significantly reduced with the electromyography signs of sternal pectoralis major muscle fatigue after multiple weight relief push-ups. In addition, participants who experienced higher shoulder pain scores and perceived exertion after shoulder external rotation fatiguing exercises showed greater AHD narrowing. Chapter 4 investigated if shoulder biomechanics during the start-up phases of propulsion were related to the AHD measurement. Twenty-one

MWUs took part in an intense wheelchair propulsion course. Pushing with a technique that resulted in higher shoulder internal rotation moments and lower posterior forces during startup was linked to more acute AHD narrowing. AHD measurements related to shoulder circumference and years since injury. The findings of this research support the clinical practice guideline of reducing overhead shoulder activities and limiting weight relief raises for pressure relief technique to protect the integrity of subacromial space following spinal cord injury. Ultrasonographic measurement of the AHD provides a reliable and direct examination, easy to implement means to identify risk factors for better understanding the mechanisms of subacromial impingement syndrome. This imaging technique may help clinicians to evaluate intervention strategies and exercise prescriptions to minimize the risks for developing subacromial impingement syndrome.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF EQUATIONS

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1.0 INTRODUCTION

The upper limbs are used extensively for mobility and activities of daily living (ADLs) in manual wheelchair users (MWUs). ADLs including wheelchair propulsion, weight reliefs, and transfers cause repetitive and intense stresses to the upper limb. The shoulder joint is the most commonly reported site of pain and injury in MWUs. Approximately 31-73% of MWUs have encountered shoulder pain and other disorders. (Ballinger, Rintala, & Hart, 2000; Boninger, Towers, Cooper, Dicianno, & Munin, 2001) A previous survey study reported 69% individuals with SCI have upper limb pain with the most complaints at the shoulder. (Turner, Cardenas, Warms, & McClellan, 2001) Shoulder pain is also one of the major factors that decrease quality of life and function among individuals with spinal cord injury (SCI). (Ehde et al., 2003; Hatchett et al., 2009; Lundqvist, Siosteen, Blomstrand, Lind, & Sullivan, 1991; Rintala, Loubser, Castro, Hart, & Fuhrer, 1998) Many believe that shoulder pain in individuals with SCI is a consequence of overuse of the weight-bearing upper limb. (Ballinger et al., 2000; Bayley, Cochran, & Sledge, 1987) The repeated weight-bearing activities induce large stresses on the upper limb, and cause these structures to be at a significant risk of overuse related injuries in *in vivo* animal model. (Soslowsky et al., 2000) The repetitive heavy loading imposes a chronic strain on the shoulder. Furthermore, because these activities are necessary for independent mobility, it is difficult to rest the shoulder to allow for recovery to decrease pain and inflammation. Without resting, shoulder pain and impingement syndromes are further exaggerated. It is likely that the prevalence of this problem will grow as greater numbers of individuals with SCI are living longer.

Although many different pathologic conditions result in shoulder pain in the SCI population, musculoskeletal changes particularly injuries to the rotator cuff are the most common. It is believed that narrowing of the subacromial space during weight bearing activities is a common cause of impingement. (Ballinger et al., 2000; Boninger et al., 2005; Koontz, Lin, Kankipati, Boninger, & Cooper, 2011; Lee & McMahon, 2002; Mercer et al., 2006) Previous studies used the acromiohumeral distance (AHD) as a linear measurement of the subacromial space. (Bey et al., 2007; Chen, Simonian, Wickiewicz, Otis, & Warren, 1999; Chopp, O'Neill, Hurley, & Dickerson, 2010; Deutsch, Altchek, Schwartz, Otis, & Warren, 1996; Saupe et al., 2006; Werner et al., 2008) The height of the AHD in normal shoulders can range between 7mm and 16mm in a neutral shoulder position. (Petersson & Redlund-Johnell, 1984) The distance is generally less in symptomatic shoulders. The thickness of the supraspinatus tendon in this area is 6 to 9mm, (Leong, Tsui, Ying, Leung, & Fu, 2011) leaving very little clearance in cases of enlargement of the bursa or tendon. AHD measurement less than 7mm is indicative of a tear of the rotator cuff tendons and surgical consideration. (Weiner & Macnab, 1970) AHD has been measured using different medical imaging modality such as radiography and magnetic resonance imaging (MRI). (Chen et al., 1999; Chopp et al., 2010; Werner et al., 2008) Radiography is fast, inexpensive, and widely available. However, the person has to be exposed to radiation. MRI provides more details and it is easy to change the imaging plane without moving the subject. However, it is expensive, time consuming and not widely available. Previous studies also used ultrasonography-imaging techniques to measure the AHD. It has several advantages including non-invasive, portable, radiation free, and inexpensive. However, it is operator dependent. AHD measured with ultrasound has been done in many studies in different populations including able bodied with healthy shoulders (Cheng, Hulse, Fairbairn, Clarke, & Wallace, 2008; Schmidt, Schmidt, Schicke, & Gromnica-Ihle, 2004), athletes (Girometti et al., 2006; Silva, Hartmann, De Souza Laurino, & Bilo´, 2010; Wang, Lin, Pan, & Wang, 2005), patients with subacromial impingement syndrome (SIS) (Desmeules, Minville, Riederer, Cote, & Fremont, 2004; Pijls, Kok, Penning, Guldemond, & Arens, 2010; Seitz et al., 2012), individuals with poststroke hemiplegia (Kumar, Bradley, Gray, & Swinkels, 2011), and patients with rotator cuff tear. (Cholewinski, Kusz, Wojciechowski, Cielinski, & Zoladz, 2008) Surprisingly, no study has investigated if the narrowing of subacromial space occurred after repetitive activities in MWUs who represent a unique population for studying AHD due to the types of weight-bearing activities that they routinely perform and their high potential to develop SIS. (Bayley et al., 1987; Dyson-Hudson & Kirshblum, 2004; Lee & McMahon, 2002) Therefore, it is essential to clarify the mechanisms contributing to the development of subacromial impingement syndrome in MWUs to reduce the occurrence of secondary complications and help develop better rehabilitation programs.

This study was specifically focused on investigating the mechanisms leading to subacromial impingement syndrome related to wheelchair activities. Understanding the relationship between narrowing of AHD and biomechanical risk factors could be used to evaluate interventions tailored to preserving shoulder function. Chapter 2 describes intra- and inter-rater reliability of AHD measurement using ultrasonograpy in a case-control design study, along with the effects of shoulder positions and repetitive shoulder exercises on the AHD. Chapter 3 focuses on the effects of muscle fatiguing tasks on the AHD among MWUs. Chapter 4 describes the effects of an intense overground propulsion task on the AHD and shoulder biomechanics.

1.1 BACKGROUND LITERATURE

1.1.1 Subacromial Impingement Syndrome

Among MWUs, the primary pathology implicated in most cases of shoulder pain in individuals with SCI is subacromial impingement syndrome (SIS). (Bayley et al., 1987; Dyson-Hudson & Kirshblum, 2004; Lee & McMahon, 2002) The mechanisms of SIS can be divided into intrinsic and extrinsic factors. (Fu, Harner, & Klein, 1991; Neer, 1972; Seitz, McClure, Finucane, Boardman, & Michener, 2011) The intrinsic factors are mechanisms are related to anatomical factors such as degeneration, aging, arthritis, overuses, or anatomical changes, abnormalities including subacromial spur, acromioclavicular joint spurs, and acromion shape. Mayerhoefer et al. examined 47 individuals with SIS for the relationship between acromial shape and AHD and reported that acromial shape is not correlated to AHD narrowing on radiographs or on MRI. (Mayerhoefer, Breitenseher, Roposch, Treitl, & Wurnig, 2005) Furthermore, three-dimensional MRI has also excluded that acromial shape and slope are the primary causes for SIS among subjects with glenohumeral instability or impingement with and without tears. (E. Y. Chang, Moses, Babb, & Schweitzer, 2006; Moses, Chang, & Schweitzer, 2006) The extrinsic factors include postural misalignment of the acromion, altered scapular kinematics, and mechanical compression which forces the humeral head further into the glenohumeral joint, causing impingement of the supraspinatus tendon under the acromioclavicular arch and inflammation.

Kalra et al. examined the effects of trunk posture on AHD among subjects with shoulder pain and rotator cuff disease (n = 31) and those without pain as a control groups (n = 29). They found no AHD significant differences between normal and slouched postures in resting and in a 45° arm abduction position. (Kalra, Seitz, Boardman, & Michener, 2010) Intrinsic and extrinsic factors may not be mutually exclusive and are exacerbated by overuse syndromes. (Fu et al., 1991) SIS implies extrinsic compression of the supraspinatus outlet, narrowing of the subacromial space and consequent compression of the rotator cuff tendons. The mechanism of narrowing of the subacromial space is not fully understood, however, it is a well-known phenomenon at late-stage rotator cuff tear.

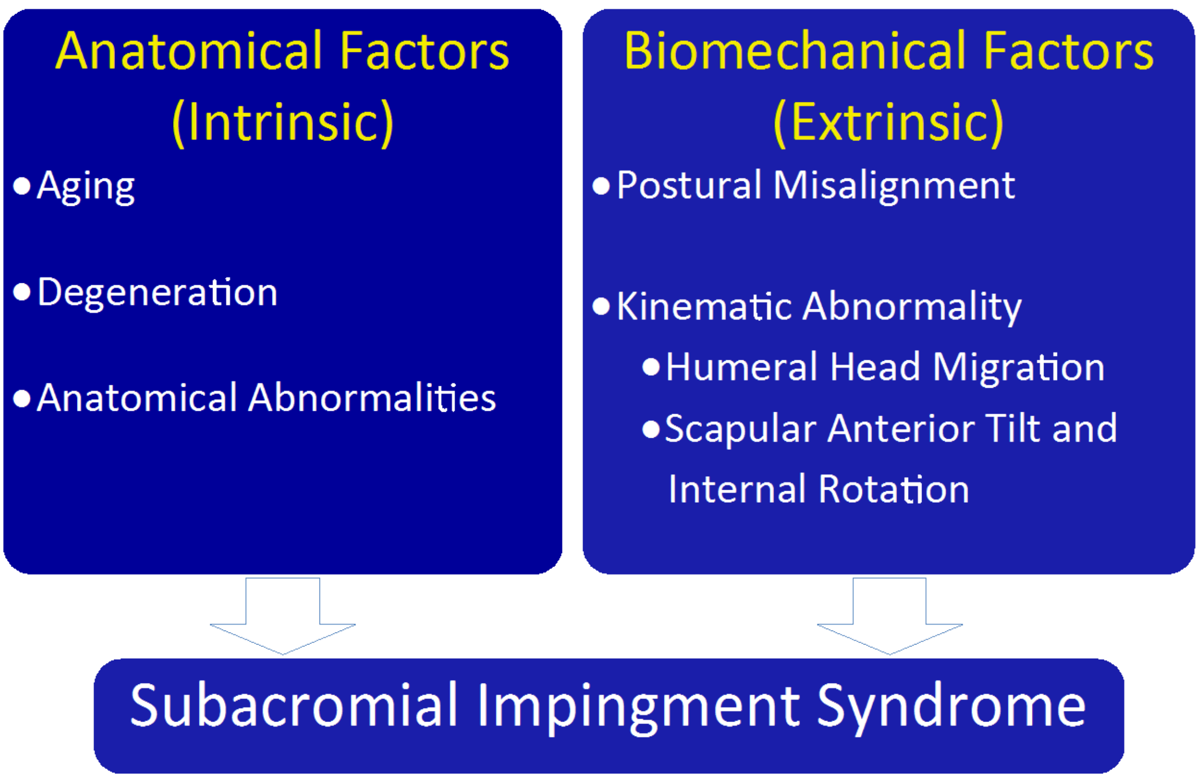


Figure 1. Intrinsic and extrinsic factors of subacromial impingement syndrome

1.1.2 Anatomy of Subacromial Space

The subacromial space is formed by the inferior aspect of the acromion of the scapula and head of humerus and contains the tendons of the rotator cuff (supraspinatus, infraspinatus, and teres minor), the long head of the biceps, and the subdeltoid/acromial bursa. (Neer, 1972; Pribicevic & Pollard, 2004) Compression of the supraspinatus tendon has been found in an animal model as one of the causes of impingement syndrome. (Soslowsky, Carpenter, DeBano, Banerji, & Moalli, 1996) Several reasons have demonstrated to directly or indirectly alter the subacromial space such as rotator cuff muscle imbalance (Burnham, May, Nelson, Steadward, & Reid, 1993), joint instability, postural changes, and altered scapular or glenohumeral kinematics. (Michener, McClure, & Karduna, 2003) The imbalances of humeral head depressors with comparative weakness of the shoulder adductors and external rotators were significantly more severe in the paraplegics' shoulders affected by rotator cuff impingement syndrome. (Burnham et al., 1993) Thoracic spine kyphosis posture has also been linked to alterations in subacromial space. (Gumina, Di Giorgio, Postacchini, & Postacchini, 2008) The subacromial space narrowing may be counteracted with scapular external rotation and posterior tilting that moves the acromion superior or posterior that may increase the subacromial space.

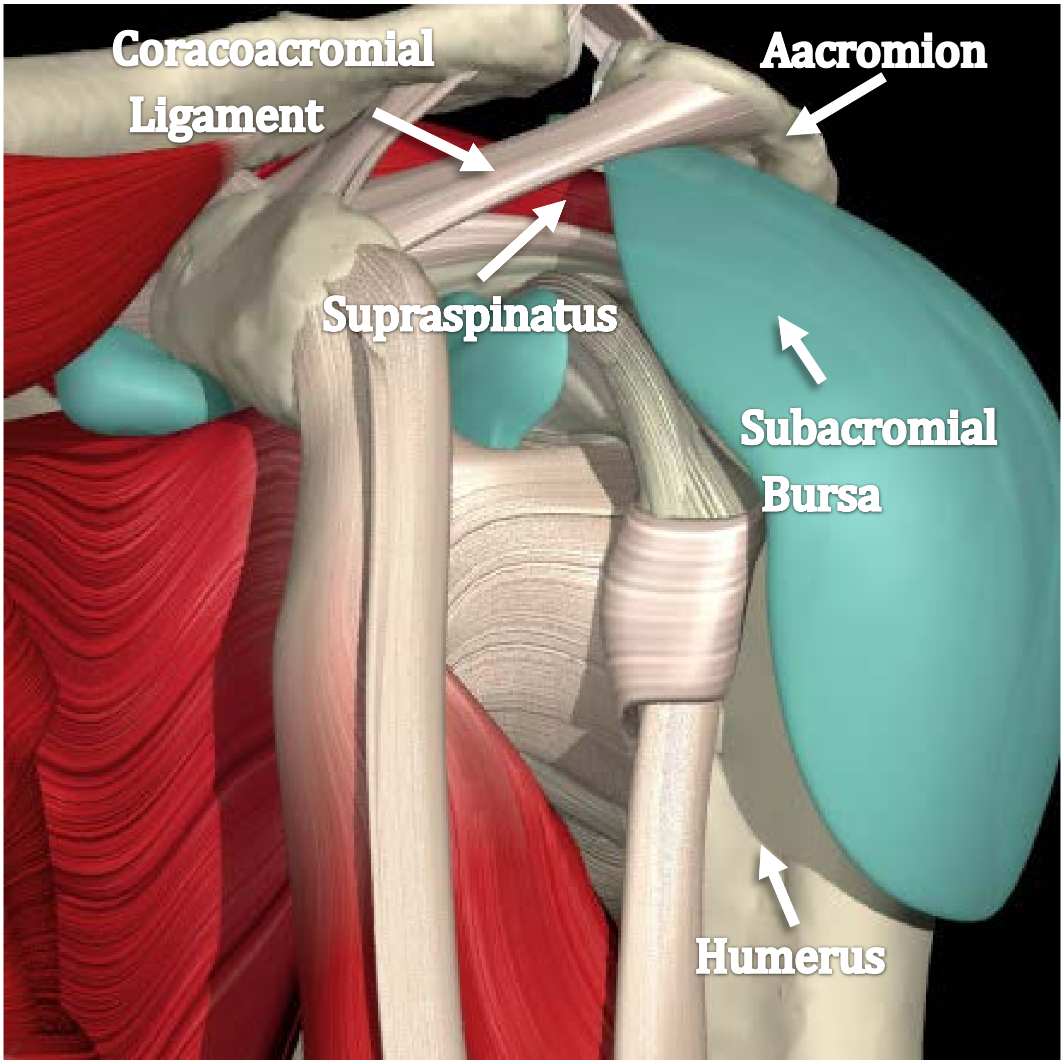


Figure 2. Anatomy of subacromial space (Adapted From: Interactive Shoulder v1.0 © 2000 Primal Pictures Ltd.)

1.1.3 Ultrasound to Investigate Acromiohumeral Distance

Diagnostic ultrasonography is an imaging technique that uses sound waves with a frequency between 2 to 15 MHz. Ultrasonography provides real-time, gray scale, B-mode display in which the variations in display intensity or brightness are used to indicate reflected signals of differing amplitude. When an ultrasound image is shown in black background, signals of greatest intensity appear as white while absence of signal is shown as black and signals of intermediate intensity appear as shades of gray. A wider dynamic range permits better identification of subtle differences in tissue echogenicity. (Dambrosio, Amy, & Colombo, 1995) The application of ultrasound imaging in medical diagnosis began in the late 1950s in surgery and obstetrics, being later followed in the musculoskeletal ultrasonography. (Carol M Rumack, 2010) Musculoskeletal ultrasound has been used to evaluate shoulder pathology. (Cheng et al., 2008; J. L. Collinger, Fullerton, Impink, Koontz, & Boninger, 2010; Moosmayer & Smith, 2005; Zanetti & Hodler, 2000) Ultrasound has been widely used to examine the shoulder pathology including rotator cuff disease, SIS, and biceps tendon disruption. (Ottenheijm et al., 2010) Besides the evaluation of the soft tissue structure of the shoulder, ultrasound is also used to identify glenohumeral joint instability problems, nerve entrapment syndromes, and assessment for subacromial space. (Martinoli et al., 2003) Moreover, ultrasound imaging not only characterizes the anatomical structures at rest but also displays the musculoskeletal components during functional movement. (Hashimoto, Kramer, & Wiitala, 1999) In certain cases, the asymptomatic shoulder is normal in appearance. Therefore taking ultrasound images of the shoulder during functional movement may provide objective evidence of a pathological condition. Musculoskeletal ultrasonography provides several advantages over other imaging techniques (e.g. MRI, fluoroscopy, X-ray) such as non-invasive, ionizing radiation free, portable and relatively cost-effective. Ultrasonographic imaging identifying bone surfaces and boundaries produce brighter responses than the surrounding soft tissue structures. Bone appears more hyper-echoic in contrast to surrounding soft tissues that are filled with fluid and appear more hypo-echoic. (Hacihaliloglu, Abugharbieh, Hodgson, & Rohling, 2009) Compared to soft tissues which are anisotropic and sensitive to probe orientation, the surface of bone is less subject to change in appearance. These properties make it promising for reliable measurement of AHD using ultrasound.

AHD is the linear measurement of subacromial space outlet. AHD has been studied in patients with rotator cuff impingement using conventional radiographs (Bey et al., 2007; Chen et al., 1999; Chopp et al., 2010; Deutsch et al., 1996; Saupe et al., 2006; Werner et al., 2008), MRI (Graichen et al., 1998; Hebert, Moffet, Dufour, & Moisan, 2003; Hinterwimmer et al., 2003; Saupe et al., 2006; Werner et al., 2008), fluoroscopy (Royer et al., 2009; Teyhen, Miller, Middag, & Kane, 2008), arthroscopics (Ryu, Burkhart, Parten, & Gross, 2002; Verhelst et al., 2010) and ultrasonography. (Cholewinski et al., 2008; Desmeules et al., 2004; Pijls et al., 2010; Silva et al., 2010) AHD has been measured using radiography in several studies. (Chen et al., 1999; Chopp et al., 2010; Deutsch et al., 1996; Gumina et al., 2008) Radiography has the limitation of radiation exposure and projectional artifacts. (Lochmuller, Anetzberger, Maier, Habermeyer, & Muller-Gerbl, 1997; Peh, Cheng, & Chan, 1995) Borsa compared the correlation of glenohumeral laxity determined by ultrasound and conventional radiography. (Borsa, Jacobson, Scibek, & Dover, 2005) They concluded that dynamic ultrasound could be used as a viable replacement for asymptotic shoulder. Ultrasound modality is especially desirable for MWUs because it enables imaging during a functional wheelchair activity such as a weight relief raise. Taking images using radiography or MRI may be difficult, time-consuming, and inconvenient for MWUs. Previous studies also used ultrasonographic imaging techniques to measure the AHD. (Cholewinski et al., 2008; Desmeules et al., 2004; Pijls et al., 2010; Silva et al., 2010) Changes in the size of subacromial space can provide a sensitive marker of rotator cuff dysfunction. (Cholewinski et al., 2008)

1.1.4 Acromiohumeral Distance in Manual Wheelchair Users

Ultrasonographic measurement of AHD has been done in many studies with healthy shoulders (Cheng et al., 2008; Schmidt et al., 2004), athletes (Girometti et al., 2006; Silva et al., 2010; Wang et al., 2005), patients with SIS (Desmeules et al., 2004; Pijls et al., 2010), individuals with different stages of rotator cuff degeneration (Azzoni, Cabitza, & Parrini, 2004), and patients with rotator cuff tear. (Cholewinski et al., 2008) The AHD in normal shoulders can range between 7mm and 16mm in a neutral shoulder position. (Petersson & Redlund-Johnell, 1984; Tillander & Norlin, 2002; Weiner & Macnab, 1970) The thickness of the rotator cuff tendon in this area is 5 to 9mm, leaving very little clearance in cases of enlargement of the bursa, tendon, or irregularities of the gliding surface. The distance is generally less in symptomatic shoulders. (Cotton & Rideout, 1964; Leong et al., 2011; Weiner & Macnab, 1970) An AHD measurement less than 7mm is indicative of a tear of the rotator cuff tendons and surgical consideration. (Weiner & Macnab, 1970) Prior studies have used ultrasound to describe differences in AHD between patients that are symptomatic for impingement syndrome and healthy controls. (Cholewinski et al., 2008; Desmeules et al., 2004; Pijls et al., 2010; Seitz et al., 2012) From these studies, AHD narrowing (0.8mm to 2.5 mm) from neutral to 90° scapular plane elevation occurred in healthy subjects. Several recent studies suggested that deficits in the AHD resulting from muscle weakness are more likely to appear when the shoulder is actively abducted. (Desmeules et al., 2004; Graichen, Bonel, Stammberger, Haubner, et al., 1999; Hinterwimmer et al., 2003; Seitz & Michener, 2011) Under active shoulder abduction, greater narrowing of the AHD has been demonstrated for shoulders with subacromial impingement compared to those without. (Desmeules et al., 2004) Narrowing of the AHD in a functional position has also been associated with altered scapular kinematics which is common among symptomatic shoulders.

(Deutsch et al., 1996; Keener, Wei, Kim, Steger-May, & Yamaguchi, 2009; Lewis, Green, & Wright, 2005; Paula M. Ludewig & Cook, 2002) One study reported that 26% to 45% narrowing in subacromial space resulted from scapular retraction to protraction. (Solem-Bertoft, Thuomas, & Westerberg, 1993) Another study showed that less scapular posterior tilting was found in impinged shoulders (25.1°±9.1°) compared to nonimpaired shoulders (34.6°±9.7°). (Lukasiewicz, McClure, Michener, Pratt, & Sennett, 1999)

Very few studies have investigated the AHD measurement in MWUs. MWUs represent a unique population for studying AHD due to the types of weight-bearing activities that they perform routinely. MWUs with paraplegia demonstrated shoulder muscle imbalances with comparative weakness of humeral head depressors placing them at a high risk in the development of rotator cuff impingement syndrome. (Burnham et al., 1993) Our study is the first to describe ultrasonographic measurement of AHD in a wheelchair user population. Reliability of AHD measurement using ultrasound in relation to various shoulder positions before and after repetitive exercises is discussed in Chapter 2.

1.1.5 Acromiohumeral Distance and Shoulder Muscle Imbalance

Narrowing of AHD could be caused by imbalance of humeral head depressors and shoulder surrounding muscles. (Lochmuller, Maier, Anetzberger, Habermeyer, & Muller-Gerbl, 1997) Superior humeral head migration (0.60 mm to 2.21mm) was found after rotator cuff (RC) muscle fatigue using radiographic (Chopp et al., 2010) and digital fluoroscopic imaging (Royer et al., 2009; Teyhen et al., 2010) While electromyography (EMG) signs of local muscle fatigue were apparent for several shoulder girdle muscles, the infraspinatus muscle was fatigued to a greater extent than any of the other muscles during shoulder external rotation. (Brookham, McLean, &

Dickerson, 2010; Chopp et al., 2010; Ebaugh, McClure, & Karduna, 2006b; MacDermid, Ramos, Drosdowech, Faber, & Patterson, 2004; Stackhouse, Stapleton, Wagner, & McClure, 2010) These results indicated that infraspinatus muscle fatigue played a significant role in the migration of the humeral head. The infraspinatus is the primary external rotator muscle of the glenohumeral joint. It is also an active depressor of the humeral head. (Nove-Josserand, Levigne, Noel, & Walch, 1996) The contraction force generated by infraspinatus contributes to superior stability of the gleonohumeral joint. Reductions in external rotator muscle strength and endurance have been identified in subjects with shoulder impingement syndrome or rotator cuff tear. (W. K. Chang, 2004; Ebaugh, McClure, & Karduna, 2006a; Roy, Moffet, Hebert, & Lirette, 2009) Other major shoulder depressors are the pectoralis major, latissimus dorsi, and teres major muscles. A deficiency in these depressor muscle strength has also been postulated to lead to subacromial impingement syndrome. (Sharkey & Marder, 1995)

Studies on non-wheelchair users have shown that fatigue of the RC muscles reduces their ability to stabilize the humeral head against the glenoid cavity of the scapula, and therefore causes migration of the humeral head into the subacromial space. (Chopp et al., 2010; Teyhen et al., 2008) Chopp et al. investigated radiographic measurement of humeral head migration following two types of fatiguing protocols: 1) a global shoulder fatiguing protocol that simulated job tasks, and 2) a local fatiguing protocol that targeted fatigue of the shoulder external rotators. (Chopp, Fischer, & Dickerson, 2011; Chopp et al., 2010; Tsai, McClure, & Karduna, 2003) While both protocols were expected to show reduction in the AHD, the global protocol induced greater changes in humeral head translation. (Chopp et al., 2010) Although the amount of humeral translation may be considered small (1 to 3 mm), the compressive effects on the subacromial structures were considered significant due to the small size of the subacromial space.

Wheelchair propulsion and weight relief raises result in excessive shoulder joint loading. Both activities demand RC muscles to maintain glenohumeral joint stability during the maneuvers. (M. M. B. Morrow, Kaufman, & An, 2011; Reyes, Gronley, Newsam, Mulroy, & Perry, 1995; S. van Drongelen, van der Woude, & Veeger, 2011) For example, a person performs a weight relief raise by adducting their arms and using them to lift and support the body for the purposes of reducing pressure loading on the buttocks. Among the shoulder depressors muscles during a weight relief raise in a group of 13 paraplegic individuals, Reyes et al. reported that the sternal pectoralis major and latissimus dorsi displayed greater muscle activity than other shoulder muscles, reaching 32% and 58% of the maximum voluntary contraction during the lift phase, respectively. (Reyes et al., 1995) During wheelchair propulsion, the infraspiantus was active approximately 40% of the propulsion cycle and reached a maximum intensity of 44% in the push phase to stabilize the glenohuneral joint. (Mulroy, Gronley, Newsam, & Perry, 1996) High muscle activation during wheelchair activity makes shoulder muscles vulnerable to fatigue. van Drongelen et al. simulated shoulder joint reaction forces during a weight-relief raise using musculoskeletal modeling. They found that large weight-bearing forces (1288 N) acted to drive the humerus into the GH joint during the weight-relief raise. (S. van Drongelen et al., 2011) It is unclear whether these forces cause compression of the subacromial space directly, or if other factors such as pain, pathological deficits, muscle weakness, altered shoulder kinematics, and fatigue may be associated with unwanted narrowing of subacromial space. (Sharkey & Marder, 1995) Chapter 3 examined the effects of muscle fatiguing tasks on the AHD in manual wheelchair users.

1.1.6 Wheelchair Propulsion Biomechanics

Manual wheelchair propulsion is a primary form of locomotion for individuals with SCI. Relying on a manual wheelchair for mobility over an extended period of time often leads to arm pain and thus, to secondary disability. Previous studies reveal that over 50% of MWUs with SCI experience shoulder pain that limits one or more of their activities of daily living. (Boninger et al., 2001; Dyson-Hudson, Shiflett, Kirshblum, Bowen, & Druin, 2001; M. M. Morrow et al., 2009; R. N. Robertson, Boninger, Cooper, & Shimada, 1996; Samuelsson, Tropp, & Gerdle, 2004) A substantial number of these studies confirm that manual wheelchair propulsion is a contributing factor in the development of shoulder pain. (Boninger & Cooper, 1999; Mercer et al., 2006) Moreover, an inappropriate wheelchair, improper assessment, poor set-up and fitting are associated to shoulder pain. (Boninger, Baldwin, Cooper, Koontz, & Chan, 2000)

Wheelchair propulsion biomechanics for steady-state conditions have been extensively explored for decades. (Rory A. Cooper, 2009) However, wheelchair propulsion biomechanics in start-up phases and the effects of intense wheelchair propulsion on the upper limbs are rarely investigated. Wheelchair users experienced start-up propulsion over 100 times per day on average. (Tolerico et al., 2007)The start-up propulsion generates higher forces and moments in a relatively short duration. A rapid acceleration results in higher joint force, moments, velocities, and powers than comfortable steady-state propulsion. In addition, intense wheelchair activity accompanied with muscle fatigue may amplify the effects of muscle imbalance. (Price et al., 2007) The component of propulsion force directed toward the wheel hub is required to generate friction for propulsion. This force acts equal and opposite to the amount of force applied towards the shoulder which may translate the humeral head into the subacromial space. (Finley, McQuade, & Rodgers, 2005; M. M. B. Morrow et al., 2011; Nawoczenski et al., 2003; Philip

Santos Requejo et al., 2008; S. van Drongelen et al., 2006) This force may potentially lead to compression and damage of soft tissue caused by impingement. In people with SCI, uneven loading on surrounding muscles during propulsion and a weak rotator cuff may lead to impingement of the soft tissue structures within the acromiohumeral space. (Lippitt & Matsen, 1993) In a prior work, Mercer et al. found a relationship between shoulder joint kinetics and magnetic resonance imaging (MRI) shoulder abnormalities. (Mercer et al., 2006) More specifically, posterior directed force at the shoulder was related to coracoacromial ligament edema, which is a risk factor for rotator cuff injury. (Hawkins & Kennedy, 1980; Mercer et al., 2006) The same study found that internal rotation moment at the shoulder was associated with physical examination abnormalities.

In another previous study, longitudinal views were used to determine diameter and echogenicity of the biceps tendon using quantitative ultrasound in pre- and post-rugby and basketball game images. (Stefan van Drongelen, Boninger, Impink, & Khalaf, 2007) The ratio of echogenicity of the tendon to a reference area superficial to the tendon sheath decreased significantly after the sports game. The 13 subjects who reported pain during the last month showed a lower tendon echogenicity ratio before and after the event than that of subjects who did not report pain. This study attests to the ability to use ultrasound to detect acute changes in soft tissue at the shoulder after a propulsion task that is correlated with pain. Known biomechanical factors of injury (increased cadence, increased propulsion forces) were found related to post-propulsion quantitative ultrasound measures. (J. L. Collinger, Fullerton, et al., 2010) Chapter 4 built upon this work and utilized ultrasonographic measurement to determine the relationship between AHD changes after intense wheelchair activity and start-up propulsion biomechanics.

1.2 RESEARCH GOAL

The overall goal of this dissertation was to evaluate ultrasonographic measurement of acromiohumeral distance to identify the mechanism of injury and risk factors of subacromial impingement syndrome after acute shoulder muscle fatiguing tasks and intense wheelchair propulsion. The purpose of Chapter 2 was to examine the intra-rater and inter-rater reliability of ultrasonographic measurement of the acromiohumeral distance (AHD). The objectives of Chapter 3 and 4 were to investigate the effects of shoulder muscle fatiguing exercises and intense wheelchair propulsion on subacromial space among manual wheelchair users (MWUs), respectively.

This research is important because it provides direct measurement and practical application of the AHD measurement to injury mechanism. Outcomes on treatment of upper limb injury could be very costly and may take years to show results. If we could identify predictors that are sensitive to changes and related to long-term risk of injury, we could create targeted therapeutic interventions and gain insight into their effectiveness.

2.0 ULTRASONOGRAPHIC MEASUREMENT OF THE ACROMIOHUMERAL DISTANCE IN SPINAL CORD INJURY: RELIABILITY, EFFECTS OF SHOULDER POSITIONING AND REPETITIVE EXERCISES

2.1 INTRODUCTION

Subacromial impingement syndrome (SIS) is reported as the most common reason for shoulder discomfort. (van der Windt, Koes, de Jong, & Bouter, 1995) Research has shown that shoulder discomfort due to SIS is associated with muscle fatigue (Wiker, Chaffin, & Langolf, 1989) and shoulder dysfunction. (P. M. Ludewig & Cook, 2000) The subacromial space consists of the humeral head, acromion, coracoacromial ligament, subacromial bursa, and the acromioclavicular joint. (Neer, 1972) SIS refers to the encroachment of the supraspinatus as a result of the subacromial space narrowing. (Michener et al., 2003) Manual wheelchair users (MWUs) are at an extremely high risk for developing shoulder pathology. (M. M. B. Morrow et al., 2011) The prevalence of rotator cuff tears in individuals with paraplegia is 63% which is higher than their able-bodied counterparts (15%). (Akbar et al., 2010) Essential repetitive weight bearing activities such as wheelchair transfers, weight relief raises, and wheelchair propulsion are likely responsible for the increased prevalence of shoulder pathology in individuals with SCI. Moreover, individuals with SCI are not able to rest a shoulder that becomes painful because of the reliance on the upper limbs for independence with mobility and other essential daily tasks which further perpetuate the problem.

Acromiohumeral distance (AHD) is the 2-D linear measurement between the most inferior aspect of the acromion and the humeral head and is a widely recognized marker for rotator cuff disease. (Cholewinski et al., 2008) Recently, ultrasonography has been used increasingly as a viable imaging modality for evaluating the subacromial space because it is portable, radiation-free, and non-invasive. AHD measurement using ultrasound has been well established in previous studies with healthy shoulders, (Cheng et al., 2008; Kumar et al., 2011; Schmidt et al., 2004) athletes, (Girometti et al., 2006; Silva et al., 2010; Wang et al., 2005) patients with SIS, (Desmeules et al., 2004; Pijls et al., 2010) patients with poststroke hemiplegia, (Kumar et al., 2011) individuals with different stages of rotator cuff degeneration, (Azzoni et al., 2004) and patients with rotator cuff tear. (Cholewinski et al., 2008) Moderate to excellent inter-rater reliability (0.64-0.92) and excellent intra-rater reliability (0.87-0.94) of the AHD have been demonstrated using ultrasound in able-bodied with healthy and impinged shoulders. (Kumar, Bradley, & Swinkels, 2010; Pijls et al., 2010; Schmidt et al., 2004) Moderate intra- and inter-observer reliability using unmarked sonograms were reported. (Pijls et al., 2010) Discriminant validity of the AHD between affected and unaffected shoulders was determined in a hemiplegic population. (Kumar et al., 2011) Therefore, AHD measures using ultrasound would be useful for quantitatively evaluating effects of an intervention and identifying mechanisms of rotator cuff disease and SIS in a wheelchair user population.

AHD narrowing may be caused by both intrinsic and extrinsic factors. (Michener et al., 2003) Intrinsic factors such as tendon tears could occur due to degeneration of the tendon from long-term use, (Budoff, Nirschl, & Guidi, 1998) whereas extrinsic factors such as poor posture (e.g. scapular protraction and kyphotic trunk postures) or altered glenohumeral kinematics can mechanically compress structures surrounding the tendon. (Neer, 1972; Seitz et al., 2011) The primary mechanism responsible for subacromial impingement is most likely superior humeral migration, which results in AHD narrowing. (Chopp & Dickerson, 2012) Previous studies measured AHD with the shoulder in a resting neutral position (Cholewinski et al., 2008; Desmeules et al., 2004), active or passive shoulder abduction at 45° and 90° arm elevation (Chopp et al., 2010; Graichen, Bonel, Stammberger, Eeglmeier, et al., 1999; Seitz et al., 2012) and reported that shoulder position might affect the reliability of AHD measurement. (Pijls et al., 2010) Superior humeral migration occurs in healthy individuals as the shoulder abducts from 0 to 90°. (Graichen, Bonel, Stammberger, Eeglmeier, et al., 1999; Lippitt & Matsen, 1993) Within this range of shoulder motion, the upward force of the deltoid muscle overwhelms the stabilizing force of the rotator cuff muscles, thus resulting in a decrease in the AHD. (Chopp et al., 2010) Rotator cuff muscles weakness following SCI may impact the AHD due to alteration of force couple mechanism in the shoulder. Because of this counterbalance relationship between the deltoid and rotator cuff muscles, investigators have studied the effects of rotator cuff muscle fatigue on the subacromial space. (Chopp & Dickerson, 2012) Teyhen et al. reported that the AHD narrowing increased following fatiguing exercises regardless of the degree of shoulder abduction with the use of digital fluoroscopy imaging techniques. (Teyhen et al., 2008) The mechanism leading to AHD narrowing in an able-bodied population might be different from MWUs with SCI. Normal shoulder function is comprised in individuals with SCI due to altered scapulothoracic rhythm, glenohumeral kinematics, and muscle strength imbalances around the shoulder joint. (Lee & McMahon, 2002; Mulroy et al., 1996) The objectives of this study were to:

1) Assess the intra-rater and inter-rater reliability of ultrasonographic-measured AHD in MWUs with SCI (case) and able-bodied population (control);

2) Evaluate differences in the AHD as a function of shoulder position and muscle activation;

3) Investigate the acute changes in the AHD following a repeated weight relief raise task and rotator cuff exercises and

4) Compare baseline and acute changes in the AHD measures within and between the case and control group.

We hypothesized that 1) ultrasonographic measurement of the AHD would be reliable (ICC > 0.8). 2) Effects of shoulder positions on the AHD changes would be different between MWUs with SCI and able-bodied controlsdue to the altered shoulder biomechanics and muscle imbalances that follow SCI. 3) Both case and control groups would show acute AHD narrowing following repeated weight relief raises and rotator cuff exercises.

2.2 METHODS

2.2.1 Study Design and General Procedures

All participants read and signed the informed consent before participating in this study. The research protocol was approved by the Veteran Affairs Pittsburgh Healthcare System Institution Review Board. They were instructed not to perform strenuous activities for 24 hours before the testing sessions. Before starting the reliability session, participants transferred to a Biodex System 4 Isokinetic Dyanometer ™ (Biodex Medical Systems, Inc, Shirley, New York) with custom-made adjustable height arm rests (Figure 3A). Armrests were fitted to each participant to allow participants to pushup from a sitting position with full elbow extension and arms adducted to off-load the buttock tissues (Figure 3B).

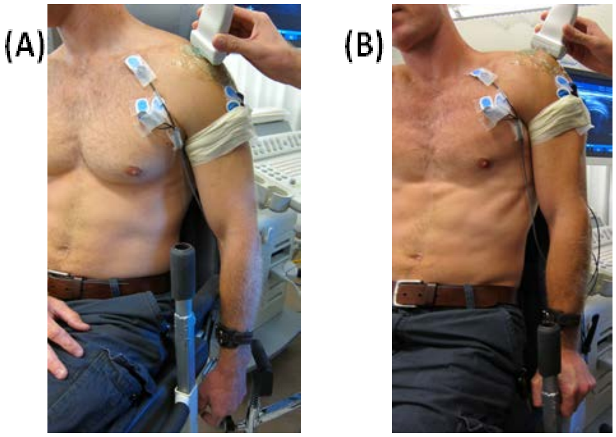


Figure 3. Imaging positions in the neutral resting (A) and weight relief raise position (B).

Age, height, weight, and date of injury/diagnosis were self-reported. Anthropometric data including shoulder circumference and upper arm length were measured before the experiment. The non-dominant side was chosen for all the measures in order to minimize the effects caused by performing activities of daily living on the dominant shoulder. A general questionnaire was used to document medical history including history of shoulder pain and surgery.(Boninger et al., 2001) MWUs with SCI completed the Wheelchair Users Shoulder Pain Index (WUSPI). The questionnaire contains 15 items to document shoulder pain during transfer, wheelchair mobility, personal care and general activities. Each item documents pain score from 0 (lowest pain) to 10 (worst pain ever experienced). The OMNI Pain Scale, previously validated by Faces pain scale for pediatric oncology, was used to assess exercise-induced muscle pain intensity. (R. J. Robertson et al., 2009) The OMNI scale was administered prior to all experimental procedures to establish a baseline measurement of pain, and after each fatigue task to determine the amount of exercise-induced pain.

2.2.2 Participants

Two groups of participants were recruited, one being MWUs with SCI and the other one being able-bodied volunteers. For the individuals with SCI, they must have had their injury for more than one year and use a manual wheelchair as their primary means for mobility. Inclusion criteria for both groups were 18 years of age or older, English speaking, and able to complete multiple weight relief raises. Exclusion criteria for both groups included having a history of fractures or dislocations in the shoulder, elbow and wrist from which the participant had not fully recovered, the presence of implants or pacemakers, any pain in an upper limb that could interfere with normal function and activity, and history of a cardiopulmonary condition that could be exacerbated. Able-bodied participants were chosen by matching their age within 5 years of each MWUs with SCI.

2.2.3 AHD Reliability Protocols

The subacromial space was quantified by measuring the acromiohumeral distance (AHD) using ultrasound techniques as described in previous studies. (Lin, 2012) Two ultrasound operators underwent training to learn the techniques and then practiced on three to five healthy volunteers to become familiar with the protocol and measurement procedure before the reliability study. A Philips HD11 1.0.6 ultrasound machine with a 5-12 MHz linear transducer was used to scan the shoulder from the anterior aspect of glenoid to the flat segment of posterior scapula to capture the bright reflection of the bony contour of the acromion and humeral head (Figure 4)

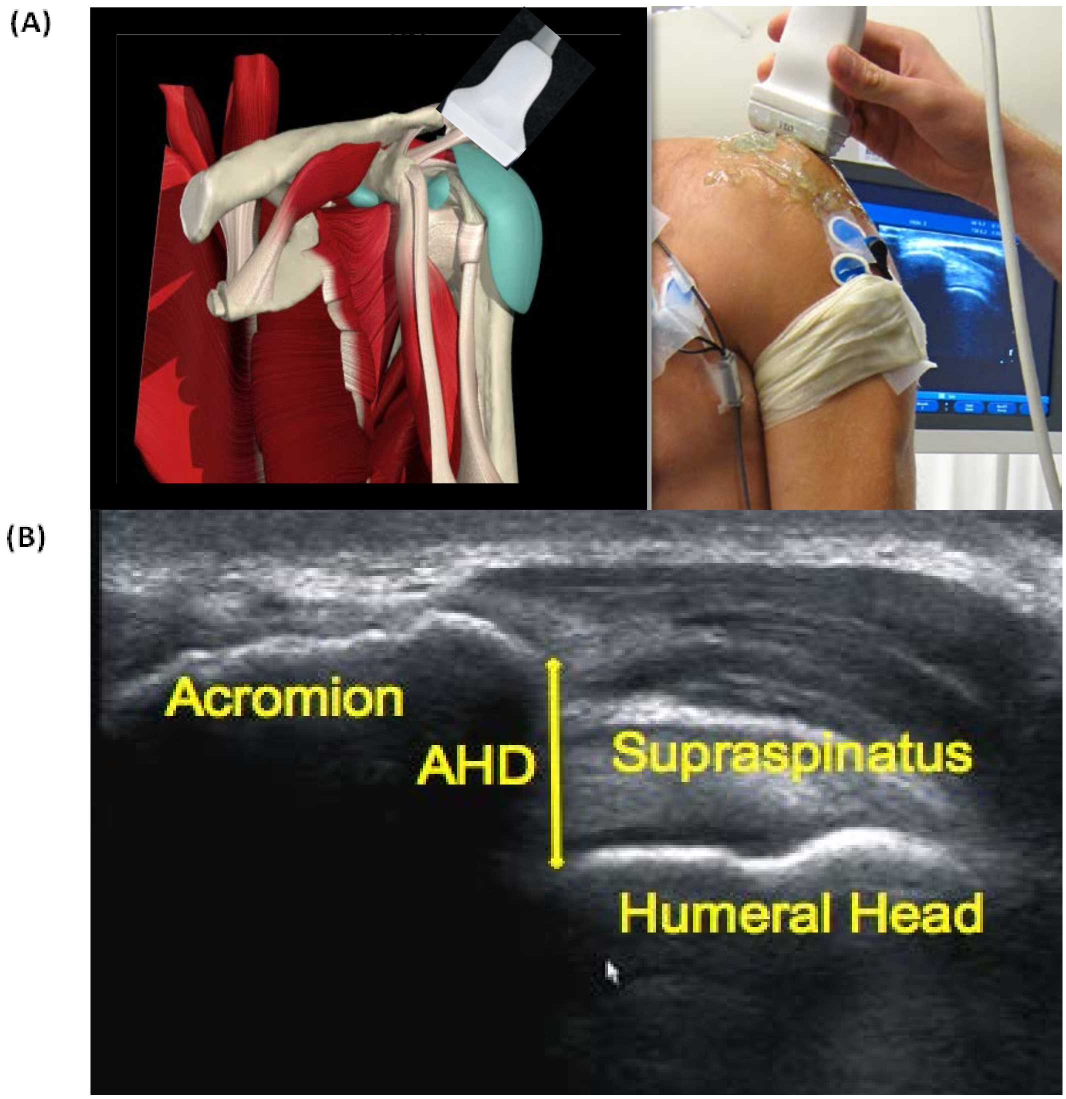


Figure 4. Ultrasonographic probe positioning (A) and image of the acromiohumeral distance (B).

Ultrasound video was recorded for the duration of scanning (which took approximately 10 seconds) at 10 Hz. Each rater recorded the AHD video in randomized order in the following shoulder positions: neutral resting position (Neutral), arm abducted at 45° and 90° in scapular plane (with and without resistance), and isometrically holding the weight relief raise position (WR) (Figure 3B). For the arm abduction trials, participants were instructed to grab the handle of the Biodex which was set to 45° and 90° of arm elevation in the scapular plane. (Figure 5)

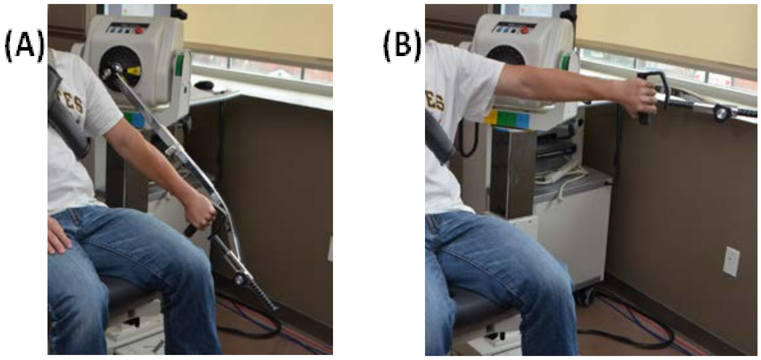


Figure 5. Participants maintained their arm at the prescribed angle of shoulder elevation by grabbing the handle bar of the Biodex. Ultrasound images were collected at 45°(A), and 90°(B) at scapular plane elevation with humeral internal rotation with and without weight. These images are from a demonstration and not an actual participant.

Participants grabbed the handle with arm internally rotated and thumb downward. The Biodex was used to provide a 5-lb weight in the active trials (45A, 90A) and provided no resistance in the passive trials (45P, 90P). (Graichen, Bonel, Stammberger, Eeglmeier, et al., 1999) The weight was determined through pilot testing and was determined to provide adequate muscle activity without causing discomfort to the participant. Once this set-up was completed (Time 1), the AHD videos were recorded again by each rater using the same procedures after a 30-minute time interval (Time 2). All raters were blinded to each other's measurements. The AHD absolute values averaged across raters were used as the baseline AHD.

2.2.4 Fatiguing Protocols

The fatiguing protocols were performed approximately 5 minutes after the reliability protocols. Both groups of participants performed two fatiguing exercise tasks (global and local). The order of the two tasks was randomized for each participant. The global fatiguing task involved performing repeated weight relief raises (WR) and holding the buttocks off the seat with both elbows in locked positions. (M. M. B. Morrow et al., 2011; Reyes et al., 1995) The WR task was repeated at a rate of 30 repetitions per minute with the use of a metronome. Participants were instructed to stop when they were no longer able to keep up the task due to self-perceived fatigue. The local fatiguing task involved performing isokinetic shoulder external rotation (ER) at an angular velocity of 60 degrees per second for external rotation and 180 degrees per second for internal rotation to minimize shoulder internal rotator fatigue. The subject was instructed to externally rotate their forearm from a shoulder neutral position to 45 degrees or the maximum range of ER that they could comfortably reach similar to that done in other rotator cuff muscle fatiguing protocols. (Ebaugh et al., 2006b) The participant's trunk was secured using straps from the Biodex that crossed the chest and lap to minimize compensatory movements. At the end of both global and local fatiguing tasks, participants provided their exertion rating score. A Borg scale reading of 10 or more was the threshold to confirm self-reported fatigue, which has been found to be closely related to EMG signs of fatigue.(Hummel et al., 2005) Participants' rating scores were obtained after the first 300 repetitions for each exercise. If their rating was below a '10' the protocol continued for another session of 300 repetitions or until they could not do any more. A 30-minute washout period was provided between the two fatiguing tasks. The AHD was measured before each exercise and immediately after each exercise. Rater 2's data were used to compare the pre-post exercise AHD measures.

2.2.5 Data Analysis

An investigator blinded to the subject's shoulder positions and timing of the video used a customized Matlab program to manually review each frame of the video and mark the inferior edge of acromion and humeral head. The distance between the bony landmarks was calculated for each frame of the video and the narrowest distance was used for statistical analyses. A subset of the videos (n=120) were randomly and independently analyzed by a second investigator to access intra and inter-video reliability of the manual techniques used to post-process the images. Reliability of the post-processing procedures and the ultrasound image data collection process were assessed using intraclass correlation coefficients (ICC, two way random, absolute agreements). The following ICC interpretation scale was used: almost perfect (0.81-1), excellent (0.61-0.80), moderate (0.41-0.60), and poor to fair (below 0.40). (Landis & Koch, 1977) The standard error of measurement (SEM) was calculated using the formula (Portney & Watkins, 2009):

$$SEM = SD\sqrt{1-ICC}$$, **Equation 1**

where SD is the baseline standard deviation of the entire sample. The minimum detectable difference (MDD) was computed based on a confidence interval of 90% following the formula(J. L. Collinger, Gagnon, Jacobson, Impink, & Boninger, 2009):

$$MDD_{90} = 1.65 \times SEM \times \sqrt{2}$$, **Equation 2**

Chi-square or independent t-tests depending on the nature of the variable were used to compare demographic differences between the case and control groups. A three-way mixed-design analysis of variance (ANOVA) was used to identify differences in the AHD between groups, pre-post exercise, and shoulder positions. As this was a pilot study secondary exploratory analyses consisted of running post-hoc independent t-tests controlling for group differences as appropriate to analyze AHD differences between subjects (SCI and able-bodied) or paired t-tests for within subject conditions. Pearson's or Spearman's correlation statistics were used where appropriate to examine the relationships between the absolute AHD measures, AHD percentage change determined as the ratio of the amount of change between AHD baseline and post-task, AHD to the AHD baseline (Equation 3), OMNI scale score, and demographic data (e.g. height, weight, shoulder circumference, arm length, age, and years since injury). Bonferroni correction was applied to the planned four pairwise comparisons for active and passive muscle conditions, with the alpha corrected level at 0.01. An alpha level of significance was set at 0.05. Trends in the data were noted when the level of significance was set to 0.1.

$$\text{AHD percentage change (\%)} = \frac{\text{post AHD measure - pre AHD measure}}{\text{pre AHD measure}} \times 100\%$$ **, Equation 3**

2.3 RESULTS

2.3.1 Subject Characteristics

Ten MWUs with a spinal cord injury including nine men and one woman (2 tetraplegia and 8 paraplegia) and ten able-bodied individuals including eight men and two women participated in the study. The demographic data and statistical results are summarized in Table 1.

Table 1. Subject Characteristics

	Case (n = 10)	Control (n=10)	P Value
Sex			0.53
Men	9	8	
Women	1	2	
Age	34.8 ± 10.4	35.8 ± 11.5	0.84
	Range 25-55	Range 20-53	
Height (inch)	68.2 ± 4.9	68.8 ± 3.6	0.78
	Range 60-75	Range 61-73	
Weight (lbs)	152.9 ± 10.4	175.1 ± 29.7	0.28
	Range 101-283	Range 124-215	
Number of WR	44.3 ± 19.4	97.5 ± 100.6	0.13
Borg Scale after WR	14.5 ± 3.0	13.6 ± 1.8	0.43
OMNI after WR	3.3 ± 2.3	2.9 ± 1.4	0.64
Number of ER	247.0 ± 297.7	394.9 ± 355.0	0.33
Borg Scale after ER	12.8 ± 1.9	13.2 ± 2.6	0.70
OMNI after ER	2.8 ± 2.0	3.7 ± 2.5	0.38

WR: Multiple Weight Relief Raises
ER: Repetitive Shoulder External Rotation Exercises

2.3.2 Reliability of Ultrasonographic AHD Measurement

The intra-rater (ICC > 0.83) and inter-rater (ICC > 0.78) reliability of AHD measurement for each shoulder position was excellent among MWUs with SCI (Table 2). For rater 2, the ICC values for the intra-rater reliability of the AHD measurement were almost perfect in MWUs with SCI (ICC > 0.90) and able-bodied individuals (ICC > 0.81) (Table 2). For the AHD measured by rater 1 in able-bodied, the intra-rater reliability was fair to poor (ICC < 0.40) at 45A and excellent for all other positions (ICC > 0.85). Inter-rater reliability was excellent to almost perfect (ICC > 0.78) at both time points for the case group at all shoulder positions. Inter-rater reliability was excellent (ICC > 0.75) at both time points for the control group for all shoulder positions except at 45A in time 1 (ICC < 0.60).

Table 2. Intra- and interclass correlation coefficients.

	MWUs with SCI (n = 10)		Able-Bodied Subjects (n = 10)	
Intraclass correlation coefficients				
Position	Rater1	Rater2	Rater1	Rater2
Neutral	0.83(0.33-0.96)	0.98(0.93-0.99)	0.94(0.74-0.98)	0.95(0.78-0.99)
45A	0.94(0.72-0.0.99)	0.93(0.72-0.98)	0.24(-3.06-0.82)	0.96(0.83-0.99)
45P	0.92(0.68-0.98)	0.97(0.88-0.99)	0.69(-0.08-0.92)	0.85(0.38-0.96)
90A	0.90(0.62-0.98)	0.97(0.88-0.99)	0.88(0.54-0.97)	0.81(0.24-0.95)
90P	0.92(0.69-0.98)	0.90(0.62-0.98)	0.97(0.87-0.99)	0.92(0.68-0.98)
WR	0.93(0.70-0.98)	0.93(0.73-0.98)	0.85(0.41-0.96)	0.96(0.86-0.99)
Interclass correlation coefficients				
Position	Time1	Time2	Time1	Time2
Neutral	0.78(0.19-0.94)	0.92(0.67-0.98)	0.85(0.38-0.96)	0.95(0.82-0.99)
45A	0.93(0.72-0.98)	0.95(0.83-0.99)	0.52(-1.25-0.89)	0.88(0.50-0.97)
45P	0.84(0.34-0.96)	0.95(0.80-0.99)	0.84(0.30-0.96)	0.66(-0.42-0.92)
90A	0.86(0.41-0.97)	0.94(0.76-0.99)	0.75(-0.08-0.94)	0.84(0.36-0.96)
90P	0.94(0.79-0.99)	0.93(0.70-0.98)	0.83(0.26-0.96)	0.94(0.73-0.98)
WR	0.89(0.59-0.97)	0.97(0.88-0.99)	0.75(-0.08-0.94)	0.89(0.52-0.97)
Intra-video reliability			Inter-video reliability	
0.81(0.71-0.87)			0.85(0.78-0.90)	

Data are given as average-measure values (lower-upper bound 95% confidence interval).
Time: Time order of recorded ultrasound video
Neutral: neutral resting position; 45A, 45P: Arm fully extension with humeral internal rotation at 45° in scapular plane with and without resistance; 90A, 90P: Arm fully extension with humeral internal rotation at 90° in scapular plane with and without resistance; WR: Holding the weight relief raise position

Figure 6 shows the agreement among raters for the AHD measurements across all shoulder positions in both groups. The Bland-Altman plots, used to compare the individual differences in the AHD absolute value for both raters showed good agreement in the case and control groups. (Figure 6) The absolute AHD measurements for both groups are shown in Table 4.

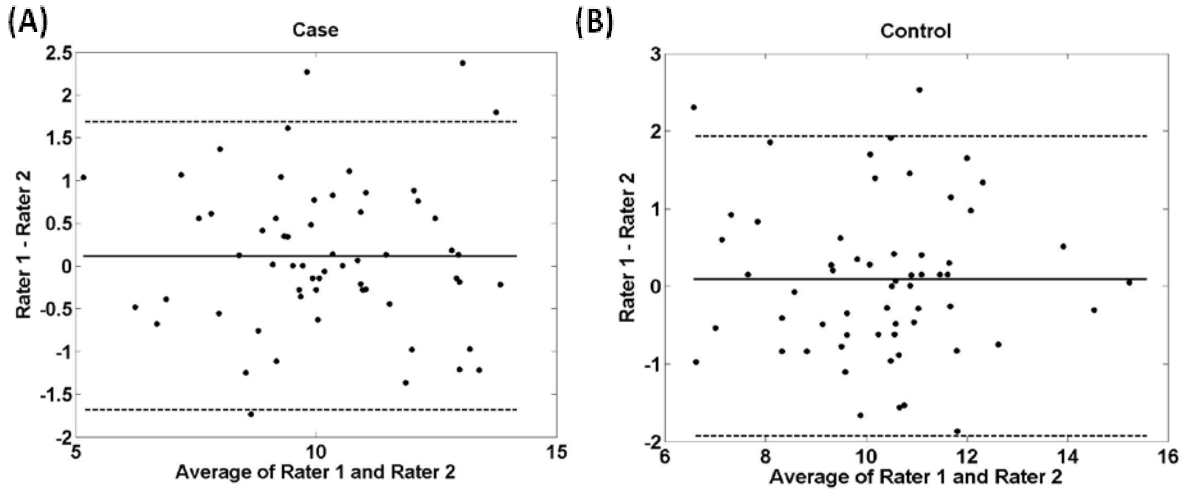


Figure 6. Bland-Altman plot of average rater 1 and 2 of the AHD measurement in MWUs with SCI (A) and able-bodied (B). Dotted line represents 1.96 standard deviations above and below the mean difference.

The AHD is widest in a neutral resting position and narrowest in the 90A positions. The absolute reliability was examined using SEM and the MDD for each rater. The SEM and MDD were less than 0.73mm and 1.71mm, respectively (Table 3). The inter- and intra-video reliability was excellent (ICC > 0.81).

Table 3. Standard error of measurement (SEM) and minimum detectable difference (MDD) of AHD measurement in six shoulder positions.

	MWUs with SCI (n = 10)		Able-Bodied Subjects (n = 10)	
	SEM (mm)	MDD(mm)	SEM (mm)	MDD(mm)
Intra-Rater 1				
Neutral	0.66	1.53	0.42	0.98
45A	0.47	1.09	1.01	2.35
45P	0.54	1.27	0.97	2.27
90A	0.75	1.76	0.50	1.16
90P	0.66	1.55	0.39	0.90
WR	0.39	0.90	0.44	1.03
Mean	0.58	1.35	0.62	1.47
Intra-Rater 2				
Neutral	0.21	0.50	0.39	0.90
45A	0.58	1.35	0.42	0.97
45P	0.36	0.83	0.56	1.32
90A	0.33	0.78	0.60	1.40
90P	0.76	1.77	0.47	1.10
WR	0.52	1.21	0.29	0.68
Mean	0.46	1.07	0.46	1.06
Inter-Rater				
Neutral	0.70	1.63	0.65	1.52
45A	0.53	1.23	1.08	2.51
45P	0.77	1.80	0.62	1.44
90A	0.78	1.82	0.66	1.55
90P	0.58	1.35	0.77	1.81
WR	0.56	1.31	0.61	1.43
Mean	0.65	1.52	0.73	1.71

2.3.3 Effects of Shoulder Position, Exercise and Group Type on the AHD

MWUs with SCI experienced a continued decrease in AHD from neutral, 45P to 90P (Table 4). Able-bodied subjects, however, displayed a pattern in which mean AHD slightly increased from neutral to 45P and then decreased from 45P to 90P. For baseline in both groups measured by both raters, there was a significant main effect of arm position ($p = 0.003$). We found that AHD was significantly narrower at 90P compared to neutral ($p = 0.01$). The AHD at 90A is significantly narrower than that at neutral, 45P, and WR ($p < 0.001$). There were no interaction effects among fatiguing tasks, shoulder positions and groups. Case has greater AHD narrowing occurred between the neutral and 45A position than did the control group after shoulder external rotation exercise ($p = 0.03$).

Table 4. Ultrasonographic measurement of acromiohumeral distance in six shoulder positions at baseline (averaged across two measures in each rater), before, and after two should fatiguing exercises (rater 2 only).

AHD (mm)	MWUs with SCI (n = 10)				Able-Bodied Subjects (n=10)			
Position	**Baseline from Rater 1**		**Baseline from Rater 2**		**Baseline from Rater 1**		**Baseline from Rater 2**	
Neutral	11.43±1.59		11.13±1.51		11.38±1.71		11.41±1.73	
45A	10.07±1.91		9.90±2.18		9.72±1.16		9.75±2.08	
45P	10.97±1.92		10.77±2.06		11.60±1.75		11.36±1.46	
90A	9.24±2.38‡		9.25±1.93‡		8.94±1.44‡		8.58±1.38‡	
90P	9.78±2.35*		9.78±2.40*		9.50±2.23*		9.49±1.67*	
WR	10.18±1.46		10.17±1.96		10.60±1.14		10.61±1.45	
AHD (mm)	**PreWR**	**PosWR**	**PreER**	**PosER**	**PreWR**	**PosWR**	**PreER**	**PosER**
Neutral	10.91±1.38	11.51±1.47	11.24±1.38	11.76±2.02	11.33±2.04	11.31±1.62	11.74±1.57	11.41±1.49
45A	9.64±2.22	9.67±2.07	9.32±2.25	9.27±2.53†	9.25±2.31	9.40±1.68	9.42±2.61	10.10±1.80†
45P	10.93±1.53	10.69±1.62	10.32±1.98	10.24±2.45	11.80±2.12	11.57±2.05	11.54±2.01	11.95±2.00
90A	8.91±2.40	8.70±2.28	8.75±2.02	8.16±1.97	8.76±1.66	8.55±1.44	8.52±1.11	8.17±1.53
90P	9.47±2.51	9.38±2.42	9.05±2.18	9.37±2.34	9.93±1.96	9.16±1.88	9.91±1.81	9.33±2.21
WR	10.29±1.31	10.23±1.20	10.08±1.28	10.21±1.63	10.51±1.85	10.51±1.36	10.53±1.46	10.62±1.49

‡ AHD at 90A was significantly narrower than neutral, 45P, and WR ($p < 0.001$)
* AHD at 90 P was significantly narrower than neutral ($p = 0.01$)
†Significant between-group difference while the arm elevated from neutral to 45A after repetitive shoulder external rotation
Neutral: neutral resting position; 45A, 45P: Elbow fully extension with humeral internal rotation (thumb down) at 45° in scapular plane with and without resistance, respectively; 90A, 90P: Elbow fully extension with humeral internal rotation (thumb down) at 90° in scapular plane with and without resistance, respectively; WR: Holding the weight relief raise position; PreWR, PosWR: Measured before and after multiple weight relief push-ups; PreER, PosER: Measured before and after repetitive shoulder external rotation exercises

2.4 DISCUSSION

The study was performed to assess the intra-rater and inter-rater reliability of ultrasonographic-measured AHD in individuals with SCI and able-bodied population, to study the differences between the two groups in shoulder positioning and AHD measurement; and to identify acute changes in the AHD following repetitive shoulder exercises.

2.4.1 Reliability of Ultrasonographic AHD Measurement

The results showed excellent intra-rater and inter-rater reliability in MWUs with SCI (ICC > 0.78). The inter-rater reliability in able-bodied population is moderate to excellent and consistent with previous studies (ICC > 0.52). (Desmeules et al., 2004; Pijls et al., 2010) However, the intra-rater reliability at 45° arm elevation with humeral internal rotation for rater 1 was poor to fair (ICC < 0.40). Pijls et al. reported high to excellent inter-rater reliability but moderate intra-rater reliability in individuals with impingement at 60° abduction without restricting the humeral internal and external rotation. It is unclear how the intra-rater reliability of AHD measurement was influenced by humeral internal rotation in 45° abduction in scapular plane as other studies have not reported this data. Because intra-rater ICC's were excellent for both raters in this shoulder position for the case group, it may be due to a learning effect since almost all the control subjects were tested before the case subjects. Our study found that the reliability in the AHD measurement in MWUs with SCI, whose shoulders are prone to shoulder instability, pathologies and altered kinematics is as excellent as that in an control group.

Bone surfaces produce brighter response than the surrounding soft tissue structures on ultrasound. The brightness and contrast of ultrasonographic bone surfaces are less affected by gain, depth, focal zones, or slightly tilting or translation from the ultrasound probe due to the dramatic difference in acoustic impedance between bone and soft tissue so rater scanning errors are expected to be negligible. (Sanders & Winder, 2007). Other sources of variability relate to the video analysis and selection of the 2D slice. There is uncertainty with the snapshot selection of the narrowest distance and the manual determination of the feature points on the acromial and humeral head within and between the video observers.

2.4.2 Effects of Shoulder Positioning

Muscle activation and motor control play important roles for joint stability, function and preserving the subacromial space. Consistent with previous studies, greater AHD narrowing was found during scapular plane elevation with humeral internal rotation in healthy subjects. (Graichen, Bonel, Stammberger, Eeglmeier, et al., 1999) A similar tendency occurred in the case group. The AHD was also narrower in arm elevated positions with muscle activation compared to without muscle activation. This was expected as the pull of the middle deltoid draws the humeral head into the glenoid when the arm is abducted in the scapular plane. (Yanagawa et al., 2008) Our findings are consistent with a previous MRI imaging study that found the co-contraction imbalance between deltoids and shoulder depressors were most prominent around 90° abduction which resulted in narrower subacromial space. (Hinterwimmer et al., 2003) Previous studies also reported that scapular kinematics prone to increased anterior tipping and internal rotation in the scapular abduction with internal rotation as the arm elevated may lead to AHD narrowing. (M. M. B. Morrow et al., 2011; Thigpen, Padua, Morgan, Kreps, & Karas, 2006) Therefore, minimizing overhead shoulder activities are necessary for protecting the subacromial space from impingement syndrome.

2.4.3 Effects of Exercise

MWUs with SCI had significantly narrower AHD with the shoulder in 90° active scapular elevation with humeral internal rotation after repetitive shoulder external rotation exercises. Our results also agree in part with those from previous studies in which fatiguing exercises resulted in decreased AHD. (Graichen, Bonel, Stammberger, Eeglmeier, et al., 1999) This may be because the shoulder muscles (e.g. rotators) that are used to keep the glenohumeral joint stable at 90° arm abduction become fatigued after the repetitive exercises, and the imbalance of the deltoid and rotators causes the subacromial space narrowing. This finding points to the potential danger of impingement when performing repetitive overhead shoulder activities especially after muscle fatigue. In the case group, AHD was narrowing at the 45P compared to control group after rotator cuff exercise. One possible explanation for finding the decreased AHD in case but not in control could be that the case group has altered scapular kinematics compared to the control group. A future study is needed to explore the relationship between scapular kinematics and the AHD.

2.4.4 AHD Differences Between Case and Control

The mean AHD measures obtained in control group are similar to published data from previous study utilizing ultrasound imaging technique. (Schmidt et al., 2004) The AHD tended to reduce continuously from neutral to 90° abduction in the MWU group. The apparent increase in mean AHD from neutral to 45° active abduction in healthy individuals compared to that found in the MWUs with SCI may provide insight into the altered biomechanics of the wheelchair users' shoulders. 'Healthy' shoulders may have a protective mechanism that keeps the space intact through arm abduction. Both groups were similar in age and weight, however a majority of wheelchair users have early degenerative changes in the shoulder that predispose them to shoulder problems due to overuse. (Lal, 1998) Factors such as scapular orientation, trunk posture, acromial shape, and tendon deterioration can all affect the subacromial space. (Chopp et al., 2010) It would be beneficial for further studies to examine how these other factors may impact the subacrominal space.

SIS is believed to be secondary to shoulder joint instability. (Lee & McMahon, 2002)While most studies evaluate the influences of shoulder muscle fatigue on the subacromial space, there is limited understanding of the influences of spinal cord injury on static and dynamic restraints concerning the subacromial space. MWUs with SCI are prone to have superior glenohumeral joint instability due to weakness of rotator cuff muscle. (Powers, Newsam, Gronley, Fontaine, & Perry, 1994) Muscle forces contributed significantly in the midranges of shoulder elevation when the capsule and glenohumeral ligaments are believed to be lax. (Lippitt & Matsen, 1993) Repetitive rotator cuff muscle exercises likely exaggerate the influences of uneven loading on the subacromial space while fatiguing rotator cuff muscles. The joint instability combined with fatigue could explain why the case group had greater AHD narrowing when the arm actively elevated from neutral to 45° after repetitive shoulder external rotation exercises. It is important to incorporate muscular training exercises into the rehabilitation program to minimize the impact of fatigue on subacromial space.

2.4.5 Study Limitation

There were a few limitations to this study. Although the results showed excellent inter- and intra-rater reliability of the AHD measurement, the accuracy of ultrasonographic measurement was not examined. However, Azzoni et al. compared the accuracy of sonographic measurements to radiographic measurements of AHD. Both measurements were highly correlated and the concurrent validity was 0.77-0.85. (Azzoni & Cabitza, 2004; Azzoni et al., 2004) In addition, High correlation had also been demonstrated between AHD measurement taken with radiographs and those with MRI (r = 0.81). (Saupe et al., 2006) Muscle fatigue was not objectively confirmed in this study, and it is possible that some fatiguing tasks were limited by pain or discomfort in performing the activities in some subjects. Since the fatigued state of the infraspinatus muscle of the rotator cuff can limit the stabilizing force and result in encroachment of the humeral head into the space, (Chopp & Dickerson, 2012) future research is needed to confirm infraspinatus fatigue using electromyography. Further research combine methods of recording humeral, scapular-thoracic and clavicular kinematics with the ultrasonographic measurement of AHD to determine the impact of shoulder joint kinematics on the space pre and post fatigue.

2.5 CONCLUSIONS

Findings from our study demonstrated that ultrasonography is a reliable means to evaluate the subacromial space by ultrasound in manual wheelchair users with spinal cord injury and provides reference measures (e.g. minimum detectable difference) for identifying meaningful differences in future interventional type studies. MWUs shoulders actively positioned in a 90° scapular plane elevation with humeral internal rotation showed increased narrowing in comparison to the other shoulder positions that were tested and following rotator cuff fatiguing exercises. The AHD consistently narrowed throughout the range of shoulder abduction movement in manual wheelchair users with SCI which was different than that observed in the control subjects who mainly demonstrated narrowing between 45° and 90° of shoulder elevation. Our findings provide insight into the mechanisms of subacromial impingement syndrome among individuals with SCI. Future studies are needed to further evaluate the relationship between subacromial space narrowing and other activities of daily living such as wheelchair transfers, wheelchair propulsion, and overhead activities.

3.0 EFFECT OF MUSCLE FATIGUING TASKS ON ACROMIOHUMERAL DISTANCE IN MANUAL WHEELCHAIR USERS

3.1 INTRODUCTION

Manual wheelchair users (MWUs) are at a high risk for subacromial impingement syndrome (SIS). Approximately 31-73% of MWUs have shoulder pain, much of which is believed to be associated with SIS due to repetitive weight-bearing activities such as wheelchair propulsion, weight relief raises, and transfers. (Boninger et al., 2001) SIS occurs when the rotator cuff (RC) tendons, subacromial bursa, the long head of biceps tendon, and coracoacromial ligament become compressed and irritated as they pass through the subacromial space, which is the area located above the humeral head and below the acromion. (Neer, 1972) Risk factors that have been linked to subacromial impingement syndrome include imbalances in shoulder strength, limitations in shoulder range of motion, excessive thoracic kyphosis or flexed posture, scapular positioning malalignments and muscle fatigue. (Burnham et al., 1993; Niemeyer, Aronow, & Kasman, 2004; Seitz & Michener, 2011)

Studies of non-wheelchair users have shown that fatigue of the RC muscles reduces their ability to stabilize the humeral head against the glenoid cavity of the scapula, causing migration of the humeral head into the space. (Chopp et al., 2010; Teyhen et al., 2008) Chopp et al. investigated radiographic measurement of humeral head migration following two types of fatigue protocols: 1) a global shoulder fatigue protocol that simulated job tasks, and 2) a local fatigue protocol that targeted fatigue of the shoulder external rotators. (Chopp et al., 2011; Chopp et al., 2010; Tsai et al., 2003) While both protocols were expected to show reduction in the AHD, the global protocol induced greater changes in humeral head translation.(Chopp et al., 2010) Although the amount of humeral translation may be considered small (on the order of 1 to 3 mm), the compressive effects on the subacromial structures were viewed as significant due to the limited size of the subacromial space.

MWUs represent a unique population for studying AHD due to the types of weight-bearing activities they routinely perform and their high potential to develop shoulder impingement syndrome. Propulsion and weight relief raises result in excessive shoulder joint loading and demand on RC muscles to maintain glenohumeral joint stability during the maneuvers. (M. M. B. Morrow et al., 2011; Reyes et al., 1995; S. van Drongelen et al., 2011) A person performs a weight relief raise by adducting their arms and using them to lift and support the body for the purposes of alleviating pressure under the buttocks. A musculoskeletal modeling study of weight-relief raises found large weight-bearing forces (1288 N) acted to drive the humerus into the GH joint. (S. van Drongelen et al., 2011) It is unclear if these forces cause compression of the subacromial space and what other factors such as pain and pathological deficits, muscle weakness, altered shoulder kinematics, or fatigue may be associated with unwanted superior translation of the humeral head. (Sharkey & Marder, 1995)

The primary purpose of this study was to investigate initial and acute changes (i.e. narrowing) in AHD after wheelchair users performed repetitive weight-relief raises (global fatigue protocol) and an isolated RC exercise (local fatigue protocol) to self-perceived fatigue. Shoulder pain is a significant reason for functional decline in manual wheelchair users and a factor correlated with decreased quality of life. (Gerhart, Bergstrom, Charlifue, Menter, & Whiteneck, 1993) A secondary goal of this study was to examine the relationship between shoulder pain, subject characteristics, and AHD. A better understanding of these relationships may help to elucidate mechanisms leading to subacromial impingement in wheelchair users and enable tailored therapeutic interventions that preserve upper limb function.

3.2 METHODS

3.2.1 Subjects

Study participants were recruited during the 2011 National Veterans Wheelchair Games (NVWG) in Pittsburgh, Pennsylvania. Based on previous research (Teyhen et al., 2008), a priori power analysis revealed that a sample size of 23 was required to achieve a minimum statistical power of 95% at an α level of $p = 0.05$. Inclusion criteria were using a manual wheelchair as primary means of mobility, able to perform multiple weight-relief raises and between 18 and 65 years of age. The exclusion criteria included history of fractures or dislocations in the shoulder from which the subject had not fully recovered (i.e. the subject may no longer experience pain or limited/altered function due to the injury); upper limb dysthetic pain as a result of a syrinx or complex regional pain syndrome (only for individuals with paraplegia); and history of cardiovascular or cardiopulmonary disease. Informed consent was obtained from all the subjects before participation in this study. The research protocol was approved by the Department of Veteran Affairs institution review board.

3.2.2 Questionnaires

Basic demographic information including age, height, weight, and date of injury/diagnosis using self-report and anthropometrics of the shoulder circumference and upper arm length were obtained from all subjects at the beginning of testing. All subjects completed the Wheelchair Users Shoulder Pain Index (WUSPI), which has test-retest reliability of the total index score 0.99 and Cronbach's alpha (internal consistency) 0.98. (Curtis et al., 1995b) The WUSPI is a 15-item self-report instrument that measures shoulder pain intensity in wheelchair users during various functional activities of daily living including transfers, wheelchair mobility, dressing, overhead lifting, and sleeping. (Curtis et al., 1995a) Each item is scored using a 10 cm visual analog scale anchored at the ends with the descriptors of "no pain" and "worst pain ever experienced." Total score was calculated by summing the individual scores divided by the number of performed activities and then multiplying by 15. (Curtis et al., 1999) A general questionnaire was used to document the medical information including history of shoulder pain and surgery. (Boninger et al., 2001) The non-dominant side was chosen for all the measures in order to minimize the effects caused by performing ADLs on the shoulder from other general activities. The OMNI Pain Scale, previously validated by Faces pain scale for pediatric oncology, was used to assess exercise-induced muscle pain intensity. (R. J. Robertson et al., 2009) This scale is a numerical rating scale ranging from 0 to 10. The OMNI scale was administered prior to the beginning of testing, to establish a baseline measure of pain, and after each fatigue protocol, to determine amount of exercise-induced pain experienced during the testing.

3.2.3 Fatiguing Protocols

For both the global fatigue and local fatigue tasks, subjects transferred to a Biodex System 3 dynamometer (Biodex Medical System, Inc, Shirley, New York) with custom-made adjustable height arm rests (Figure 1A). Armrests were fitted to each subject to allow pushing straight up with full elbow extension and arms adduction to off load the buttock tissue (Figure 1B). The global fatigue task involved performing weight relief raises (WR) which entailed lifting and holding the buttocks off the seat with an elbow locked position. (M. M. B. Morrow et al., 2011; Reyes et al., 1995) The WR task was repeated at a rate of 20 repetitions per minute with the use of a metronome. Subjects were instructed to stop when they were no longer able to keep up the task due to self-perceived fatigue or at a cutoff time of 2 minutes, whichever occurred first. The local fatigue task followed the same protocol but involved isotonic shoulder external rotation (ER). For this task the subject was instructed to externally rotate their forearm from a shoulder neutral position to 45 degrees or the maximum range of ER that they could comfortably reach similar to that done in other RC fatigue protocols. (Ebaugh et al., 2006b)The trunk was secured to minimize compensatory movements using straps from the Biodex that crossed the chest and lap. Resistance for the external rotation motion was set for 5% of self-reported body weight. To minimize the shoulder internal rotator fatigue, the minimum resistance setting of 1 lb was used for the internal rotation motion. (Reinold et al., 2004) Both fatigue protocols were administered during a single test session. The subjects rested for a period of approximately 15 minutes in between the two fatigue protocols.

3.2.4 AHD Ultrasound Examination

The subacromial space was quantified by measuring the acromiohumeral distance (AHD) using ultrasound techniques as described previously in studies with healthy shoulders, (Cheng et al., 2008) athletes, (Girometti et al., 2006) patients with subacromial impingement syndrome, (Pijls et al., 2010) individuals with different stages of rotator cuff degeneration, (Azzoni et al., 2004) and patients with a rotator cuff tears. (Cholewinski et al., 2008) A single examiner (Lin) conducted all scans for each subject using a Philips HD11 1.0.6 ultrasound machine with a 5-12 MHz linear transducer. A water-based gel was applied on the skin to enhance ultrasound conduction between the ultrasound probe and the skin surface. The non-dominant shoulder was scanned from the anterior aspect of glenoid to the flat segment of posterior scapula to capture the bright reflection of the bony contour of the acromion and humeral head (Figure 4). Ultrasound video was recorded at 60 Hz and scanning the AHD took approximately 10 seconds. A total of five videos of the AHD were recorded during the study: one took place at the beginning of the study with the shoulder in a neutral and resting position (Figure 3A), and the other four were obtained pre-post each fatigue protocol while isometrically holding the weight relief raise position (Figure 3B).

3.2.5 Surface Electromyography

Surface electromyography was performed with the bi-polar Noraxon Telemyo 2400T electromyography system (Noraxon Inc., Arizona, USA). Reyes et al reported in a fine-wire EMG study that the primary muscles involved in the weight relief task among persons with low paraplegia (T8 to L1) were the latissimus dorsi, sternal pectoralis major, and the triceps, and therefore these muscles would be more prone to fatigue. (Reyes et al., 1995) In the absence of triceps (e.g. subjects with cervical SCI at C6 or above), the pectoralis major and shoulder depressors become more vital to enabling successful weight-relief raises. (Harvey & Crosbie, 2000) Thus, for this study we placed electrodes over the sternal pectoralis major, lattismus dorsi, long head of the triceps, and infraspinatus, an external rotator and shoulder depressor, as they can be accessed reliably by surface electrodes. (Bitter et al., 2007) Electrodes were placed on the non-dominant arm with 2 cm spacing over the muscle belly using standards previously developed for these muscles. (Chopp et al., 2011) A ground electrode was placed on the lateral portion of the clavicle. Prior to marker placement the skin was cleansed with alcohol wipes. Participants performed three repetitions of maximum voluntary contractions (MVCs) for each of the monitored muscles. Muscle activities were collected for the entire duration of the fatiguing protocols, except triceps activity was not recorded during the ER task.

3.2.6 Data Analysis

An investigator blinded to the subject testing and timing of the video (e.g. pre or post) used a custom developed Matlab program to manually review each frame of the video and mark the inferior edge of acromion and humeral head. The distance between the bony landmarks was calculated for each frame of the video and the narrowest distance was used for statistical analyses. To assess reliability of the AHD measure, we compared the two pre-fatigue AHD measurements with the shoulder in the weight relief position using the intraclass correlation coefficient (ICC, two way random, absolute agreement). Standard error of measurement (SEM)

(Equation 1) and the minimum detectable difference (MDD) (Equation 2) was computed based on the equations used in Chapter 2.

EMG data were used as reference for fatigue onset. Raw EMG signals were sampled at 1500 Hz. The signals were then full-wave rectified and filtered using a fourth-order Butterworth low pass filter with 450 Hz cut-off frequency. The average of the first three repetitions of each fatigue task was defined as a fresh state, whereas the average of the last three repetitions was defined as the fatigued state. Local muscle fatigue was confirmed by computing the median power frequency (MPF) and mean amplitude and using joint analysis of spectral and amplitudes (JASA). The use of JASA has been validated to differentiate fatigue from other various EMG-change causations. (Luttmann, Jager, & Laurig, 2000) The results of JASA plots were classified into the following four categories:

(1) Force increase (frequency increase and amplitude increase)

(2) Recovery (frequency increase and amplitude decrease)

(3) Force decrease (frequency decrease and amplitude decrease)

(4) Muscle fatigue (frequency decrease and amplitude increase)

The power spectral density was used to determine the MPF for each 1-second interval over the pre-fatigue and post-fatigue envelopes. Percentage changes in MPF were determined as the ratio of the amount of MPF change between fresh and fatigued state to the averaged MPF values in the fresh state. The percentage change in the mean magnitude of the EMG signal was obtained during the same time interval as the MPF with the normalization of 100% MVCs from each muscle.

3.2.7 Statistical Analyses

Based on the result of Shapiro-Wilk normality test, paired t-tests were used to assess differences in the AHD absolute values between the neutral (unloaded) and weight-relief shoulder position and before and immediately after performing the WR and ER tasks for subjects exhibiting EMG signs of fatigue for the primary muscles of interest (infraspinatus, pectoralis major, and latissimus dorsi). Spearmans' nonparametric correlations between the absolute AHD measures, AHD percentage changes (Equation 3), WUSPI score, OMNI scale score, and demographic data (e.g. height, weight, shoulder circumference, arm length, age, and years since acquiring the disability or injury) were examined. An alpha level less than 0.05 was established for significant changes. The standardized thresholds of effect size above 0.8 and around 0.5 were used to define large and moderate effects, respectively. (Faul, Erdfelder, Lang, & Buchner, 2007)

3.3 RESULTS

3.3.1 Subjects

Twenty-three MWUs (22 male and 1 female) convenience samples were recruited for this study. Sixteen MWUs had a spinal cord injury (5 cervical, 11 thoracic), one had unilateral transfemoral amputation, three had bilateral transtibial amputation, and three had multiple sclerosis. The average age (standard deviation) of the sample was 46(12) years old, post injury or diagnosis was 15(10) years, and the average height and weight were 178(8) cm and 81(18) kg, respectively.

Twenty-two participants were right hand dominant. Descriptive data for AHD measurements is provided in Table 5.

Table 5. Absolute AHD values and percentage change of AHD for each subject. Bold font represents subjects with no self-reported fatigue within the maximum 2-minute time limit of exercise. Symbols represent EMG signs of local muscle fatigue on the Infraspinatus(I), Pectoralis Major(P) and Lattisimus Dorsi(L), and Triceps(T).

		Weight Relief (mm)			**Rotator Cuff Exercise(mm)**		
Disability	Rest	Pre	Post	% change	Pre	Post	% change
C3 spinal stenosis	14.07	10.85	10.85	0.00[P,T]	10.67	9.31	-12.72[I]
T4 com. SCI	11.53	9.32	11.27	20.85[T]	9.18	9.04	-1.49[I,L]
C6 inc. SCI	10.96	10.14	9.03	-10.94	8.77	8.90	1.56
MS	12.64	8.08	9.45	16.95	11.25	10.82	-3.80
Amp (LAK)	12.88	12.76	10.17	-20.30	10.17	10.34	1.67[I]
T4 com. SCI	11.51	10.00	9.31	-6.94[I,P,T]	9.72	10.82	11.36[I]
Amp (RBK, LAK)	12.37	9.83	11.93	21.39[L,T]	9.32	10.41	11.65[I,P]
T7 inc. SCI	11.64	10.28	11.37	10.58[T]	10.70	10.69	-0.09
T9 inc. SCI	12.50	11.64	11.51	-1.18[T]	11.67	11.10	-4.89[P]
MS	9.32	9.04	11.53	27.51	10.27	8.92	-13.19[I]
C3 inc. SCI	10.96	10.55	10.83	2.70[I,T]	10.00	8.45	-15.49[L]
MS	12.36	9.03	7.16	-20.67[T]	8.47	8.36	-1.37
T12 com. SCI	9.44	10.00	9.31	-6.94[P,L]	10.00	9.73	-2.70
T12 inc. SCI	11.81	10.00	10.27	2.74[I,T]	10.27	10.69	4.04[I]
Amp (RAK, LAK)	10.00	8.38	9.31	11.07	7.95	8.08	1.72[I]
T12 com. SCI	10.14	9.31	8.77	-5.79[P,T]	8.75	8.49	-2.93[I,P,L]
Amp (RAK, LBK)	10.14	8.49	7.36	-13.33[I]	7.50	9.04	20.55[P]
C5 inc. SCI	13.06	11.39	10.82	-4.98[P,L]	11.39	10.95	-3.89[I,P]
C7 inc. SCI	16.32	10.86	9.66	-11.11[I,T]	10.52	10.17	-3.31[L]
T10 inc. SCI	13.83	12.71	12.28	-3.39[T]	12.41	13.10	5.55[I]
T11 inc. SCI	11.22	10.27	9.45	-8.00[I,P]	10.14	10.96	8.09[I,L]
T12 com. SCI	13.84	11.10	11.51	3.70[I,L]	9.73	10.41	7.04[I]
T9 inc. SCI	8.22	6.03	6.08	0.89[I,P,T]	6.71	5.83	-13.10[P]

SCI, spinal cord injury (com., complete; inc. incomplete); Amp, amputee; RAK, right leg above knee; RBK, right leg below knee; LAK, left leg above knee; LBK, left leg below knee; MS, multiple sclerosis.

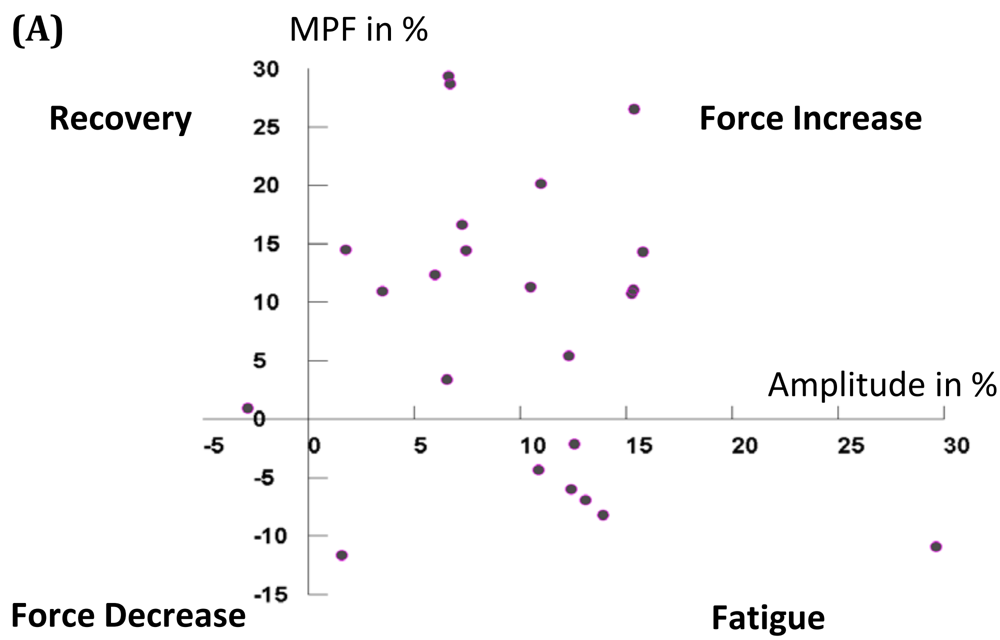
The AHD in the first weight-relief position (10.00 ± 1.51 mm) was significantly smaller than the AHD in the baseline shoulder neutral position (11.77 ± 1.83 mm, $p < 0.01$). According to the JASA plots, eight subjects after the repeated weight relief raises and thirteen subjects after the ER task showed EMG signs of fatigue of the infraspinatus (Table 5). Seven subjects after the WR task and six subjects after the ER task fell into the quadrant representing fatigue for the pectoralis major muscle (Table 5, Figure 7). Fewer numbers of subjects showed fatigue of the latissimus dorsi muscles during the two tasks (Table 2). The triceps were the most common muscle group to fatigue during the WR task (n=13, Table 2) while more subjects showed fatigue of the infraspinatus muscle during the ER task (n=13, Table 6).

AHD significantly decreased after repeated weight relief raises in subjects with EMG signs of sternal pectoralis major muscle fatigue (p = 0.046, Table 6). No statistical significant reduction but moderate effect size was found for subjects with confirmed EMG signs of infraspinatus muscle fatigue after the WR task (p = 0.263, Table 6). There were no significant differences in the AHD after the ER task for subjects showing objective signs of fatigue in any monitored muscle and effect sizes ranged from 0.08 to 0.36.

Table 6. AHD absolute value changes (Mean±SD mm and effect size) among subjects who showed EMG signs of muscle fatigue

Muscle	Multiple Weight Relief Raise	Shoulder External Rotation
Infraspinatus	-0.35±0.68 (d = 0.53); n = 8	0.12±0.82 (d = 0.15); n = 13
Pectoralis Major	-0.47±0.35 (d = 1.25); n = 7†	0.08±0.99 (d = 0.08); n = 6
Latissimus Dorsi	0.31±1.29 (d = 0.24); n = 4	-0.29±0.84 (d = 0.36); n = 5
Triceps	0.07±1.13 (d = 0.06); n = 13	

† p =0.046.



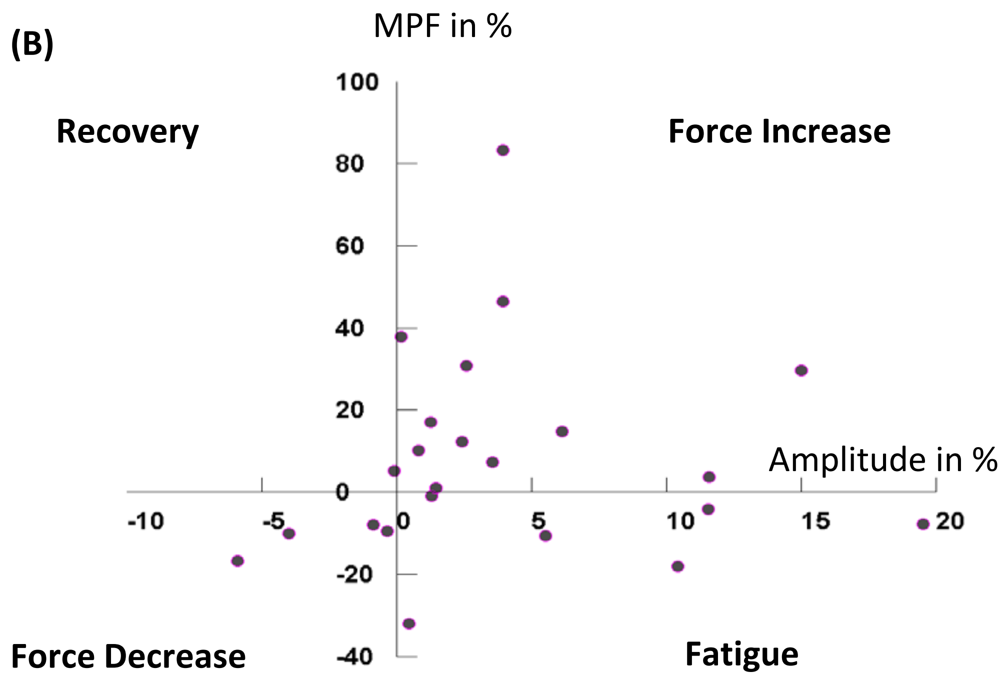


Figure 7. JASA analysis for sternal pectoralis major between the fresh and fatigue state at weight relief raises (n = 23) (A) and shoulder external rotation tasks (n = 23) (B).

3.3.2 AHD Changes versus Subject Characteristics

Among all subjects, no relationship between baseline AHD and age, height, weight, or arm length was found. Individuals with narrower AHD in the resting neutral position had smaller shoulder circumferences (r = 0.42, p = 0.044, Figure 8A). Individuals with increased years of disability had more AHD percentage narrowing after the WR task (r = -0.54, p = 0.008, Figure 8B). The WUSPI scores measured at baseline were 14.08±18.07. More shoulder pain on WUSPI was associated with greater percentage narrowing of the AHD after the ER task (r= -0.41, p = 0.007, Figure 8C). The OMNI pain scale results measured at baseline, after WR and after ER were 1.04 ± 1.58, 2.09 ± 2.56, 2.30 ± 2.42 respectively. Individuals with higher scores on the OMNI pain scale after ER had more percentage narrowing of the AHD after ER (r = -0.59, p = 0.003) (Figure 8D).

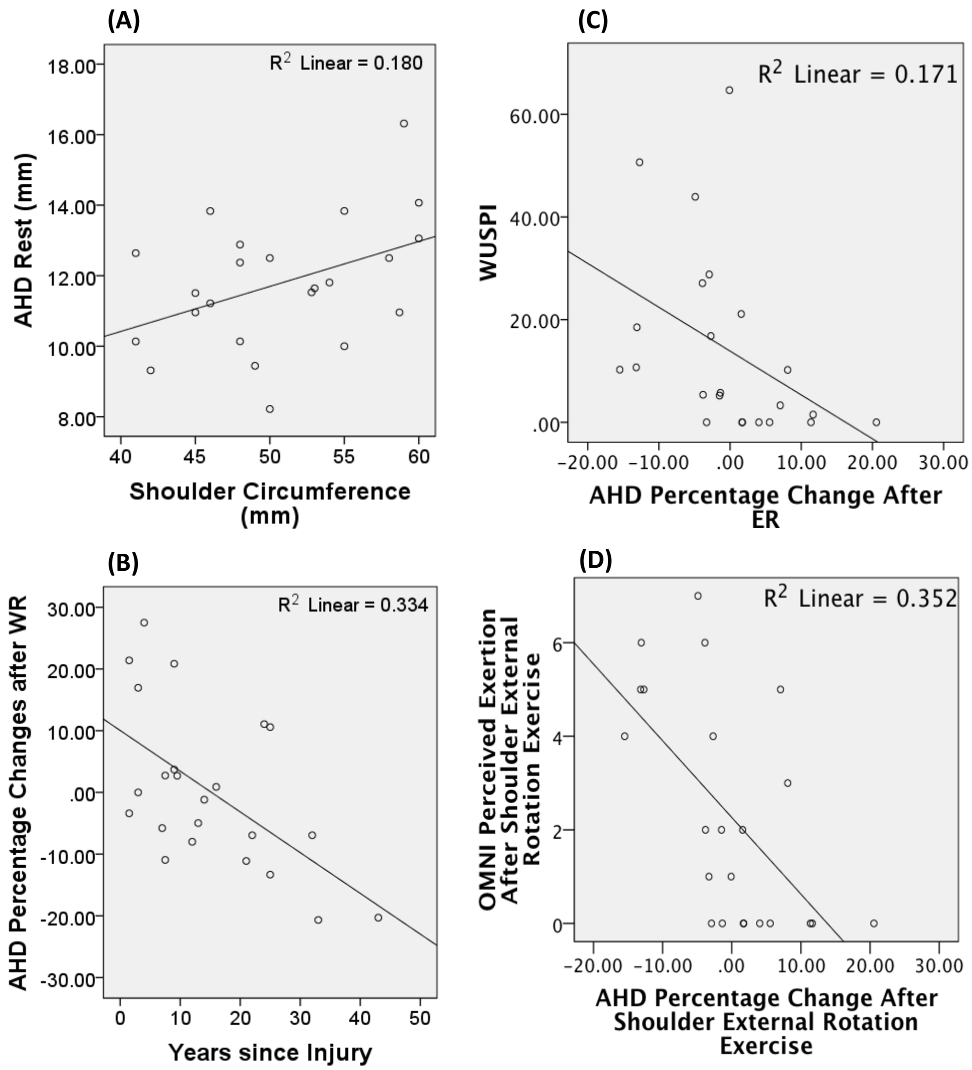


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Figure 8. Correlation analysis for the AHD in neutral shoulder position with the shoulder circumference (p = 0.044, n = 23) (A), AHD percentage change after multiple weight relief raises with years since injury (p = 0.008, n = 23) (B), AHD percentage change after shoulder external rotation exercise with WUSPI (p = 0.007, n = 23) (C), and AHD percentage change with OMNI pain scale after ER (p = 0.003, n = 23) (D).

3.4 DISCUSSION

The results confirm that AHD narrowing occurs when assuming a weight-bearing position with their arms. In healthy shoulders, the height of the AHD can range between 7 mm and 16 mm when the shoulder is in a neutral position. (Weiner & Macnab, 1970) Our baseline data were consistent with this result (range = 8 to 16 mm). Given that the thickness of the supraspinatus tendon in this area is 6 to 9 mm, little clearance remains for enlarged bursa, swollen tendons, or irregularities of the gliding surface which are common pathologies found in the shoulders of wheelchair users. (Philip S. Requejo et al., 2008) When our subjects assumed the weight-relief position, a statistically significant reduction in space occurred. In this position, the elbows are in full extension allowing the humeral head to be oriented more directly upward and into the joint. In addition, during the weight relief raise the scapula is anteriorly tilted and internally rotated. (Nawoczenski et al., 2003) This humeral and scapular position combined with the large weight-bearing forces likely led to the reduction in subacromial space. Narrowing of the AHD can overstress the supraspinatus tendon, diminish blood flow, and lead to shoulder impingement. (Fu et al., 1991) As weight bearing positions are difficult to avoid and occur daily in high frequency such as during wheelchair propulsion, transfers, and pressure relief, wheelchair users are at risk for developing impingement. These findings support clinical practice guidelines that recommend MWUs limit the WR technique for pressure relief and use propulsion and transfer techniques that minimize forces at the shoulders. (Boninger et al., 2005)

Weight-bearing tasks require the shoulder depressors to stabilize the humeral head within the glenoid cavity. (Sharkey & Marder, 1995) A repetitive weight relief task was employed to see if globally fatiguing the shoulder muscles would lead to greater narrowing of space. However, we found after performing the WR task to self-reported fatigue there was no further narrowing of the AHD ($p = 0.89$ for all 23 subjects). As subjects could have quit the protocol due to fatigue of the triceps or other reasons, we performed a JASA analysis to identify those subjects with objective signs of fatigue on all monitored muscle groups. Subjects who had objective evidence of muscle fatigue for the pectoralis major muscle (large effect size) and infraspinatus (moderate effect size) showed greater percentage narrowing of the AHD after WR activity. As the pectoralis major is the primary muscle involved in performing weight relief raises, its fatigue not only affects the recruitment patterns of other smaller muscles to perform the job, but also affects its concomitant function as a humeral depressor. The sternal portion of the pectoralis major, with origins on the sternum and insertions on the lateral lip of bicipital groove, provides a compressive and downward force on the humerus when the arms are extended and the trunk is elevated. (Philip S. Requejo et al., 2008) Thus impairment in this function could lead to unwanted translations. For these reasons, others (Rankin, Richter, & Neptune, 2011) have also found that pectoralis major and infraspinatus during intense wheelchair activity are particularly susceptible to muscle fatigue or injury, which may increase the chance of subacromial impingement. The infraspinatus along with other RC tendons serves the purpose of helping to stabilize the GH joint and controlling translations. (Sharkey & Marder, 1995) Thus it follows that maintaining a healthy force balance around the glenohumeral joint plays a significant role in preserving subacromial space for activities involving weight-relief positions. The results support therapeutic programs or exercise prescription in an effort to balance muscle forces around the shoulder and minimize risk of impingement. (Boninger et al., 2005)

The ER exercise in this study used a similar protocol to other studies involving neurologically intact individuals without shoulder disorders and designed to fatigue the infraspinatus. (Bitter et al., 2007; Ebaugh et al., 2006b; Tsai et al., 2003) Superior migration of the humeral head has been shown to occur after fatiguing the infraspinatus with this protocol. (Chopp et al., 2010) The JASA analysis for this study proved that the ER task was effective in fatiguing the infraspinatus but we found no difference in the AHD after the task. The prior studies on neurologically intact individuals measured subjects in a non-weight bearing position with their arms during scapular plane abduction. With arm elevation, the deltoid muscle enhances the upward pull of the humerus. This would likely magnify the upward shift of the humeral head in arm elevation compared to the weight relief position in which we measured all subjects pre-post fatigue. We chose to examine AHD while subjects held the weight relief raise position because it provides a measure of what the AHD looks like under realistic, functional loading conditions. The ER exercise is an isolated muscle fatigue protocol targeting the external rotators (primarily the infraspinatus muscle), while very little involvement of other shoulder muscles are needed to execute the task. In comparing the two tasks, not finding greater differences in the ER task (local fatigue protocol) compared to after the WR task (global fatigue protocol) may mean that compensatory motor strategies or muscle firing patterns were being used to preserve the acromiohumeral space when the shoulder was scanned in the WR position. (Szucs, Navalgund, & Borstad, 2009) Further studies are needed to understand the compensatory muscle activities and if there are other arm positions that would be more sensitive to detecting changes with fatigue.

In our study, the baseline and acute changes in the AHD measure were not significantly correlated with the characteristics commonly linked to shoulder impingement syndrome such as age, weight, and BMI. However, AHD in the shoulder neutral position was related to shoulder circumference and suggests that future studies should consider normalizing the AHD or statistically controlling for this anatomical measurement. A positive correlation was found between percentage narrowing of the AHD after WR and years of injury/diagnosis and shoulder pain after controlling for shoulder circumference. These relationships are likely related to the problems commonly seen in long-term wheelchair users such as chronic shoulder pain and pathology, muscle strength imbalances around the shoulder, joint instability, altered scapular kinematics and abnormal glenohumeral motion, and subluxation. (Bigliani & Levine, 1997) Our findings are consistent with studies on non-wheelchair users, which have shown that the AHD is smaller in symptomatic shoulders. (Azzoni et al., 2004; Weiner & Macnab, 1970)

Our study had several limitations. Because our protocol was conducted at a national wheelchair sporting event, it was difficult to control for the amount of upper limb activity experienced before the testing. In addition, wheelchair users who participate in sporting events may be considered more active than the general population. However, Tolerico et al found that veterans who participate in the NVWG were not significantly different in the mobility characteristics and activity levels of their community-dwelling wheelchair using counterparts. (Tolerico et al., 2007) The two fatigue exercises were performed in order (WR followed by ER) on the same day and it is possible that there was not enough muscle recovery time to compensate for the fatigue effects on the muscles; however, the two tasks were quite different in their goals and the two pre-fatigue AHD measures taken before each task were not significantly different ($p = 0.38$). We relied on self-reported fatigue to stop the tasks, which did not always correspond with objective signs of fatigue for the muscles of interest. Each task does provide a simulation of how overuse could affect the shoulder, which may be more meaningful considering that most wheelchair users when performing ADLs in daily life are not pushing themselves to the point of muscle fatigue. Only a few specific shoulder depressors were monitored using surface EMG and crosstalk from neighboring muscles could affect the signal integrity. However, surface EMG is often preferred to fine-wire because it provides a non-invasive means of fatigue monitoring. (Cifrek, Medved, Tonkovic, & Ostojic, 2009)

Effect sizes were used to judge the significance of the findings, as there were few numbers of subjects with objective evidence of fatigue on the selected muscle groups. Significant findings after the WR task should be interpreted with caution as the mean magnitude difference of the AHD was small (0.5 mm) and within the realm of measurement error. However the significant associations found with markers of pain, muscle fatigue, and years post injury/disability supports the clinical relevancy of the AHD measure. Other variables such as acromial shape, abnormal scapular kinematics, and impaired RC function were not investigated and could be additional sources to explain AHD narrowing. As many wheelchair users have signs and symptoms of shoulder pathology and altered shoulder kinematics, future studies should look at AHD changes in MWUs relative to healthy controls to further elucidate extrinsic mechanisms leading to reductions in the subacromial space. Acute changes were examined with the shoulders in a loaded position and differences may have been more apparent had the arm been scanned in an elevated, unloaded position. As scapular orientation has also been shown to affect AHD, future work should investigate scapular and humeral positioning during weight-bearing tasks to gain further insight into injury mechanisms.

3.5 CONCLUSIONS

The results of this study suggest that MWUs should limit weight relief raises for pressure relief, as placing the shoulder in this position led to a significant reduction in the subacromial space. Fatigue of the pectoralis major after performing repetitive weight relief raises led to greater percentage narrowing of the AHD, which points to its importance in functioning as a humeral depressor in addition to serving as the largest contributor to performance of a successful weight relief raise. This study provides objective evidence that the AHD is associated with pain and long-term use of a wheelchair. Future work should consider how alterations in humeral and scapular kinematics affect the subacromial space when performing daily tasks to elucidate more clearly the mechanisms of injury. In addition, the findings indicate the efficacy of quantitative ultrasound to identify changes in the AHD. This could be helpful in evaluating the impact of clinical interventions such as wheelchair propulsion or transfer training on preserving the subacromial space in future studies.

4.0 EFFECTS OF INTENSE WHEELCHAIR PROPULSION AND START-UP SHOULDER BIOMECHANICS ON THE SUBACROMIAL SPACE AMONG INDIVIDUALS WITH SPINAL CORD INJURY

4.1 INTRODUCTION

The shoulder is the most commonly reported site of pain and injury in manual wheelchair users (MWUs) with spinal cord injury (SCI). Approximately 31-73% of MWUs with SCI have encountered shoulder pain and pathology.(Boninger et al., 2001) The primary pathology found in most shoulder pain cases is subacromial impingement syndrome (SIS) in individuals with SCI.(Bayley et al., 1987; Dyson-Hudson & Kirshblum, 2004; Lee & McMahon, 2002) The SIS may result from several factors, including extrinsic compression of the supraspinatus outlet, narrowing of the subacromial space and consequent compression of the rotator cuff tendons. Manual wheelchair propulsion is a repetitious high force task that is believed to contribute to the development of SIS. (Bayley et al., 1987) During the propulsive phase, forces applied at the pushrim act in equal and opposite directions and are absorbed by the joints of the upper limbs. These forces may translate the humeral head into the subacromial space(Philip Santos Requejo et al., 2008) and compress the soft tissue, therefore causing tissue damage.(Lippitt & Matsen, 1993) Moreover, extreme ranges of shoulder motion observed during propulsion combined with high forces likely places MWUs at a higher risk for SIS. (Boninger et al., 2005) In addition, the imbalance of muscle strength around the shoulder joint and abnormal scapular and clavicular kinematics found in MWUs further predispose them to impingement of the soft tissue structures within the subacromial space. (Burnham et al., 1993)

Ultrasonography has been used to diagnose rotator cuff disorders and abnormalities of the biceps tendon and supraspinatus. (Brose et al., 2008; Campbell & Dunn, 2008; Morag et al., 2012; Zanetti & Hodler, 2000) In addition to the pathological assessment, quantitative ultrasonography (QUS) has also been used to detect the acute changes in the biceps and supraspinatus tendons after wheelchair propulsion. (J. L. Collinger, Impink, Ozawa, & Boninger, 2010; Stefan van Drongelen et al., 2007) Increased cadence and larger resultant propulsive forces were related to post-propulsion QUS changes of the biceps tendon after an intensive bout of overground wheelchair propulsion. (J. L. Collinger, Impink, et al., 2010) In this study wheelchair users pushed as fast as they could for as many laps as they could around a figure-8 course in 12 minutes. Because higher velocities are associated with higher cadences and resultant forces, a follow-up study controlling for speed on a dynamometer found a link between shoulder joint kinetics and post-acute biceps and supraspinatus tendon changes on ultrasound after propulsion on the figure-8 course. (Jennifer L. Collinger, 2009) Because the shoulder kinetics was collected under different conditions (e.g. sub-maximal constant speed dynamometer propulsion) they may not be representative of shoulder kinetics during intense overground wheelchair propulsion. The figure-8 course consists of three distinct propulsion tasks: acceleration, turning and sudden braking which simulates the types of propulsion activity that may occur during court sports like wheelchair basketball or rugby. The percentages of start-up strokes from complete stop, steady-state strokes, turning strokes, and braking in each figure-8 course are approximately 22%, 12%, 33%, and 33%, respectively. Propulsive strokes during start-up (e.g. acceleration from rest) propulsion have significantly different characteristics from those observed for steady-state speeds. (Koontz et al., 2005; Koontz et al., 2009) The main purpose of this study was to determine if shoulder biomechanics during the startup phases of the figure-8 course are related to acute changes on ultrasound after controlling for the velocity of startup.

The acromiohumeral distance (AHD) is a linear measure of the subacromial space and a marker for SIS. We demonstrated our ability to reliability measure the AHD and detect acute narrowing of the subacromial space after a repeated weight relief raise task. (Chapter 2 and 3) (Lin, 2012) Previous work also showed that changes in the AHD were correlated with shoulder pain and subject characteristics (Chapter 3). For this study, we hypothesized that individuals who propelled with higher biomechanical risk factors to shoulder pathology including increased shoulder posterior force and peak internal rotation moments during start up propulsion would have greater AHD narrowing compared to those who propelled with lower forces and moments controlling for the peak velocity and subject demographics. The secondary aim of this study was to investigate the relationship between AHD changes and subject demographics.

4.2 METHODS

4.2.1 Subjects

Twenty-one subjects volunteered and provided informed consent before participation in this study. The inclusion criteria of the study included age between 18 and 65 years old, have SCI that occurred over 1 year prior to the start of the study, and use a manual wheelchair as the primary means of mobility (self-propel at least 40 hours per week). People were excluded from this study if they had a history of fractures or dislocations in the shoulder, from which the participant has not fully recovered, upper limb dysthetic pain as a result of a syrinx or complex regional pain syndrome, and history of cardiovascular and cardiopulmonary disease. They also had no pain in an upper limb that interfered with normal function and daily activity.

4.2.2 Questionnaires

Basic demographic information including age, diagnosis, and date of diagnosis/wheelchair prescription was collected using self-report questionnaires. Subject's body weight and wheelchair weight were measured using a wheelchair scale. Subjects were also asked to report whether they had experienced shoulder pain in the previous month and whether the shoulder pain was related to specific activities of daily living during wheelchair use, as measured by Wheelchair Users Shoulder Pain Index. (Curtis et al., 1999) The WUSPI is a 15-item self-report instrument that measures shoulder pain intensity in wheelchair users during various functional activities of daily living, such as transfers, wheelchair mobility, dressing, overhead lifting, and sleeping.(3) Each item is scored using a 10 cm visual analog scale anchored at the ends with the descriptors of "no pain" and "worst pain ever experienced." Individual item scores are summed to arrive at a total index score. (Curtis et al., 1995a) A Borg scale reading of 10 or more was the threshold to confirm self-reported exertion.(Hummel et al., 2005)

4.2.3 Kinematic and Kinetic Instrumentation

The SmartWheel [b], a three-dimensional force and torque sensing device, was attached to non-dominant side of the participant's own chair while an inertia-matched dummy wheel was fitted to the other side.(R. A. Cooper, Robertson, VanSickle, Boninger, & Shimada, 1997) The non-dominant side was chosen because it would be less affected by other daily activities not related to wheelchair propulsion. Depending on the size of the subjects' wheel diameter, a different size SmartWheel (24" and 26") was used to ensure consistency of axle position, camber, wheel placement and alignment. Individuals with tetraplegia could use a rubber band to facilitate the grip on the SmartWheel handrim. Kinetic data were collected at a 240-Hz sampling frequency and digitally filtered with an eighth-order, zero-phase, and low-pass Butterworth filter with a 20-Hz cutoff frequency. Kinematic data were collected using a Vicon Motion Systems[c] at 120-Hz filtered with fourth-order, zero-lag Butterworh lowpass filter with a cut off frequency at 10Hz. (Koontz et al., 2011) Twenty cameras were surrounded an area of 22 x 3 square meters allowing for an optimized capture volume around the fiture-8 course. (Figure 9) Following the International Society of Biomechanics (ISB) recommendations, reflective markers were placed on bony landmarks of the trunk and non-dominant arm.(Wu et al., 2005) Four markers were also placed on the wheel hubs during data collection to determine the SmartWheel orientation in the lab global coordinate system. Redundant markers were used on each segment to ensure the reliability of the captured kinematic data. Local coordinate systems were created for the trunk and upper arm segments using previous definition. (Koontz et al., 2011) A static calibration trial was collected to compensate for the unstable or missing markers in the dynamic trials. Kinetic and kinematic data collection was synchronized using a custom switch.

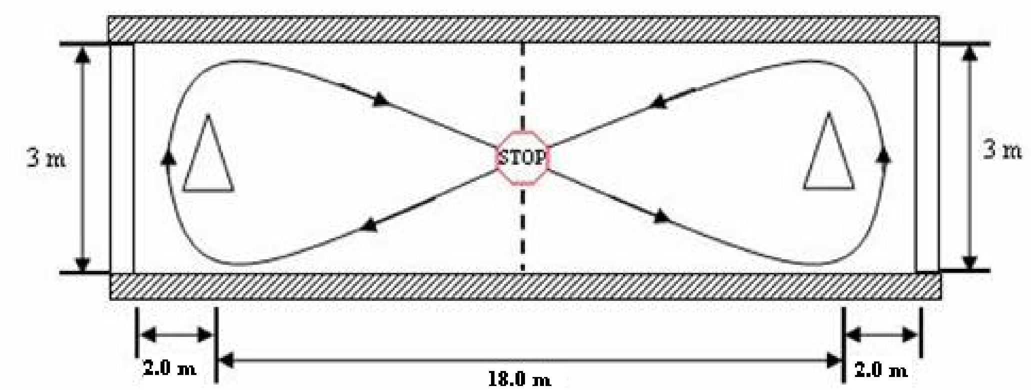

Figure 9. A schematic of the figure-8 shaped propulsion course.

4.2.4 Wheelchair Propulsion Protocols

The figure-8 course is an intense over-ground propulsion task specifically designed to stress the upper limbs and simulate overuse as a result of wheelchair propulsion. The course resembles a figure-8 and spans 18 meters on a concrete floor centered in front of the motion capture cameras. Cones were placed on the floor to outline the course. Participants were asked to push at a self-selected maximum speed, turn around the cones, and come back to center making a sudden complete stop before looping around the other half of the course (Figure 9). Subjects were asked to push their wheelchair for 4 minutes followed by a 90 second rest break. This sequence was repeated three times resulting in a 12-minute propulsion task, which is about 1/3 of the amount of propulsion activity that occurs over the course of an average day. (Tolerico et al., 2007) Each subject was encouraged to complete as many laps as possible during each 4-minute trial. Biomechanical variables in the first minute and the number of whole figure-8 laps completed in 12 minutes were recorded.

4.2.5 AHD Measurement

Ultrasonography was collected using a Philips HD11 1.0.6 ultrasound machine [a] with a 5-12 MHz linear transducer. AHD measurements were taken at two time points by the same examiner: before and immediately after the Figure-8 course. At each time point, the AHD measurements were recorded on the non-dominant shoulder in 45° and 90° arm elevation in the scapular plane with humeral internal rotation (IR) and holding a 3-lb weight similar to that used in other research.(Chopp et al., 2011) For each AHD measurement, the shoulder was scanned from the anterior aspect of glenoid to the flat segment of posterior scapula to capture the bright reflection of the bony contour of the acromion and humeral head (Figure 4). AHD ultrasonographic images were recorded using an external video recorder at 10 Hz for each scan. The AHD measurement has excellent intra-rater reliability in 45° and 90° scapular plane elevation with IR (ICC > 0.841) (See Chapter 1).

4.2.6 Data Analysis

The narrowest distance of the inferior edge of acromion and humeral head was determined through manual observation for each frame of the video using a customized Matlab program [d], which allowed blinded assessment of the AHD videos randomly. The reliability of the manual image processing techniques for identifying the AHD was proven in an earlier study (see Chapter 1). The first three strokes after accelerating from a resting position are different from steady-state strokes and constitute startup. (Koontz et al., 2005) During the first minute of the figure-8 trials, all the second stroke that occurred upon acceleration from a rest position (e.g. center point of figure-8) were considered for biomechanical analysis. This resulted in approximately five strokes analyzed per person. Kinetic data were downsampled to 120 Hz to match the kinematic data collection sampling rate. Pushrim forces were used as input to an inverse dynamic model using a customized Matlab program [d] to calculate 3D shoulder joint kinetics. (R. A. Cooper, Boninger, & Lawrence, 1999) Shoulder movement was described in Euler angles in the plane of elevation, elevation, and rotation. (Collinger JL et al., 2008) Pushrim variables included peak velocity of each start-up stroke, cadence, body-weight normalized peak resultant force (F_{Total}), the fraction of effective force (FEF) defined by the ratio of force that contributed toward forward motion (F_t) in relation to the resultant force (F_{Total}), and push angle. Shoulder biomechanical variables included 3D angles, forces, and moments. All biomechanical variables were analyzed for each stroke and then averaged over the total number of strokes obtained during the first minute of figure-8 propulsion. Ultrasound variables included absolute AHD measures and AHD percentage changes (Equation 1), pre and post figure-8 propulsion.

4.2.7 Statistical Analysis

Paired *t*-tests were used to determine changes in the AHD pre-post propulsion tasks. Pearson's or Spearman's correlation were used where appropriate between the absolute AHD measures, AHD percentage changes (Equation 3), propulsion kinetics, shoulder resultant forces and moments, shoulder kinetics and kinematics, number of laps during figure-8 propulsion, and demographic data (e.g. age, body weight, shoulder circumference, and years post SCI. Stepwise linear regressions were used to determine if baseline AHD and shoulder biomechanics were significant predictors of AHD percentage narrowing. All statistical analyses were performed by using SPSS statistic software (IBM SPSS Statistics, Version 21). The level of significance was set to 0.05.

4.3 RESULTS

4.3.1 AHD and Demographics

Fifteen men and six women participated in this study. The mean age (standard deviation) was 37(9.5) years old, the average duration with SCI was 13(7.9) years, and the average weight was 75.31(20.14) kg. Six persons with tetraplegia (C5-C7) and fifteen individuals with paraplegia (T3-L4) were tested. All participants were right hand dominant. Shoulder circumferences were related to AHD baseline measures in 90° scapular plane elevation. ($r = 0.47$, $p = 0.03$). The mean and median WUSPI scores were 2.94 and 2.77 out of 150 (Range from 2.31 to 14.57), respectively. Mean and standard deviation of Borg scale were 14.43 and 2.89, respectively.

4.3.2 AHD and Propulsion Variables

There were no statistically significant differences in the AHD measures before and after intense propulsion (Table 7). Table 8 displays the propulsion data during the start-up portions of the figure-8 course. Since peak velocity was significantly correlated to most propulsion kinetics and shoulder biomechanical variables ($r > 0.50$, $p < 0.05$) but not the AHD measure, it was statistically controlled using a semi-partial correlation. AHD narrowing immediately after intense propulsion was not associated with number of laps ($p > 0.16$).

Table 7. Mean (SD) AHD measures before and after wheelchair propulsion tasks (n = 21).

AHD Measure (mm)	Before	After	Difference
45° weighted AE w/ IR	10.25(2.10)	10.54(1.90)	0.29(1.43)
90° weighted AE w/ IR	9.64(2.60)	9.20(2.30)	-0.44(1.58)

Table 8. Pushrim variables for start-up overground propulsion for self-selected maximum speed in the first minute of the figure-8 course.

Pushrim Kinetics	Figure-8 first minute (n= 21)
Peak Velocity (m/s)	1.26±0.28
Cadence (1/s)	1.20±0.19
Peak F_{Total} (% BW)	15.11±4.49
FEF	0.35±0.13
Push Angle (deg)	96.62±14.51

4.3.3 AHD and Shoulder Biomechanics

Table 9 and Table 10 summarize the peak shoulder kinetics and kinematics during the first minute of start-up figure-8 propulsion, respectively.

Table 9. Peak shoulder kinetics at start-up overground propulsion for self-selected maximum speed in the first minute of figure-8 course.

Shoulder Kinetics	Figure-8 first minute (n= 21)		
Force (N)		Moment (N•m)	
Anterior	23.81±8.11	Abduction	11.52±5.31
Posterior	22.11±4.74§	Adduction	16.18±9.01
Superior	42.57±13.65	ER	21.53±9.75
Inferior	30.34±13.64	IR	22.67±8.57§
Medial	52.78±31.72	Flexion	17.59±11.80
Lateral	46.93±13.39	Extension	17.28±9.59
Max Resultant Force	92.43±19.72		

Correlated to AHD narrowing at 90° (§) arm elevation in the scapular plane with humeral internal rotation

Table 10. Peak shoulder kinematics at start-up overground propulsion for self-selected maximum speed in the first and last minute of figure-8 course.

Kinematics	Figure-8 first minute (n= 21)
Shoulder Angles (degree)	
Max Plane of Elevation	65.68±29.82
Max Elevation	65.26±16.41
Min Internal Rotation	52.19±16.20
Min Plane of Elevation	52.89±21.06
Min Elevation	33.78±11.52
Max Internal Rotation	73.99±26.96§

Since the peak shoulder posterior forces at the first minute of figure-8 course have the strongest correlation coefficients, they were selected as independent variables in the linear regression models to predict AHD narrowing. The AHD baseline measures were always the strongest predictors of the AHD post-propulsion measure in all measurement positions ($r > 0.56$, $p < 0.01$). As a result, findings that link biomechanics to the AHD percentage changes have been normalized to account for the AHD at baseline. In 90° scapular plane elevated shoulder position, we found that AHD baseline measure and peak shoulder posterior force at first minute of startup stroke are two predictors of AHD immediately after propulsion (Table 11).

Table 11. Predictors for AHD measure in 90° scapular plane elevation immediately after propulsion tasks

Dependent Variable	Predictors	Coefficient	*P* Value	R^2
AHD after figure-8 propulsion	AHD Baseline	0.751	< 0.01	0.751
	Peak Shoulder Posterior Force	0.341	0.01	

Peak posterior force ($r = 0.48$, $p = 0.02$) (Figure 10) and IR moments ($r = -0.47$, $p = 0.03$) (Figure 11) in the first minute were related to AHD percentage narrowing with the arm at 90° of elevation with humeral internal rotation, respectively.

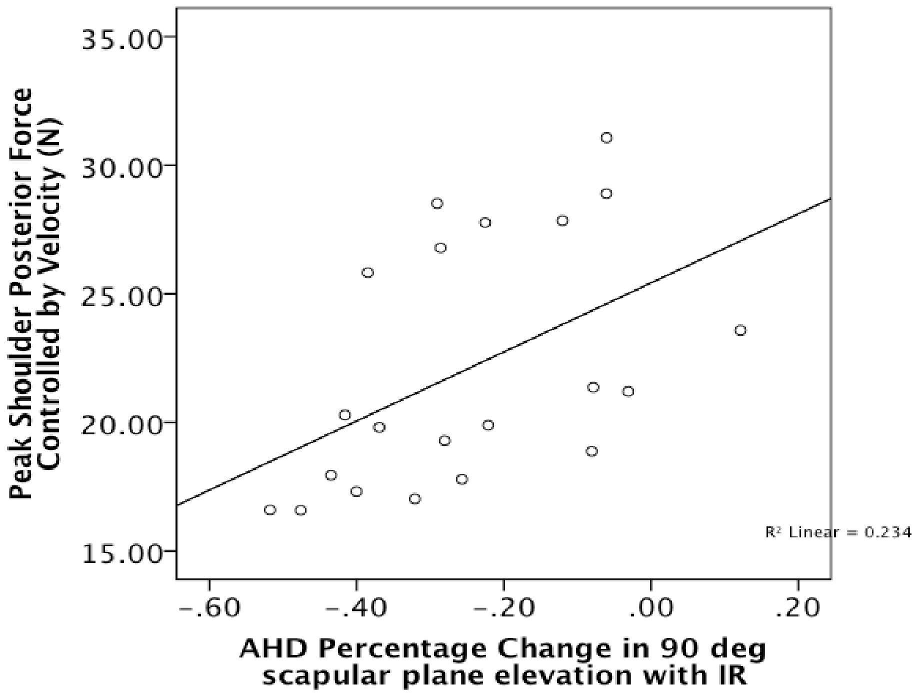

Figure 10. Scatter plots for the AHD percentage changes in 90° arm elevation with humeral internal rotated position vs. peak shoulder posterior force at the start-up of figure-8 propulsion course.

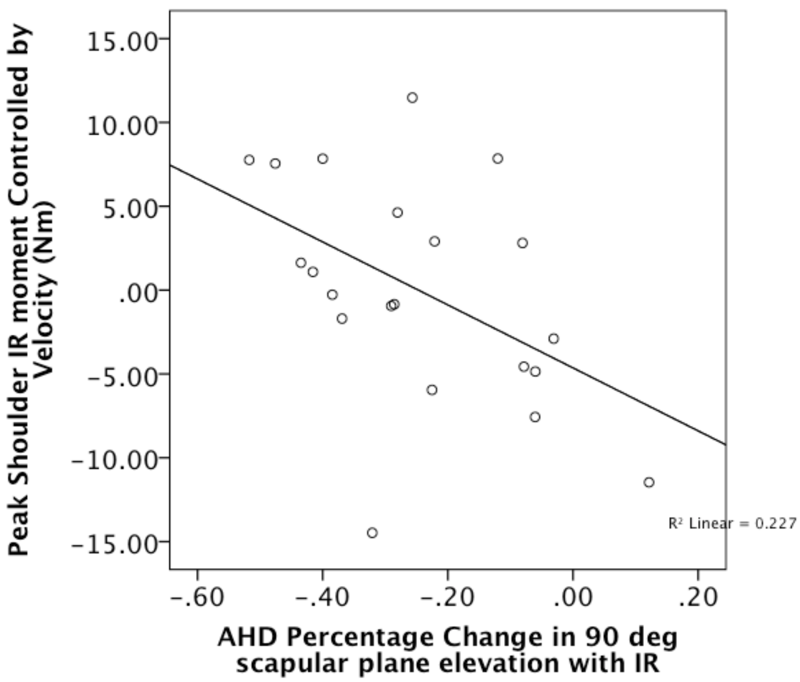

Figure 11. Scatter plots for the AHD percentage changes in 90° arm elevation with humeral internal rotated position vs. peak shoulder internal rotation moment at the start-up of figure-8 propulsion course.

4.4 DISCUSSION

This is the first study to report shoulder joint kinetics during start-up of intense wheelchair propulsion on overground surfaces in relation to changes in the subacromial space. Although the AHD acute changes before and immediately after intense propulsion were not statistically significant, we found AHD percentage changes at 90° scapular plane elevation were associated with shoulder kinetics. Our pushrim kinetic variables for all the second start-up strokes during the figure-8 course are slightly larger than those reported in previous studies. (Koontz et al., 2005; Koontz et al., 2009) A major difference between the previous studies and ours was that our participants were asked to push at a self-selected maximum speed and for as many laps as possible.

The figure-8 course resulted in participants experiencing a high level of exertion according to their self-reported Borg ratings. The peak shoulder joint resultant forces were similar to the findings observed in the glenohumeral joint *in vivo* measurement during wheelchair propulsion. (Westerhoff et al., 2011) However, each component of forces and moment's magnitudes are slightly different in the current study, but this could be attributed to the start-up phase, which may require higher demands on the shoulder. (Koontz et al., 2005; Koontz et al., 2009) We found that AHD narrowing immediately after propulsion at 90° arm elevation with humeral internal rotation was associated with increased peak shoulder internal rotation moments. The relationship was consistent with previous findings which linked the internal rotation moments obtained during steady-state dynamometer propulsion to increased signs of shoulder pathology upon physical examination. (Mercer et al., 2006) Contrary to the hypothesis, greater shoulder posterior force was found in AHD with less narrowing. Our hypothesis was based on a previous study which showed that greater shoulder posterior forces was associated with more shoulder tendon changes on ultrasound. (Jennifer L. Collinger, 2009) One explanation for the difference found could be due to the type of stroke analyzed in each study, this study being start-up strokes and the other one steady-state strokes. Although no studies have compared the trunk positions and shoulder kinetics between these two conditions, we observed that many subjects use their trunk more during startup (e.g. lean forward) which results in reaction forces at the shoulder to be more posteriorly directed. It is also been suggested that leaning forward helps to engage the larger muscles around the shoulder (e.g. pectoralis major and anterior deltoid) which helps to circumvent humeral head translation. (Perry, Gronley, Newsam, Reyes, &

Mulroy, 1996) Thus, leaning forward during propulsion, while resulting in higher shoulder posterior forces, may have helped to keep the humerus from encroaching into the subacromial space. The AHD changes in relation to trunk and shoulder muscle activity during wheelchair propulsion should be examined in future study.

Joint loading during vulnerable positions of the shoulder may lead to shoulder injuries. It is not surprising that ranges of motion of shoulder kinematics are slightly larger than previous findings on dynamometer propulsion due to start-up propulsion. Greater internal rotation and greater flexion angles occurring simultaneously may cause the greater tuberosity to approach the anterior acromion which may lead to SIS. (Neer, 1972) Studies have shown that the internal rotated humerus is prone to subacromial impingement since the position does not allow the greater tuberosity to clear from under acromion during humeral elevation. (Escamilla, Yamashiro, Paulos, & Andrews, 2009) This is also a valuable finding because the shoulder in extremes position could be harmful to supraspinatus tendon caused by the narrowing of subacromial space. Thus the clinical interventions such as wheelchair skill training or exercise prescription could have a significant impact on preservation of shoulder function to enhance the glenohumeral joint stability. Finding the relationship between narrowing and biomechanical risk factors to shoulder pathology testified that this ultrasonographic AHD measurement is valid and clinically relevant. In addition, muscle fatigue may have occurred leading to the reduction in space. This later finding would be consistent with prior work that showed AHD narrowing in manual wheelchair users with electromyography signs of shoulder muscle fatigue after performing weight relief raises. (Lin, 2012)

Study Limitation

A weakness of this study is the diversity of the sample. The sample size was too small to investigate the influence of specific demographic characteristics like disability type and level of injury on the shoulder biomechanics and pushrim kinetics. Other variables such as acromial shape, abnormal scapular kinematics, and impaired rotator cuff function were not investigated and could be additional sources to explain AHD narrowing. Dynamic imaging of the AHD using ultrasound is limited. The three-dimensional bi-plane fluoroscopy could be used to investigate dynamic mechanisms within the glenohumeral joint during arm elevation and wheelchair tasks. In addition, objective signs of muscle fatigue were not measured during the figure-8 propulsion. Instead, we recorded the Borg Scale after each propulsion task to identify the self-reported fatigue. Due to the cross-sectional nature of this study, we cannot draw evidence linking the AHD measurement to shoulder pathology. As scapular orientation has also been shown to affect AHD, future work should investigate scapular and humeral positioning during weight-bearing tasks to gain further insight into injury mechanisms. Studies incorporating electromyography to determine the objective muscle fatigue after intense overground wheelchair propulsion as well as metabolic variables may provide a more comprehensive understanding of the effects of subject-specific factors on the mechanism of subacromial impingement syndrome.

4.5 CONCLUSIONS

Manual wheelchair users using certain propulsion techniques may be at risk for AHD narrowing after intense propulsion. This study provides objective evidence that reductions in the subacromial space occur with biomechanical risk factors including greater internal rotation moment and less shoulder posterior force during the start-up strokes of intense wheelchair propulsion. In addition, shoulder circumference was the primary demographic variable related to AHD narrowing. Future work should involve longitudinal study to investigate the biomechanical and pathological changes that may occur over an extended period of time. In addition, the AHD measurement may be useful for evaluating the impact of clinical interventions such as wheelchair setup optimization or wheelchair skill training on preserving the subacromial space.

5.0 CONCLUSIONS

Based on the results of all three experiments in this dissertation, the linear measurement of the acromiohumeral distance can be reliably obtained via ultrasound in manual wheelchair users with SCI and used to investigate the effects of acute shoulder muscle fatigue and intense wheelchair propulsion on the subacromial space.

Findings from Chapter 2 showed that AHD measurement using ultrasound is a reliable tool to evaluate subacromial space in MWUs with SCI. The AHD narrowing that occurred for the various shoulder positions increases our understanding of the risk factors of repetitive strain injuries. In all of the chapter studies the narrowest distance was determined from a single frame from the video clip. It is possible that this led to larger desirable measurement errors making it difficult to detect significant changes in the AHD across all the studies. The uncertainty is related to both the snapshot selection of the frame with the narrowest distance and the manual determination of the feature points on the acromial and humeral head within and between the video observers on that frame. To address this issue we conducted a secondary analysis to see if manual errors could be reduced by averaging 5 frames forward and backward totally 11 frames around the narrowest distances. A single rater studied 50 random ultrasound videos at two points in time. The intra-video reproducibility was improved from 0.81 to 0.94. Additional subjects and videos need to be analyzed to confirm this finding but if proven future studies should consider this method to reduce error when determining the AHD on ultrasound. The findings in Chapter 2 support the clinical practice guideline recommendation that overhead shoulder positions, particularly those combining abduction with internal rotation, cause a reduction in the space and should be avoided in both MWUs with SCI and able-bodied controls. This recommendation has been made in clinical practice guideline. (Boninger et al., 2005) Muscle imbalances commonly in MWUs can lead to glenohumeral instability, impingement, and degenerative joint diseases. (Burnham et al., 1993) Moreover the onset of muscle fatigue may further exacerbate the effects of muscle imbalance on the subacromial space. (Szucs et al., 2009) Our findings support this theory as MWUs with SCI had decreased narrowing between the neutral shoulder and 45° of scapular plane abduction compared to the control group immediately following repetitive rotator cuff exercises (see Chapter 2).

Findings from Chapter 3 indicated that MWUs should limit weight relief raises as a pressure relief technique, as placing the shoulder in this position led to a significant reduction in subacromial space. Fatigue of the sternal pectoralis major after performing repetitive weight relief raises led to greater percentage narrowing of the AHD, which points to its importance in functioning as a humeral depressor in addition to serving as the largest contributor to performance of a successful weight relief raise. In addition to investigating AHD measurement and muscle fatiguing activities, we applied ultrasonographic measurement of AHD to understand the mechanisms of SIS associated with intense overground wheelchair propulsion among MWUs with SCI (Chapter 4). The study in Chapter 4 found that pushing with a technique that resulted in higher shoulder internal rotation moments and lower posterior forces during startup was linked to more acute narrowing of the AHD. Furthermore, shoulder circumference was related to AHD measurement (Chapter 3, Chapter 4). The findings of this study provided better understanding of the mechanisms of SIS. Wheelchair skill training to optimize the propulsive techniques with lower shoulder internal rotation moment during the start-up propulsion is important. The results of these studies can inform clinical decision-making and therapeutic treatment outcomes.

5.1.1 Limitations

Minimum detectable difference (MDD) describes the smallest threshold to detect true AHD changes beyond the measurement error at a 90% level of confidence interval. For individual bases, MDD is appropriate for clinical decision-marking to determine the real differences. However, MDD may be too conservative for examining AHD changes among a group. Even though some of the statistically significant mean group differences in the AHD were below the MDD, the MDD for our ultrasound methods was in line with reported in other studies. (Leong et al., 2011) Previous studies supported that ultrasonographic measurement of AHD is able to detect the differences after SIS or therapeutic interventions. For example, Cholewinski reported that the ultrasonograhic measurements of AHD in affected shoulder among individuals with SIS are significantly narrower than the distance in non-affected shoulder ($p < 0.001$). (Cholewinski et al., 2008) Among the individuals without shoulder pain or known shoulder pathology, the modified scapular assistance test resulted in increased ultrasonographic measurement of AHD in 45° and 90° active arm elevation in the scapular plane. (Seitz et al., 2012) The MDD in Seitz's study ranged from 0.6mm to 0.9mm which enabled them to detect 1.7 to 2.1mm changes after intervention. Although MDD in our study are similar (0.9mm to 1.32mm), it may reveal that no dramatic AHD changes occur after intense wheelchair activities or the changes are not large enough to be detected. Previous studies demonstrated that ultrasonographic measurement of AHD is able to detect the differences after SIS or therapeutic interventions. MWUs with painful shoulder were excluded in our studies since the intense wheelchair activities may exaggerate the symptom. Our data showed that the MWUs were asymptomatic (median WUSPI scores were 2.77). This may be a strength of the study in identifying mechanisms of injury as the symptomatic shoulder is frequently accompanied with narrowing of subacromial space.

Due to equipment limitations, dynamic measurement of the subacromial space throughout the range of shoulder elevation in the scapular plane or during activity was not possible. Instead the AHD measurement was taken during static shoulder positions that were based on prior literature and may not be representative of the dynamic state of the AHD while performing the actual tasks. The positions were standardized and not based on those observed during wheelchair propulsion which can vary dependent on used techniques. Differences calculated between each static position may not be representative of the synergy that occurs dynamically in between the two points with regards to the glenohumeral translations, muscle lines of action, and scapular kinematics.

5.1.2 Future Work

It is imperative that future research examines the relationship between shoulder pain, pathology and AHD measurement to attach clinical validity to the amount of subacromial space compression matters and how it relates to symptoms. In addition, measuring scapular and humeral kinematics and shoulder muscle activity during dynamic overground wheelchair activity may enable future research to validate the dynamic mechanisms of AHD narrowing in the shoulder complex. Rehabilitation programs to maintain the muscle balance could help preserve the subacromial space from impingement following spinal cord injury. The appearance on supraspinatus tendon measured by ultrasound postpropulsion could be related to AHD narrowing. Future study to identify the association between acute changes of supraspinatus tendon measured by QUS and the ultrasonographic measurement of AHD is recommended. Based on the results from these three studies, the following future investigations are recommended. Dynamic AHD measurements during wheelchair activities will provide further etiological insight into SIS among individuals with SCI. Further examination of three-dimensional scapular kinematic measures is necessary to gain more understanding the mechanism of SIS. Longitudinal studies are warranted to test interventions that enable for maintaining a healthy amount of subacromial space and help improve the rehabilitative decision-making, exercise prescription, and the clinical practice guideline to the treatment and prevention of SIS.

APPENDIX A

ULTRASONOGRAPHIC VIDEO ANALYSIS OF AHD MEASUREMENT: MATLAB CODE

```
close all;
clear;

folder_name = uigetdir;
cd(folder_name);

positions = [{'00'};{'45A'};{'45P'};{'90A'};{'90P'};{'WR'};];

rater = [11,12,21,22];

random_pos = randperm(length(positions));
random_rater = randperm(length(rater));
filelist = zeros(4,6);
frame = zeros(4,6);
ahdscale = zeros(4,6);
xAC = zeros(4,6);
yAC = zeros(4,6);
xGH = zeros(4,6);
yGH = zeros(4,6);
finish = 1;
redo = 0;

if redo == 1;
    load((folder_name(length(folder_name)-9:length(folder_name)-4)));
    i = input(['Enter the rater number  :      ']);
    j = input(['Enter the position number  :      ']);

    TrialNM =
strcat('Rater',num2str(rater(i)),'_',positions(j),'.avi');
```

```
        obj=VideoReader(TrialNM{1});

        nFrames=obj.NumberOfFrames;

        vidHeight=obj.Height;

        vidWidth=obj.Width;

        % Preallocate movie structure.
        mov(1:nFrames) = ...
            struct('cdata', zeros(vidHeight, vidWidth, 3, 'uint8'),...
            'colormap', []);
        h = implay(TrialNM{1});

%         disp('Press any keys to enter the frame number');
%         pause;
%         close(h);

        frame(i,j) = input(['Enter the desired frame number for AHD
measurement:   ']);
        while frame(i,j)>nFrames
            disp('The frame number entered was too large.');
            frame(i,j) = input('Enter another frame number');
            if frame(i,j)<=0
                disp('The frame number can not be zero. Enter a
positive value');
            end

        end

        for k = 1 : nFrames
            if k== frame(i,j)
                mov(k).cdata=read(obj,k);
            end
        end


        depth = input(['Enter the depth  :      ']);
        if depth == 4
            ydist=145;  % depth 4cm;
        elseif depth == 5
            ydist=114;
        end

        if frame(i,j)~=0

            imshow(mov(frame(i,j)).cdata)
            title('First click is the acromion position, Second click
is the humerus position');

            [xinput,yinput]=ginput(2);
            xAC(i,j)=xinput(1);
```

```
            yAC(i,j)=yinput(1);

            xGH(i,j)=xinput(length(yinput));
            yGH(i,j)=yinput(length(yinput));
            close

            ahdist=abs(yAC(i,j)-yGH(i,j));
            ahdscale(i,j)=ahdist/ydist;

            disp(' ');
            display(['The acromiohumeral distance is '
num2str(ahdscale(i,j)) ' centimeters.'])

            filelist(i,j)=1;

            save(folder_name(length(folder_name)-
9:length(folder_name)-4), 'filelist', 'ahdscale', 'frame', 'xAC',
'yAC', 'xGH', 'yGH');

            close all;
            clear obj mov; close(h);
            return;
        end
end

for i = 1:length(rater)
    for j = 1:length(positions)
        if  i == 1&& j == 1 &&
exist(strcat(folder_name(length(folder_name)-9:length(folder_name)-
4),'.mat')) == 2
            load((folder_name(length(folder_name)-
9:length(folder_name)-4)));
        end
        if filelist(random_rater(i),random_pos(j))== 1;
            continue;
        end

        if finish == 0;
            save(folder_name(length(folder_name)-
9:length(folder_name)-4), 'filelist', 'ahdscale', 'frame', 'xAC',
'yAC', 'xGH', 'yGH');
            return;
        elseif finish == 2 && j ~= 1 && j <= length(positions)
            j = j-1;
        elseif finish == 2 && j == 1
            i = i-1;
            j = length(positions);
        end



        TrialNM =
```

```
strcat('Rater',num2str(rater(random_rater(i))),'_',positions(random_po
s(j)),'.avi');


        obj=VideoReader(TrialNM{1});

        nFrames=obj.NumberOfFrames;

        vidHeight=obj.Height;

        vidWidth=obj.Width;

        % Preallocate movie structure.
        mov(1:nFrames) = ...
            struct('cdata', zeros(vidHeight, vidWidth, 3, 'uint8'),...
            'colormap', []);
        h = implay(TrialNM{1});

        frame(random_rater(i),random_pos(j)) = input(['Enter the
desired frame number for AHD measurement:   ']);
        while frame(random_rater(i),random_pos(j))>nFrames
            disp('The frame number entered was too large.');
            frame(random_rater(i),random_pos(j)) = input('Enter
another frame number');
            if frame(random_rater(i),random_pos(j))<=0
                disp('The frame number can not be zero. Enter a
positive value');
            end

        end


        % Read one frame at a time.
        for k = 1 : nFrames

            if k== frame(random_rater(i),random_pos(j))
                mov(k).cdata=read(obj,k);
            end
        end

        depth = input(['Enter the depth  :       ']);
        if depth == 4
            ydist=145;  % depth 4cm;
        elseif depth == 5
            ydist=114;
        end

        if frame(random_rater(i),random_pos(j))~=0

            imshow(mov(frame(random_rater(i),random_pos(j))).cdata)
            title('First click is the acromion position, Second click
is the humerus position');
```

```
            [xinput,yinput]=ginput(2);
            xAC(random_rater(i),random_pos(j))=xinput(1);
            yAC(random_rater(i),random_pos(j))=yinput(1);

            xGH(random_rater(i),random_pos(j))=xinput(length(yinput));
            yGH(random_rater(i),random_pos(j))=yinput(length(yinput));
            close

            ahdist=abs(yAC(random_rater(i),random_pos(j))-
yGH(random_rater(i),random_pos(j)));
            ahdscale(random_rater(i),random_pos(j))=ahdist/ydist;

            display(['The acromiohumeral distance is '
num2str(ahdscale(random_rater(i),random_pos(j))) ' centimeters.'])

                        filelist(random_rater(i),random_pos(j))=1;

            close all;
            clear obj mov; close(h);
            finish = input(['Continue AHD analysis? Yes = 1,  No and
Save = 0,  Redo the trial = 2   :       ']);

        end
    end
end

save(folder_name(length(folder_name)-9:length(folder_name)-4),
'filelist', 'ahdscale', 'frame', 'xAC', 'yAC', 'xGH', 'yGH');

[ahdscale(1,:),ahdscale(2,:),ahdscale(3,:),ahdscale(4,:)]*10
```

APPENDIX B

ELETROMYOGRAPHIC SIGNS OF MUSCLE FATIGUE: MATLAB CODE

```
clear all;
close all;

path = 'C:\Documents and Settings\liny\My Documents\My
Dropbox\WULACAP\Fatigue MWP';
cd(path);
tp = pwd;

for trial = 1:2
    if trial == 1
        load TRIDIPS
    else
        load RTC
    end

    EMG.Pecs = Data{1}(1:length(Data{1}));
    EMG.Infraspinatus = Data{2}(1:length(Data{1}));
    EMG.Latts = Data{3}(1:length(Data{1}));

    interval = samplingRate;  % 1500

    MuscleName = [{'Infraspinatus'};{'Pecs'};{'Latts'}];

    for muscle = 1:3
        switch muscle
            case 1
                absEMG = abs(EMG.Infraspinatus);
            case 2
                absEMG = abs(EMG.Pecs);
            case 3
                absEMG = abs(EMG.Latts);
        end

        meanEMG = absEMG;
```

```
        stdEMG =  absEMG;
        Wn = 4/750;
        [num, den] = butter(4, Wn, 'low'); % Design Butterworth
filter.
        AnalyzedEMG = filtfilt(num,den,absEMG);

        eval(['AvgPeakEMG.',MuscleName{muscle},' =
mean(AnalyzedEMG(localMaximum(AnalyzedEMG, interval, true)));']);

        eval(['StdPeakEMG.',MuscleName{muscle},' =
std(AnalyzedEMG(localMaximum(AnalyzedEMG, interval, true)));']);

        eval(['[median_frequency.',MuscleName{muscle},'] =
MDF2(EMG.',MuscleName{muscle},', samplingRate, interval);;']);

        eval(['PercentMPFPercent_Fatigue.',MuscleName{muscle},' =
(mean(median_frequency.',MuscleName{muscle},'(6:10))-
mean(median_frequency.',MuscleName{muscle},'(length(median_frequency.'
,MuscleName{muscle},')-
4:length(median_frequency.',MuscleName{muscle},'))))/mean(median_frequ
ency.',MuscleName{muscle},'(6:10));;']);

        eval(['[RMS.',MuscleName{muscle},'_start] =
rms(EMG.',MuscleName{muscle},'(1:5*samplingRate));']);
        eval(['[RMS.',MuscleName{muscle},'_end] =
rms(EMG.',MuscleName{muscle},'(length(EMG.',MuscleName{muscle},')-
5*samplingRate:length(EMG.',MuscleName{muscle},')));']);


eval(['[RMSMVC.',MuscleName{muscle},'] =
RMS.',MuscleName{muscle},'_end-RMS.',MuscleName{muscle},'_start;']);

resultpath = 'C:\Users\Johnny\Dropbox\Dissertation\Proposal\Results';
        cd(resultpath);

        if trial == 1
            fid = fopen('Fatigue3Muscles.xls','a');
            if muscle == 1
                eval(['fprintf(fid,''USF''''',num2str(subject),''''
\n'');']);
                fprintf(fid,'Infra \t\t Pecs \t\t Latts \n');
            end
            eval(['fprintf(fid, ''%6.6f\t'',
PercentMPFPercent_Fatigue.',MuscleName{muscle},');;']);
            eval(['fprintf(fid,
''%6.6f\t'',RMSMVC.',MuscleName{muscle},');']);
            save Fatigue_TRIDIPS median_frequency
PercentMPFPercent_Fatigue AvgPeakEMG StdPeakEMG RMS RMSMVC
        else
            eval(['fprintf(fid, ''%6.6f\t'',
PercentMPFPercent_Fatigue.',MuscleName{muscle},');;']);
            eval(['fprintf(fid,
```

```
''%6.6f\t'',RMSMVC.',MuscleName{muscle},');']);
            save Fatigue_RTC median_frequency
PercentMPFPercent_Fatigue AvgPeakEMG StdPeakEMG RMS RMSMVC
        end

    end
    cd(tp);
    fprintf(fid, '\n');
    clear EMG median_frequency
end
fprintf(fid, '\n');
fclose(fid);
```

APPENDIX C

UPPER LIMB KINEMATICS AND KINETICS DURING OVERGROUND PROPULSION: MATLAB CODE

```
close all;
clear all;
clc;

loadvicondata = 1;      % Read = 0; Load = 1;
loadSWdata = 0;      % Read = 0; Load = 1;
loadinterpmarker = 0;   % Read = 0; Load = 1;
loadanalysis = 0;       % Read = 0; Load = 1;

analyzedtype = 2;   %    Kinematics = 1; Kinetics = 2;
statisticflag = 0;  %  Save = 0; Load = 1;

if analyzedtype == 2
    sDynaTrial = 1;
else
    sDynaTrial = 2;
end

strial = 2;
numsubject = 21;
analyzedsubject = 21;
resultpath = 'J:\HERL\Dissertation\WULACAP\Results';


for subject = strial:strial+numsubject-1
    for Conditions = 5:5

        if loadanalysis == 0;
            Vicondatapath = 'J:\HERL\Dissertation\WULACAP\Vicon';
```

```
            WULACAPTrialData;


Markerset=[{'FH'};{'RTMJ'};{'LTMJ'};{'STRN'};{'XYPD'};{'C7'};{'T3'};{'
T8'};{'SHO'};{'MEP'};{'LEP'};...

{'UA1'};{'UA2'};{'UA3'};{'UA4'};{'LA1'};{'LA2'};{'LA3'};{'LA4'};...

{'RS'};{'UT'};{'HC'};{'3MP'};{'HUB1'};{'HUB2'};{'HUB3'};{'HUB4'}];


            %% Save or Load Subjects' vicon data
            if analyzedtype == 1
                if loadvicondata == 0

                    for trial = 1:length(TrialNM)
                        fileNM= strcat(TrialNM, '.csv');
                        fileNM{trial}
                        [Kinematics(trial)] =
ReadViconNexus(fileNM{trial}, Markerset);
                    end

                    eval(['save
RawData_',TrialNM{length(TrialNM)},'.mat Kinematics;']);
                else

                    eval(['load
RawData_',TrialNM{length(TrialNM)},'.mat;']);
                    loadvicondata = 1;
                end
            end

            if analyzedtype == 1
                %% Static Calibration

                StaticTrial = 1;

                for i = 1 : length(Kinematics(StaticTrial))
                    for j = 1:length(Markerset)

if strcmp(Markerset{j}, '3MP') == 1
                            Markerset{j} = 'ThirdMP';
                        end
                        eval(['',Markerset{j},'_global =
Kinematics(StaticTrial).',Markerset{j},';']);
                    end
                end

                frame_Trucali = FindCaliFrame([STRN_global,
XYPD_global, C7_global, T8_global]);

                frame_UABcali = FindCaliFrame([SHO_global, LEP_global,
```

```
MEP_global]);
                frame_UATcali = FindCaliFrame([UA1_global, UA2_global,
UA3_global, UA4_global]);

                frame_LABcali = FindCaliFrame([LEP_global, MEP_global,
RS_global, UT_global]);
                frame_LATcali = FindCaliFrame([LEP_global, MEP_global,
RS_global, UT_global]);

                frame_Handcali = FindCaliFrame([RS_global, UT_global,
ThirdMP_global]);
                frame_Hubcali = FindCaliFrame([HUB1_global,
HUB2_global, HUB3_global, HUB4_global]);

                [Rg2trC, Vg2trC] =
TrunkCoord_ISB(STRN_global(frame_Trucali,:),
XYPD_global(frame_Trucali,:), C7_global(frame_Trucali,:),
T8_global(frame_Trucali,:));
                [Rg2uabC, Vg2uabC] = HumerusCoord_ISB(Rg2trC,
STRN_global(frame_UABcali,:), SHO_global(frame_UABcali,:),
LEP_global(frame_UABcali,:), MEP_global(frame_UABcali,:));
                [Rg2uatC, Vg2uatC] =
HumerusCoord_Tech(UA1_global(frame_UATcali,:),
UA2_global(frame_UATcali,:), UA3_global(frame_UATcali,:));

                [Rg2labC, Vg2labC] =
ForearmCoord_ISB(RS_global(frame_LABcali,:),
UT_global(frame_LABcali,:), LEP_global(frame_LABcali,:),
MEP_global(frame_LABcali,:));
                [Rg2latC, Vg2latC] =
ForearmCoord_Tech(LA1_global(frame_LATcali,:),
LA2_global(frame_LATcali,:), LA3_global(frame_LATcali,:));

                [Rg2haC, Vg2haC] =
HandCoord_ISB(RS_global(frame_Handcali,:),
UT_global(frame_Handcali,:), ThirdMP_global(frame_Handcali,:));
                [Rg2hubC, Vg2hubC] = HubCoord(HUB1_global,
HUB2_global, HUB3_global);

                [STRN_local, XYPD_local, C7_local, T3_local, T8_local]
= CoordG2L(Rg2trC, Vg2trC, STRN_global(frame_Trucali,:),
XYPD_global(frame_Trucali,:), T3_global(frame_Trucali,:),
C7_global(frame_Trucali,:), T8_global(frame_Trucali,:));

                [GH_uatlocal, LEP_uatlocal, MEP_uatlocal,
UA1_uatlocal, UA2_uatlocal, UA3_uatlocal, UA4_uatlocal] =
CoordG2L(Rg2uatC, Vg2uatC, SHO_global(frame_UABcali,:),
LEP_global(frame_UABcali,:),
MEP_global(frame_UABcali,:),UA1_global(frame_UABcali,:),
UA2_global(frame_UABcali,:), UA3_global(frame_UABcali,:),
UA4_global(frame_UABcali,:));
```

```
                [LEP_latlocal, MEP_latlocal, RS_latlocal, UT_latlocal,
LA1_latlocal, LA2_latlocal, LA3_latlocal, LA4_latlocal] =
CoordG2L(Rg2latC, Vg2latC, LEP_global(frame_LABcali,:),
MEP_global(frame_LABcali,:), RS_global(frame_LABcali,:),
UT_global(frame_LABcali,:), LA1_global(frame_LABcali,:),
LA2_global(frame_LABcali,:), LA3_global(frame_LABcali,:),
LA4_global(frame_LABcali,:));

                [RS_halocal, UT_halocal, HC_halocal, ThirdMP_halocal]
= CoordG2L(Rg2haC, Vg2haC, RS_global(frame_Handcali,:),
UT_global(frame_Handcali,:), HC_global(frame_Handcali,:),
ThirdMP_global(frame_Handcali,:));


                Rtr2uaC = Rg2trC'*Rg2uabC;
                Vtr2uaC = (Rg2trC'*(Vg2uabC - Vg2trC)')';


                Rua2laC = Rg2uabC'*Rg2labC;
                Vua2laC = (Rg2uabC'*(Vg2labC - Vg2uabC)')';



                Rla2haC = Rg2labC'*Rg2haC;
                Vla2haC = (Rg2labC'*(Vg2haC - Vg2labC)')';


                Ang_g2trC = RotAngConvert(Rg2trC, 'ZXY');     %
default  ZXY
                Ang_tr2uaC = RotAngConvert(Rtr2uaC, 'YXY');     %
default  YXY
                Ang_ua2laC = RotAngConvert(Rua2laC, 'ZXY');     %
default  ZXY
                Ang_la2haC = RotAngConvert(Rla2haC, 'ZXY');     %
default  ZXY

                end
            %% Dynamic Calibration

            for DynamicTrial = sDynaTrial:length(TrialNM);
% All trial

                if analyzedtype == 1
                    if loadanalysis == 0
                        %% Marker Data Interpolation

                        if loadinterpmarker == 0
                            [b,a]=butter(2,7/30); %defines 4th order
Butterworth filter with 7Hz cutoff frequency
                            for i = 1:length(Markerset)
% All markers/frame
```

```
eval(['',Markerset{i},'_global =
Kinematics(DynamicTrial).',Markerset{i},';']);

end
                            eval(['save
MarkerData_',TrialNM{DynamicTrial},'.mat;']);
                        elseif loadinterpmarker == 1 && DynamicTrial
== sDynaTrial
                            eval(['load
MarkerData_',TrialNM{DynamicTrial},'.mat;']);
                            loadvicondata = 1;
                        end
                    end

                    %% Kinematics during propulsion
                    eval(['h=waitbar(0, ''Kinematic Data Analysis in
',TrialNM{DynamicTrial},''');']);
                    eval(['sprintf(''Analyzing trial is
',TrialNM{DynamicTrial},''')']);
                    for frame = 1 :
eval(['length(Kinematics(DynamicTrial).',Markerset{i},')']);  % All
frame/trial


                        %% Trunk Kinematics
                        [Rg2trD(:,:,frame), Vg2trD(frame,:)] =
SOM([STRN_local; XYPD_local; C7_local; T3_local; T8_local] ,
[STRN_global(frame,:); XYPD_global(frame,:); C7_global(frame,:);
T3_global(frame,:); T8_global(frame,:)] );

                        if sum(sum(isnan(Rg2trD(:,:,frame)))) == 9;
                            continue;
                        end

                        [STRN_globalD, XYPD_globalD, C7_globalD,
T3_globalD, T8_globalD] = CoordL2G(Rg2trD(:,:,frame), Vg2trD(frame,:),
STRN_local, XYPD_local, C7_local, T3_local, T8_local);

                        RtrC2trD(:,:,frame)= Rg2trC' *
Rg2trD(:,:,frame);


[Ang_g2trD(frame,:)]=RotAngConvert(Rg2trD(:,:,frame), 'ZXY');  %
default  ZXY

[Ang_trC2trD(frame,:)]=RotAngConvert(RtrC2trD(:,:,frame), 'ZXY');  %
default  ZXY


                        %% Humerus Kinematics
                        if subject ~=4 && Conditions ~=5
                            [Rg2uatD, Vg2uatD] = SOM([GH_uatlocal;
```

```
LEP_uatlocal; MEP_uatlocal; UA1_uatlocal; UA2_uatlocal; UA3_uatlocal;
UA4_uatlocal] , [SHO_global(frame,:); LEP_global(frame,:);
MEP_global(frame,:);UA1_global(frame,:); UA2_global(frame,:);
UA3_global(frame,:); UA4_global(frame,:)]);

                        elseif subject ==4 && Conditions ~=5
                            [Rg2uatD, Vg2uatD] = SOM([GH_uatlocal;
LEP_uatlocal; MEP_uatlocal; UA1_uatlocal; UA2_uatlocal; UA3_uatlocal]
, [SHO_global(frame,:); LEP_global(frame,:);
MEP_global(frame,:);UA1_global(frame,:); UA2_global(frame,:);
UA3_global(frame,:)]);
                        elseif Conditions ==5
                            [Rg2uatD, Vg2uatD] = SOM([GH_uatlocal;
LEP_uatlocal; MEP_uatlocal; UA1_uatlocal; UA3_uatlocal] ,
[SHO_global(frame,:); LEP_global(frame,:);
MEP_global(frame,:);UA1_global(frame,:); UA3_global(frame,:)]);
                        end


                        if sum(sum(isnan(Rg2uatD))) == 9;
                            continue;
                        end

                        HumTech(frame,:) =
RotAngConvert(Rg2uatC'*Rg2uatD,'ZXY');

                        [SHO_globalD(frame,:), LEP_globalD(frame,:),
MEP_globalD(frame,:)] = CoordL2G(Rg2uatD, Vg2uatD, GH_uatlocal,
LEP_uatlocal, MEP_uatlocal);
                        [Rg2uabD(:,:,frame), Vg2uabD] =
HumerusCoord_ISB(Rg2trD(:,:,frame), STRN_globalD,
SHO_globalD(frame,:), LEP_globalD(frame,:), MEP_globalD(frame,:));
                        Rtr2uabD= Rg2trD(:,:,frame)' *
Rg2uabD(:,:,frame);
                        Vtr2uabD(frame,:) =
(Rg2trD(:,:,frame)'*(Vg2uabD - Vg2trD(frame,:))')';

                        [Ang_tr2uabD(frame,:)]=RotAngConvert(Rtr2uabD,
'YXY');  % default  ZXY

                        [Ang_g2humerusD(frame,:)] =
RotAngConvert(Rg2uabD(:,:,frame), 'YXY');

                        %% Forearm Kinematics
                        if Conditions ~= 5
                            [Rg2latD, Vg2latD] = SOM([LEP_latlocal;
MEP_latlocal; RS_latlocal; UT_latlocal; LA1_latlocal; LA2_latlocal;
LA3_latlocal; LA4_latlocal],[LEP_global(frame,:); MEP_global(frame,:);
RS_global(frame,:); UT_global(frame,:); LA1_global(frame,:);
LA2_global(frame,:); LA3_global(frame,:); LA4_global(frame,:)]);
                        else
                            [Rg2latD, Vg2latD] = SOM([LEP_latlocal;
```

```
MEP_latlocal; RS_latlocal; UT_latlocal; LA1_latlocal;
LA3_latlocal],[LEP_global(frame,:); MEP_global(frame,:);
RS_global(frame,:); UT_global(frame,:); LA1_global(frame,:);
LA3_global(frame,:)]);
                        end
                        if sum(sum(isnan(Rg2latD))) == 9;
                            continue;
                        end

                        [RS_globalD(frame,:), UT_globalD(frame,:),
LEP_globalD(frame,:), MEP_globalD(frame,:)] = CoordL2G(Rg2latD,
Vg2latD, RS_latlocal, UT_latlocal, LEP_latlocal, MEP_latlocal);


                        [Rg2labD(:,:,frame), Vg2labD] =
ForearmCoord_ISB(RS_globalD(frame,:), UT_globalD(frame,:),
LEP_globalD(frame,:), MEP_globalD(frame,:));

                        Ruab2labD= Rg2uabD(:,:,frame)' *
Rg2labD(:,:,frame);
                        Vuab2labD(frame,:) =
(Rg2uabD(:,:,frame)'*(Vg2labD - Vg2uabD)')';



[Ang_uab2labD(frame,:)]=RotAngConvert(Ruab2labD, 'ZXY');  % default
ZXY

                        [Ang_g2forearmD(frame,:)] =
RotAngConvert(Rg2labD(:,:,frame), 'ZXY');

                        %                      Vel_uab2labD(frame,:) =
diff(filtfilt(b,a,Ang_uab2labD(frame,:)));
                        %                      Acc_uab2labD(frame,:) =
diff(filtfilt(b,a,Vel_uab2labD(frame,:)));
                        %
                        %% Hand Kinematics
                        if Conditions ~=5
                            [Rg2haD(:,:,frame), Vg2haD] =
SOM([RS_halocal; UT_halocal; ThirdMP_halocal;
HC_halocal],[RS_global(frame,:); UT_global(frame,:);
ThirdMP_global(frame,:); HC_global(frame,:)]);
                        else
                            [Rg2haD(:,:,frame), Vg2haD] =
SOM([RS_halocal; UT_halocal; ThirdMP_halocal;
HC_halocal],[RS_global(frame,:); UT_global(frame,:);
ThirdMP_global(frame,:); HC_global(frame,:)]);
                        end

                        if sum(sum(isnan(Rg2latD))) == 9;
                            continue;
                        end
```

```
                        Rlab2haD= Rg2labD(:,:,frame)' *
Rg2haD(:,:,frame);
                        Vlab2haD(frame,:) =
(Rg2labD(:,:,frame)'*(Vg2haD - Vg2labD)')';


                        [Ang_lab2haD(frame,:)]=RotAngConvert(Rlab2haD,
'ZXY');  % default  ZXY

                        [Ang_g2handD(frame,:)] =
RotAngConvert(Rg2haD(:,:,frame), 'ZXY');

                        %                      Vel_lab2haD(frame,:) =
diff(filtfilt(b,a,Ang_lab2haD(frame,:)));
                        %                      Acc_lab2haD(frame,:) =
diff(filtfilt(b,a,Vel_lab2haD(frame,:)));
                        %




waitbar(frame/eval(['length(Kinematics(DynamicTrial).',Markerset{i},')
']));

                    end
                    close(h);

                    Vel_tr2uabD = diff(filtfilt(b,a,Ang_tr2uabD));
                    Acc_tr2uabD = diff(filtfilt(b,a,Vel_tr2uabD));

                    Vel_uab2labD = diff(filtfilt(b,a,Ang_uab2labD));
                    Acc_uab2labD = diff(filtfilt(b,a,Vel_uab2labD));


                    Vel_lab2haD = diff(filtfilt(b,a,Ang_lab2haD));
                    Acc_lab2haD = diff(filtfilt(b,a,Vel_lab2haD));

                end

                % %Written by Yen-Sheng (Johnny) Lin
                % %                 ver 1: Oct 2012
Based on BioCalc programs written by previous Biolab students
Updated to calculate moments relative to the distal segment of joint

Wrist moments given in hand coordinate system

Elbow moments given in forearm coordinate system
Shoulder moments given in upper arm coordinate system

Forces and moments are still in proximal segment coordinate system
```

```
Wrist forces given in forearm coordinate system

Elbow forces given in upper arm coordinate system

Shoulder forces given in trunk coordinate system

References used in this program:

Hanavan, EP.  A Mathematical Model of the Human Body.  Wright-
Patterson Air Force Base. Pub:AMRL-TR-64-102, 1964.

Winter, DA. Biomechanics and Motor Control of Human Movement, Second
Edition. Wiley-Interscience, New York, 1990.

Cooper RA, Boninger ML, Shimada SD, Lawrence BM. (1999) Glenohumeral
Joint Kinematics and Kinetics for

Three Coordinate System Representations During Wheelchair Propulsion.
Am J Phys Med Rehab. 78(5):435-446.

Wu G, van der Helm FCT, Veeger HEJ, Makhsous M, Van Roy P, Anglin C,

Nagels J, Karduna AR, McQuade K, Wang X, Werner FW, Bucholz B. (2005)
ISB
Recommendation on definitions of joint coordinate systems of various

Joints for the reporting of human joint motion-PartII: shoulder,
elbow,

Wrist, and hand. Journal of Biomechanics. 38: 981-992.

This version will work with the icon marker set (6 digit subject IDs)
and old smartwheel data

Uses trunk markers (instead of hub marker) to compute trunk angle


cd('C:\Users\Johnny\Dropbox\Dissertation\Program\WULACAP\SW');

if (subject < 6 && analyzedtype == 1) || (subject < 10 && analyzedtype
== 2)%% 6 10
                    cd([TrialNM{2}(1:4),'0',TrialNM{2}(5)]);
                else
                    cd(TrialNM{2}(1:6));
                end
                if analyzedtype == 1
                    if subject == 2 || subject == 3
                        FM= load(strcat(TrialNM{2}(1:4),TrialNM{2}(5),
'wwL', num2str(Conditions),
num2str(TrialNM{DynamicTrial}(length(TrialNM{DynamicTrial}))),'06fm.tx
t'));
                    elseif subject < 6 && subject ~= 2 && subject ~= 3
```

```
%% 6 10
                        FM=
load(strcat(TrialNM{2}(1:4),'0',TrialNM{2}(5), 'wL',
num2str(Conditions),
num2str(TrialNM{DynamicTrial}(length(TrialNM{DynamicTrial}))),'06fm.tx
t'));
                    else
                        FM= load(strcat(TrialNM{2}(1:6), 'wL',
num2str(Conditions),
num2str(TrialNM{DynamicTrial}(length(TrialNM{DynamicTrial}))),'06fm.tx
t'));
                    end

                else
                    if subject == 2 || subject == 3
                        FM= load(strcat(TrialNM{2}(1:4),TrialNM{2}(5),
'wwL', num2str(Conditions),
num2str(TrialNM{DynamicTrial}(length(TrialNM{DynamicTrial}))),'06fv.tx
t'));
                    elseif subject < 10 && subject ~= 2 && subject ~=
3  %% 6 10
                        FM=
load(strcat(TrialNM{2}(1:4),'0',TrialNM{2}(5), 'wL',
num2str(Conditions),
num2str(TrialNM{DynamicTrial}(length(TrialNM{DynamicTrial}))),'06fv.tx
t'));
                    else
                        FM= load(strcat(TrialNM{2}(1:6), 'wL',
num2str(Conditions),
num2str(TrialNM{DynamicTrial}(length(TrialNM{DynamicTrial}))),'06fv.tx
t'));
                    end

                end

                if analyzedtype == 1
                    plot(FM(:,7))
                    cd ..; cd ..;

anthro=xlsread('Subject Anthropometrics.xlsx');

                    Anthropometric;
                    if Conditions ==5
                        cd('J:\HERL\Dissertation\WULACAP\Inverse
Dynamics\Figure-8');
                    else
                        cd('J:\HERL\Dissertation\WULACAP\Inverse
Dynamics\Overground on two surfaces');
                    end


                    g=9.81; %gravity m\s^2
```

```
                    dt=1/120; %sampling interval

                    InertiaCOM;

kimrows=min([length(Rg2trD),length(Rg2uabD),length(Rg2labD),length(Rg2
haD)]);
                    kinrows = min([kimrows,round(swrows/2)]);



CalculateVelAcc;

CalculateNetJointFM;

F_shoulder{subject,DynamicTrial} = f_shoulder;

M_shoulder{subject,DynamicTrial} = m_shoulder;

F_elbow{subject,DynamicTrial} = f_elbow;

M_elbow{subject,DynamicTrial} = m_elbow;


F_wrist{subject,DynamicTrial} = f_wrist;

M_wrist{subject,DynamicTrial} = m_wrist;

Ang_shoulder{subject,DynamicTrial} = Ang_tr2uabD;

Ang_elbow{subject,DynamicTrial} = Ang_uab2labD;

Ang_wrist{subject,DynamicTrial} = Ang_lab2haD;

Cycle = 100;

if Conditions ~= 5;

AvgTrialCondition;
else

Figure8InverseDynamics

end


if SteadyStroke > 10 && loadvicondata == 1

PlotJointFM;

end

[TrialNM{DynamicTrial} sprintf('  done!!  ') sprintf('SteadyStroke =
```

```
') num2str(SteadyStroke)]

clear Ang_tr2uabD Ang_uab2labD Ang_lab2haD Rg2trD Rg2uabD Rg2labD
Rg2haD FM SHO_globalD LEP_globalD MEP_globalD RS__globalD UT__globalD
ThirdMP_global f_shoulder m_shoulder f_elbow m_elbow f_wrist m_wrist

else

if subject == 2 || subject == 3
                        FM_encoder=
load(strcat(TrialNM{2}(1:4),TrialNM{2}(5), 'wwL', num2str(Conditions),
num2str(TrialNM{DynamicTrial}(length(TrialNM{DynamicTrial}))),'06fm.tx
t'));
                    elseif subject < 10 && subject ~= 2 && subject ~=
3 %% 6 10
                        FM_encoder=
load(strcat(TrialNM{2}(1:4),'0',TrialNM{2}(5), 'wL',
num2str(Conditions),
num2str(TrialNM{DynamicTrial}(length(TrialNM{DynamicTrial}))),'06fm.tx
t'));
                    else
                        FM_encoder= load(strcat(TrialNM{2}(1:6), 'wL',
num2str(Conditions),
num2str(TrialNM{DynamicTrial}(length(TrialNM{DynamicTrial}))),'06fm.tx
t'));
                    end

                    Cycle = 100;
                    step = FM(:,1);
                    Fz = FM(:,4);
                    FR = FM(:,5);
                    Fr = FM(:,7);
                    %                 Mz = FM(:,10);
                    ror_FR = FM(:,12);
                    ror_Ft = FM(:,13);
                    ror_Fr = FM(:,14);
                    FEF = FM(:,15);
                    Vel = FM(:,16);
                    encoder = FM_encoder(:,8);
                    Mz = FM_encoder(:,6);

                    if Conditions ~=5
                        AvgPushrimVariable;
                    else
                        Figure8Kinetics;
                    end

                    figure(1); plot(step);
                    eval(['title(strcat(TrialNM{2}(1:6),
num2str(Conditions),
num2str(TrialNM{DynamicTrial}(length(TrialNM{DynamicTrial}))));']);
```

```
Figure_8(DynamicTrial,:)=[mean(maxFR);mean(avgFR);mean(maxMz);mean(avg
Mz);mean(maxrorFR);mean(meanfef);mean(avgvel);mean(avgpushangle);mean(
avgfreq);mean(avgpush);mean(avgrecovery);mean(avgpercentpush);mean(max
Fr);mean(avgFr);mean(maxrorFr);mean(maxFz);mean(avgFz);mean(maxrorFt)]
';
                end
                if analyzedtype == 1
                    TrialMeanMaxF_shoulder(Conditions,:) =
mean(MeanMaxF_shoulder);
                    TrialMeanMinF_shoulder(Conditions,:)=
mean(MeanMinF_shoulder);
                    TrialMeanMaxM_shoulder(Conditions,:)=
mean(MeanMaxM_shoulder);
                    TrialMeanMinM_shoulder(Conditions,:)=
mean(MeanMinM_shoulder);

                    TrialMeanMaxFR_shoulder(Conditions,:) =
mean(MeanMaxFR_shoulder);
                    TrialMeanMaxMR_shoulder(Conditions,:)=
mean(MeanMaxMR_shoulder);

                    TrialMeanMaxAng_shoulder(Conditions,:)=
mean(MeanMaxAng_shoulder);
                    TrialMeanMinAng_shoulder(Conditions,:)=
mean(MeanMinAng_shoulder);
                    AllTrialPeakFR(subject,Conditions) =
TrialMeanMaxFR_shoulder(Conditions,:);
                end
            end
            %         if analyzedtype == 1
            clear TrialNM
            %         end


            %% Save data to excel spreed sheet
            if analyzedtype == 1

cd('C:\Users\Johnny\Dropbox\Dissertation\Program\WULACAP\Inverse
Dynamics');
                if Conditions == 5
                    eval(['fid =
fopen(''InverseDynamicVariables_',num2str(Conditions),'1.xls'',''a'');
']);

%% Export Figure-8 beginning Inverse dynamics to Excel Spreed Sheet
                    if subject == 2
                        fprintf(fid,'maxFx_Shoulder \t maxFy_Shoulder
\t maxFz_Shoulder \t maxFR_Shoulder \t minFx_Shoulder\t
minFy_Shoulder\t minFz_Shoulder\t maxMx_Shoulder \t maxMy_Shoulder \t
maxMz_Shoulder \t minMx_Shoulder\t minMy_Shoulder\t minMz_Shoulder\t
maxFlex\t maxABD\t minIR\t maxExten\t minABD\t maxIR\t \n');
```

```
                    end
                    %                 fprintf(fid, '%6.6f\t %6.6f\t
%6.6f\t %6.6f\t %6.6f\t %6.6f\t %6.6f\t %6.6f\t %6.6f\t %6.6f\t
%6.6f\t %6.6f\t', max(F_shoulder{subject,2}),
min(F_shoulder{subject,2}), max(M_shoulder{subject,2}),
min(M_shoulder{subject,2}));
                    fprintf(fid, '%6.6f\t %6.6f\t %6.6f\t %6.6f\t
%6.6f\t %6.6f\t %6.6f\t %6.6f\t %6.6f\t %6.6f\t %6.6f\t %6.6f\t
%6.6f\t %6.6f\t %6.6f\t %6.6f\t %6.6f\t %6.6f\t %6.6f\t',
MeanMaxF_shoulder(2,:), MeanMaxFR_shoulder(2,:),
MeanMinF_shoulder(2,:), MeanMaxM_shoulder(2,:),
MeanMinM_shoulder(2,:), MeanMaxAng_shoulder(2,:),
MeanMinAng_shoulder(2,:));

                    fprintf(fid, '\n');
                    fclose(fid);

                    %% Export Figure-8 ending Inverse dynamics to
Excel Spreed Sheet
                    eval(['fid =
fopen(''InverseDynamicVariables_',num2str(Conditions),'2.xls'',''a'');
']);
                    %
finalout(Conditions,:)=[mean(maxFR);mean(avgFR);mean(maxMz);mean(avgMz
);mean(maxrorFR);mean(meanfef);mean(avgvel);mean(avgpushangle);mean(av
gfreq);mean(avgpush);mean(avgrecovery)];
                    if subject == 2
                        fprintf(fid,'maxFx_Shoulder \t maxFy_Shoulder
\t maxFz_Shoulder \t maxFR_Shoulder \t minFx_Shoulder\t
minFy_Shoulder\t minFz_Shoulder\t maxMx_Shoulder \t maxMy_Shoulder \t
maxMz_Shoulder \t minMx_Shoulder\t minMy_Shoulder\t minMz_Shoulder\t
maxFlex\t maxABD\t minIR\t maxExten\t minABD\t maxIR\t \n');
                    end
                    %                 fprintf(fid, '%6.6f\t %6.6f\t
%6.6f\t %6.6f\t %6.6f\t %6.6f\t %6.6f\t %6.6f\t %6.6f\t %6.6f\t
%6.6f\t %6.6f\t', max(F_shoulder{subject,2}),
min(F_shoulder{subject,2}), max(M_shoulder{subject,2}),
min(M_shoulder{subject,2}));
                    fprintf(fid, '%6.6f\t %6.6f\t %6.6f\t %6.6f\t
%6.6f\t %6.6f\t %6.6f\t %6.6f\t %6.6f\t %6.6f\t %6.6f\t %6.6f\t
%6.6f\t %6.6f\t %6.6f\t %6.6f\t %6.6f\t %6.6f\t %6.6f\t',
MeanMaxF_shoulder(3,:), MeanMaxFR_shoulder(3,:),
MeanMinF_shoulder(3,:), MeanMaxM_shoulder(3,:),
MeanMinM_shoulder(3,:), MeanMaxAng_shoulder(3,:),
MeanMinAng_shoulder(3,:));

                    fprintf(fid, '\n');
                    fclose(fid);
                else
                    eval(['fid =
fopen(''InverseDynamic_',num2str(Conditions),'.xls'',''a'');']);
                    %
```

```
finalout(Conditions,:)=[mean(maxFR);mean(avgFR);mean(maxMz);mean(avgMz
);mean(maxrorFR);mean(meanfef);mean(avgvel);mean(avgpushangle);mean(av
gfreq);mean(avgpush);mean(avgrecovery)];
                    if subject == 2
                        fprintf(fid,'maxFx_Shoulder \t maxFy_Shoulder
\t maxFz_Shoulder \t maxFR_Shoulder \t minFx_Shoulder\t
minFy_Shoulder\t minFz_Shoulder\t maxMx_Shoulder \t maxMy_Shoulder \t
maxMz_Shoulder \t minMx_Shoulder\t minMy_Shoulder\t minMz_Shoulder\t
maxFlex\t maxABD\t minIR\t maxExten\t minABD\t maxIR\t \n');
                    end
                    fprintf(fid, '%6.6f\t %6.6f\t %6.6f\t %6.6f\t
%6.6f\t %6.6f\t %6.6f\t %6.6f\t %6.6f\t %6.6f\t %6.6f\t %6.6f\t
%6.6f\t %6.6f\t %6.6f\t %6.6f\t %6.6f\t %6.6f\t %6.6f\t',
TrialMeanMaxF_shoulder(Conditions,:),
TrialMeanMaxFR_shoulder(Conditions,:),
TrialMeanMinF_shoulder(Conditions,:),
TrialMeanMaxM_shoulder(Conditions,:),
TrialMeanMinM_shoulder(Conditions,:),
TrialMeanMaxAng_shoulder(Conditions,:),
TrialMeanMinAng_shoulder(Conditions,:));

                    fprintf(fid, '\n');
                    fclose(fid);

                end
            else
                cd ..
                cd('SW Results');
                if Conditions ~= 5
                    eval(['fid =
fopen(''PushrimVariables_',num2str(Conditions),'.xls'',''a'');']);
                    %
finalout(Conditions,:)=[mean(maxFR);mean(avgFR);mean(maxMz);mean(avgMz
);mean(maxrorFR);mean(meanfef);mean(avgvel);mean(avgpushangle);mean(av
gfreq);mean(avgpush);mean(avgrecovery)];
                    if subject == 2
                        fprintf(fid,'maxFR \t avgFR \t maxMz \t
avgMz\t maxrorFR\t meanfef\t avgvel\t avgpushangle\t avgfreq\t
avgpush\t avgrecovery\t avgpercentpush\t maxFr\t avgFr\t maxrorFr\t
maxFz\t avgFz\t \n');
                    end
                    fprintf(fid, '%6.6f\t %6.6f\t %6.6f\t %6.6f\t
%6.6f\t %6.6f\t %6.6f\t %6.6f\t %6.6f\t %6.6f\t %6.6f\t %6.6f\t
%6.6f\t %6.6f\t %6.6f\t %6.6f\t %6.6f\t', finalout(Conditions,:));
                    fprintf(fid, '\n');
                    fclose(fid);
                else
                    %% Export Figure-8 beginning kinetics to Excel
Spreed Sheet
                    eval(['fid =
fopen(''PushrimVariables_',num2str(Conditions),'1.xls'',''a'');']);
                    %
```

```
finalout(Conditions,:)=[mean(maxFR);mean(avgFR);mean(maxMz);mean(avgMz
);mean(maxrorFR);mean(meanfef);mean(avgvel);mean(avgpushangle);mean(av
gfreq);mean(avgpush);mean(avgrecovery)];
                    if subject == 2
                        fprintf(fid,'maxFR \t avgFR \t maxMz \t
avgMz\t maxrorFR\t meanfef\t avgvel\t avgpushangle\t avgfreq\t
avgpush\t avgrecovery\t avgpercentpush\t maxFr\t avgFr\t maxrorFr\t
maxFz\t avgFz\t maxrorFt\t \n');
                    end
                    fprintf(fid, '%6.6f\t %6.6f\t %6.6f\t %6.6f\t
%6.6f\t %6.6f\t %6.6f\t %6.6f\t %6.6f\t %6.6f\t %6.6f\t %6.6f\t
%6.6f\t %6.6f\t %6.6f\t %6.6f\t %6.6f\t', Figure_8(1,:));
                    fprintf(fid, '\n');
                    fclose(fid);

                    %% Export Figure-8 ending kinetics to Excel Spreed
Sheet
                    eval(['fid =
fopen(''PushrimVariables_',num2str(Conditions),'2.xls'',''a'');']);
                    %
finalout(Conditions,:)=[mean(maxFR);mean(avgFR);mean(maxMz);mean(avgMz
);mean(maxrorFR);mean(meanfef);mean(avgvel);mean(avgpushangle);mean(av
gfreq);mean(avgpush);mean(avgrecovery)];
                    if subject == 2
                        fprintf(fid,'maxFR \t avgFR \t maxMz \t
avgMz\t maxrorFR\t meanfef\t avgvel\t avgpushangle\t avgfreq\t
avgpush\t avgrecovery\t avgpercentpush\t maxFr\t avgFr\t maxrorFr\t
maxFz\t avgFz\t maxrorFt\t \n');
                    end
                    fprintf(fid, '%6.6f\t %6.6f\t %6.6f\t %6.6f\t
%6.6f\t %6.6f\t %6.6f\t %6.6f\t %6.6f\t %6.6f\t %6.6f\t %6.6f\t
%6.6f\t %6.6f\t %6.6f\t %6.6f\t %6.6f\t', Figure_8(2,:));
                    fprintf(fid, '\n');
                    fclose(fid);
                end

            end
            cd ('J:\HERL\Dissertation\WULACAP\Inverse Dynamics');
            eval(['save
InverseDynamics_WULA',num2str(subject),'_',num2str(Conditions),'']);
        else
            cd ('J:\HERL\Dissertation\WULACAP\Inverse Dynamics');
            eval(['load
InverseDynamics_WULA',num2str(subject),'_',num2str(Conditions),'']);
        end
    end
    if analyzedtype == 1
    AllMeanMaxF_shoulder(subject,:) = mean(MeanMaxF_shoulder);
    AllMeanMinF_shoulder(subject,:) = mean(MeanMinF_shoulder);
    AllMeanMaxM_shoulder(subject,:) = mean(MeanMaxM_shoulder);
    AllMeanMinM_shoulder(subject,:) = mean(MeanMinM_shoulder);
    AllMeanMaxAng_shoulder(subject,:) = mean(MeanMaxAng_shoulder);
```

```
    AllMeanMinAng_shoulder(subject,:) = mean(MeanMinAng_shoulder);

    AllTrialMeanMaxF_shoulder(:,:,subject) = TrialMeanMaxF_shoulder;
    AllTrialMeanMinF_shoulder(:,:,subject) = TrialMeanMinF_shoulder;
    AllTrialMeanMaxM_shoulder(:,:,subject) = TrialMeanMaxM_shoulder;
    AllTrialMeanMinM_shoulder(:,:,subject) = TrialMeanMinM_shoulder;
    AllTrialMeanMaxAng_shoulder(:,:,subject) =
TrialMeanMaxAng_shoulder;
    AllTrialMeanMinAng_shoulder(:,:,subject) =
TrialMeanMinAng_shoulder;
    end
end
cd('C:\Users\Johnny\Dropbox\Dissertation\Dissertation
Results\WULACAP');
if analyzedtype == 1
save InverseDynamics AllTrialPeakFR AllMeanMaxF_shoulder
AllMeanMinF_shoulder AllMeanMaxM_shoulder AllMeanMinM_shoulder
AllMeanMaxAng_shoulder AllMeanMinAng_shoulder
AllTrialMeanMaxF_shoulder AllTrialMeanMinF_shoulder
AllTrialMeanMaxM_shoulder AllTrialMeanMinM_shoulder
AllTrialMeanMaxAng_shoulder AllTrialMeanMinAng_shoulder
save AllSubjectJointFM F_shoulder_cycle M_shoulder_cycle F_elbow_cycle
M_elbow_cycle F_wrist_cycle F_wrist_cycle Ang_shoulder_cycle
Ang_elbow_cycle Ang_wrist_cycle
end

for Conditions = 1:4
    if Conditions ~= 5 && analyzedtype == 1
        PlotAllSubjectJointFM;
    elseif analyzedtype == 1
        for DynamicTrial = 2:3
            PlotAllSubjectJointFM
        end
    end
end
```

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