Radiographic Examination of Humeral Head Migration after Fatiguing the Rotator Cuff

by

Jaclyn N. Chopp

A thesis
presented to the University of Waterloo
in fulfillment of the
thesis requirement for the degree of
Master of Science
in
Kinesiology

Waterloo, Ontario, Canada, 2009

Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

Undesirable work factors, such as awkward upper body postures and repetitive arm motion, in the workplace can lead to upper extremity pain. Research suggests that these work-related factors, and subsequent rotator cuff fatigue, may cause the subacromial space (the space between the inferior acromion surface and superior humerus) of the shoulder to decrease. Reducing this space can create impingement of the interposed tissues, which causes shoulder pain. The aim of this study was to examine superior humeral head excursion and changes in the width of the subacromial space (acromio-humeral interval) after fatiguing the rotator cuff musculature. Four anterior-posterior radiographs of the glenohumeral joint at arm abduction angles of 0˚, 45˚, 90˚ and 135˚ were taken before and after a fatiguing task. The fatiguing task was a simulated job task requiring shoulder flexion/abduction and internal/external rotation, with the intention of exhausting the entire rotator cuff. The position of the humeral head with respect to the glenoid cavity was significantly affected both by arm angle and fatigue state; the mean humeral superior excursion following fatigue was 0.63±1.76mm. In the pre-fatigued state, increasing arm angle was related to superior translation until 90˚, after which the humeral head moved inferiorly to a more central position. In the post-fatigued state, the inability of the rotator cuff to centralize the humeral head led to increasing translations with higher elevations. Although the magnitude of translation in this study was smaller than seen in patients with rotator cuff tears, continuous overhead work demonstrably created rotator cuff fatigue, which apparently inhibited the ability of the shoulder musculature to resist upward translation of the humerus. Therefore, jobs that require overhead and repetitive work arguably put the worker at greater risk for superior translation of the humerus and subsequent related tissue damage.

Acknowledgements

I would like to thank my advisor, Dr. Clark Dickerson, for his assistance and guidance throughout this research and for mentoring me over the past three years.

I would like to thank my committee members, Drs. Jack Callaghan and Richard Wells, for their helpful suggestions regarding this research.

I would like to thank Dr. John O'Neill, Glenn Madill and the staff at St. Joseph's hospital for their assistance and patience throughout my data collection and analysis.

I would like to thank my lab and officemates for all of their assistance and making my time as a graduate student more enjoyable.

I would like to thank Kevin Hurley, for all of his assistance during my data collection and for his unwavering support throughout my graduate program.

Finally, I would like to thank my parents, Phil and Sally, and brother, Philip, for their continued assistance, love and support.

Dedication

To my parents, Phil and Sally,

For their guidance, encouragement and support in everything that I do.

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I. Introduction

Many factors influence whether or not shoulder injuries occur. They can be work or task related, or genetic. Undesirable arm postures, frequent and/or strenuous arm motion, abnormal shoulder geometry or mechanics, and previous injury all have been implicated in the development of shoulder discomfort and injury. However, the relationship between all of these factors and injury is not firmly established. This research aims to experimentally examine the relationship between work factors and injury risk for one specific shoulder injury: subacromial impingement.

1.1 Industrial Relevance of the Research

Workplace factors strongly influence the prevalence of musculoskeletal pain and discomfort in industry. The extent of work-related upper extremity pain, specifically in the shoulder, is evident based on injury statistics outlined by the Workplace Safety and Insurance Board (WSIB) of Ontario. In 2008, 6.9% of all lost time claims reported were due to pain in the shoulder (WSIB 2008). Almost half of these total claims were due to “bodily reaction and exertion” which includes repetitive motion and static postures; thus a large proportion of industrial injuries are not due to acute trauma, but rather due to cumulative injuries resulting from awkward postures and repetitive upper body motion. Further, over a 10-year span, this percentage of shoulder injuries has increased from 5.8%; thus not only is this problem consistent, but it is growing (WSIB 2008).

1.2 Relationship between Rotator Cuff Injuries and Subacromial Impingement

A two-way relationship exists between rotator cuff tears and subacromial impingement. Radiographic evaluation of workers or patients with rotator cuff tears has indicated significant reductions in the area between the acromion and the humerus (subacromial space or acromio-humeral interval). Further, healthy individuals who have encountered an event that reduces this space may suffer a rotator cuff tear due to the compression of their tendons within this limited space. Michener et al. (2003) stated that it is uncertain whether the muscle weakness and injury causes subacromial impingement, or instead whether the reduced space and subsequent impingement causes muscle injury. Although the latter has been well documented (Golding 1962; Weiner and MacNab 1970), the mechanism or event that reduces this space, in the absence of previous tears, is unclear.

The interaction between work factors and shoulder muscle fatigue has been linked to physical changes in shoulder mechanics. Cumulative working factors, such as awkward postures and/or repetitive work are associated with worker reported pain and discomfort (Bernard 1997). Further, research has shown that this work-discomfort relationship is associated with muscle fatigue development (Wiker et al. 1989). Minimal research attempts exist that have tried to determine injury mechanisms associated with muscle fatigue (Nussbaum et al. 2001). However, studies have suggested that rotator cuff fatigue may emulate the effects of a rotator cuff tear. This implies that similar altered mechanics and subsequent injury are anticipated (Chen et al. 1999). Determining the relationship between work factors, fatigue and changes in the subacromial space may offer insight into potential injury mechanisms, thereby establishing a specific mechanism that causes subacromial impingement and likely a rotator cuff injury.

1.3 Purpose

The aim of this research was to quantify the magnitudes of both humeral head excursion and the width of the subacromial space [hereafter referred to as the acromio-humeral interval (AHI)] following a simulated job task designed to fatigue the rotator cuff. There were three primary objectives of this study:

(1) To determine whether superior humeral head excursion with respect to the center of the glenoid cavity occurred following muscle fatigue.

(2) To determine whether the magnitude of change in humeral head excursion and AHI width approximated values observed in patients with rotator cuff tears of defined severity.

(3) To determine the consequences of increasing arm abduction angle on the magnitude of humeral head excursion.

Defining the relationship between shoulder fatigue produced by work-related tasks and a known mechanism for pain (decreased acromio-humeral interval) may provide a mechanical basis for effective ergonomic interventions and rehabilitation strategies.

A secondary methodological aim of this study was to establish a standardized method and set of measurement instructions for quantifying humeral head excursion and changes to acromio-humeral interval width. This explicit approach, which has its basis in techniques outlined by Poppen and Walker (1976) should prevent misinterpretation and provide further clarification, in order to eliminate future measurement discrepancies that may have existed in earlier work.

1.4 Hypotheses

Specific hypotheses for this research are that:

(1) **The humeral head center will migrate superiorly with respect to the center of the glenoid cavity following an exertion designed to create rotator cuff fatigue.**

This upward translation will be due to the inability of the rotator cuff muscles to resist the upward direction of the deltoid vector (Weiner and MacNab 1970).

(2) **Following the fatiguing protocol, humeral head migration magnitudes will be similar to values reported for patients with full thickness rotator cuff tears** (Bezer et al. 2005). **AHI width, pre- and post- fatigue, should resemble those determined from healthy participants and those with rotator cuff tears, respectively** (Golding 1962).

The fatiguing protocol is a task designed to exhaust the entire rotator cuff. As a result, following the protocol, these muscles will no longer be able to compress the humeral head in the glenoid cavity and resist the upward pull from surrounding muscles, particularly the deltoid. Excursion magnitude should be greater than those found in shoulders with single muscle tears, as well as studies that have selectively fatigued specific muscles of the rotator cuff (i.e. Chen et al. 1999);. It is established that the entire rotator cuff contributes to stabilizing the humeral head within the glenoid (Bezer et al. 2005). This upward excursion will cause an associated decrease in the acromio-humeral interval.

(3) **The direction of excursion in the pre-fatigued state should be superior until an arm abduction angle of 90˚ is achieved; at this point excursion will occur inferiorly to a more central position** (Graichen et al. 2000)**. In the post-fatigued state, the humeral head should continue to migrate superiorly throughout the abduction range tested.**

Graichen et al. (2000) found that in the healthy shoulder where the muscles are actively abducting the arm, for the first 90˚ of abduction, the upwardly directed force vector of the deltoid should cause the head of the humerus to migrate upwards. At arm angles, above 90˚, the rotator cuff muscles are far more active in providing a stabilizing or centralizing effect than the deltoid's upward force, which causes the head of the humerus to migrate inferiorly to a more centralized position with respect to the glenoid cavity. Therefore, if the rotator cuff muscles are injured or fatigued, they will not be able to provide this centralizing effect and the humeral head will continue to migrate superiorly.

II. Literature Review

2.1 Association between Cumulative Workplace Physical Exposures and UEMSDs

Research has shown that many work factors can lead to upper extremity discomfort and disorders. Among these factors, awkward postures and repetitive motions are more likely to cause unnoticed degenerative changes or non-specific shoulder pain (Bernard 1997).

Prolonged work in awkward postures, including overhead work, has been associated with a spectrum of upper extremity disorders (Bjelle et al. 1979; Grieve and Dickerson, 2008; Miranda et al. 2005; Rosecrance et al. 1996; Svendsen et al. 2004). Specifically, working at shoulder flexion or abduction angles over 90°, for over 10% of the job cycle is strongly associated with the development of shoulder pain and disorders (Punnett et al. 2000). Past research has examined a variety of biomechanical measures and quantified the implications of elevated arm angles. Research has shown that a strong relationship exists between increasing overhead working heights and shoulder muscle activity (Anton et al. 2001; Chopp et al. 2009b; Herberts et al. 1984; Nussbaum 2001; Sporrong et al. 1998; Sood et al. 2007). Anton et al. (2001) examined an overhead drilling task and found that anterior deltoid and biceps brachii activity, as well as shoulder torque, significantly increased with a further reaching distance. More recently Sood et al. (2007) examined muscle activity levels at three overhead working heights and found anterior and middle deltoid activity to increase from 22.1 to 27.0%MVC and 16.1 to 24.4%MVC respectively, when examined at low and high working heights. In addition to increased muscular loading, research has shown that workers are more strength-limited in overhead locations and particularly so for lateral forces (Haslegrave et al. 1997). Further, studies examining subject perception of discomfort indicated increasing rates of pain and discomfort when working overhead (Garg et al. 2006; Nussbaum et al. 2001; Sood et al. 2007; Wiker et al. 1990).

Although much research has focussed on the association between awkward postures and pain, other work factors have links to increases in upper extremity discomfort. Repetitive and frequent internal and external rotation have been found to be a strong predictor (Odds Ratio [OR] = 9.3) of workplace musculoskeletal disorders (Hughes et al. 1997). A study by LeClerc et al. (2004) examined the incidence of shoulder pain across several working factors. The results from a logistic regression model determined that having the arm frequently above shoulder height (OR = 1.84) and repetitive tool use (OR = 4.34) are among the factors that were high predictors of developing shoulder pain. Further studies examined the relationship between repetitive work and upper extremity pain and discomfort and found repetitive work to be a high predictor of pain (Andersen et al. 2003; Frost et al. 2002; Kilbom 1994; Latko et al. 1999; van der Windt et al. 2000).

2.2 Association of Fatigue with the Work Factor-Pain Relationship

The work-pain relationship is well established in the literature, and consistently, muscular fatigue is an associated factor. Research indicates that overhead and/or repetitive work has a strong association with muscle fatigue (Ebaugh et al. 2006; Iridiastadi and Nussbaum 2006; Garg et al. 2002; Hagberg 1981; Oberg et al. 1994; Nussbaum et al. 2001; Roman-Liu et al. 2005; Sood et al. 2007; Wiker et al. 1989). Different parameters have been examined to evaluate this relationship. Altered muscle activity patterns and subject discomfort ratings are among those measures most often used to evaluate muscle fatigue.

2.2.1 EMG Signal

Electromyographic (EMG) signal frequency and amplitude change with muscle fatigue. As a muscle starts to fatigue there is a shift toward lower frequencies and an increase in signal amplitude (Winter 2005). Studies have examined these signal changes by monitoring muscle activity patterns in the frequency and time domains as they fatigue.

Mean and/or Median Power Frequency (MnPF/MdPF) are commonly used as muscle fatigue indicators. Muscle activity is collected via EMG and MnPF and MdPF are obtained from a Fourier Transform performed on the raw EMG signal. As a muscle fatigues these parameters (MnPF and MdPF) will decrease. Komi and Tesch (1979) examined change in the power spectral density function of vastus lateralis before and after a dynamic fatiguing protocol. This study confirmed that a decrease in MnPF is associated with the onset of fatigue. Since this study, many others have confirmed the relationship between lower frequency shifts and fatigue (Dowling 1997; Ebaugh et al. 2006; Potvin 1997). Thus, these studies provided confidence in using MnPF or MdPF as an indication of fatigue.

Although fatigue analysis typically occurs in the frequency domain, there are changes in EMG amplitude in the time domain that also result from muscle fatigue. Hagberg (1981) examined electromyographic changes of upper extremity muscles associated with repetitive arm elevations. There was a significant amplitude increase in trapezius muscle activity during work tasks. After completing the task, subjects reported discomfort to the lower part of the trapezius; this indicated that the muscle was fatigued during the task. Potvin (1997) used surface electromyography to monitor the biceps brachii during repetitive elbow flexion and extension. Subjects were instructed to perform these movements until they were no longer able, or experienced muscle discomfort. There was a significant increase in EMG amplitude after the fatiguing task ($p<0.01$). The average increases of the concentric and eccentric phase of elbow flexion/extension after the biceps brachii was fatigued were 34.6% MVC and 10.5% MVC respectively. This research confirmed early findings that an increase in EMG amplitude indicates muscle fatigue (Viitasalo and Komi 1977).

2.2.2 Perceived Discomfort Scores

Even in the absence of an identifiable mechanical injury, psychophysical research has indicated reports of pain or discomfort when repetitive or awkward working tasks are performed to fatigue. Most studies evaluating fatigue also include subjective ratings of perceived exertion using a standardized scale (Borg 1982). Wiker et al. (1989) evaluated discomfort ratings during different tasks and found that participants reported more postural discomfort when the arms were working overhead. Similarly, increased ratings of pain and discomfort have been present in repetitive working tasks. The findings of Latko et al. (1999) indicated that workers with highly repetitive jobs are at a 2-3 times greater risk of developing upper extremity discomfort than those with low repetitive jobs.

2.2.3 Other Measures

Muscle fatigue has been associated with changes in other measures. Nussbaum et al. (2001) examined endurance times during an overhead assembly task, while also monitoring psychophysical perception and decreases in force capability. They found that subjects fatigued much faster and were less able to complete the task when the work to rest duty cycle was large. Garg et al. (2002) also examined endurance time and found that as endurance time increased, so did subjective ratings of fatigue and pain. Another measure associated with muscle fatigue is decreased force capability (Roman-Liu, 2005). Komi and Tesch (1979) evaluated power spectral density changes during fatigue as well as maximum torque. Results indicated that declines in maximum torque capacity corresponded to decreases in MnPF.

2.2.4 Correlation Between Psychophysical and Muscle Activity Patterns

Psychophysical analyses have been able to predict physical exposures with some accuracy. In experimental situations when collecting muscle activity is not possible, researchers document subject perception as a means of indicating fatigue onset. Hagberg (1981) evaluated heart rate (HR), rating of perceived exertion (RPE) and muscle activity from three muscles of the upper limb during repetitive shoulder flexion (0-90˚). They identified a significant relationship ($p<0.05$) between the slope coefficients of a linear regression of RPE-HR and the logarithmic regressions of time constants of EMG amplitude increase. This implicates muscle fatigue as a potential factor leading to increased ratings of perceived exertion. A study by Oberg et al. (1994) specifically examined the relationship between electromyographic indications of fatigue (MnPF) and subjects' rating of discomfort on Borg's Category Ratio Scale (Borg 1982). They confirmed previous results, finding a statistically significant relationship ($p<0.001$) between MnPF decreases and increasing ratings of discomfort ($r=-0.46$). Further research has been performed to examine the correlation between perception and physical measures of fatigue and have found moderate to strong relationships; specifically, correlation coefficients ranging from $r=-0.42$ to -0.9 with MnPF, $r=-0.42$ to -0.50 with MdPF and $r=-0.68$ with endurance time (Dedering et al. 1999; Hummel et al. 2005).

2.3 Humeral Head Stabilization: The Role of Shoulder Musculature

Some controversy exists as to the role of the rotator cuff in the shoulder during movement (such as abduction). While a primary suggested role of the rotator cuff is stabilization of the glenohumeral joint, divergent opinions state that only some muscles of the rotator cuff act as stabilizers; whereas others assist with movement. Further, contrasting opinions exist on whether or not the rotator cuff actively assists the deltoid throughout the range of arm abduction.

2.3.1 Basic Shoulder Anatomy

The shoulder includes articulations of three bones: the scapula, humerus and clavicle. The glenohumeral joint is the articulation between the humeral head and the glenoid cavity of the scapula. There are many active and passive structures to help stabilize this joint throughout its range of motion, including the rotator cuff. The rotator cuff consists of four intrinsic muscles: the supraspinatus, infraspinatus, subscapularis and teres minor (Figure 1). These muscles act in concert with other scapulohumeral muscles (deltoid, teres major) to abduct and rotate the arm as well as stabilize the joint (Moore and Dalley 2006).

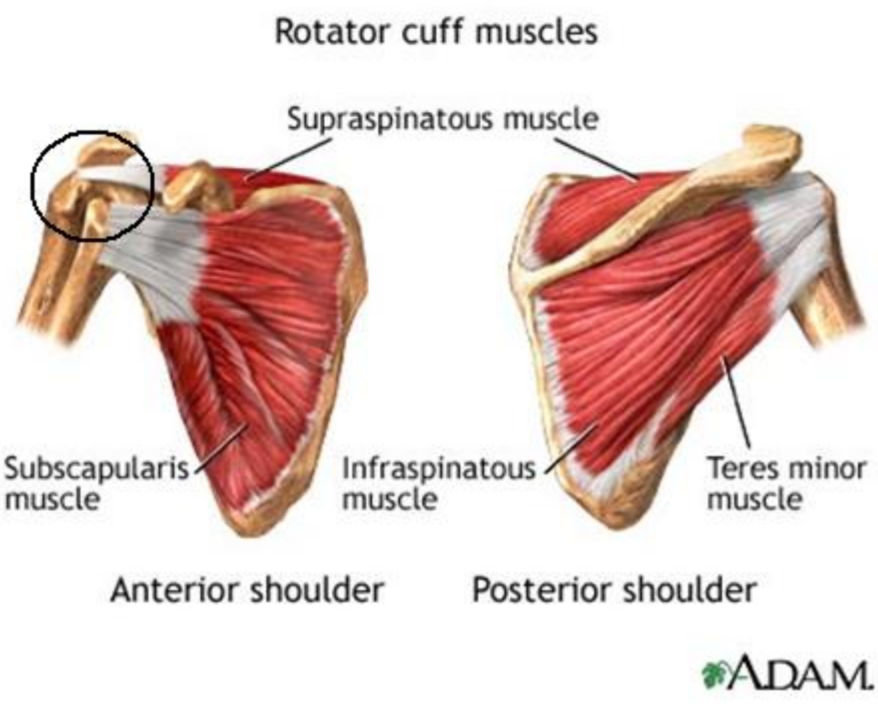

Figure 1. Anterior (Left) and Posterior (Right) view of the rotator cuff musculature. Subacromial space has been circled on anterior view (Medline Plus Medical Encyclopedia).

2.3.2 Stabilization

Numerous studies have demonstrated the stabilizing role of the rotator cuff. Additionally, many investigators have attempted to evaluate the divergent roles of the rotator cuff during abduction. Inman et al. (1944) examined shoulder function throughout abduction and stated that the supraspinatus and deltoid act together to abduct the arm throughout the range of motion. Additionally, the infraspinatus, subscapularis and teres minor were classified separately from these abductors as humeral depressors. De Luca and Forrest (1973) later confirmed this finding, identifying the supraspinatus and the middle fibres of the deltoid as the main abductors, while identifying the infraspinatus, subscapularis and teres minor as humeral stabilizers. Further studies have examined shoulder muscular function through the abduction range of motion. Yanagawa et al. (2008) provided further explanation of the stabilizing role of the rotator cuff by examining muscle lines of action. The rotator cuff muscles, specifically the supraspinatus, infraspinatus and subscapularis, were identified as perfectly positioned to apply a stabilizing compressive load directed into the central glenoid cavity.

2.3.3 Abduction

Studies examining muscle function in the shoulder with various muscle tears have provided an argument against the supraspinatus being the only rotator cuff muscle to provide active assistance to the deltoid during abduction. Staples and Watkins (1943) initiated this argument by examining two case studies in which deltoid function was absent. They found that true abduction and a good range of motion were still present, although slightly weaker, without the assistance of the deltoid; thus many muscles, including the rotator cuff, are able to contribute to abduction. Sharkey et al. (1994) examined changes in deltoid tension at different angles of abduction and the contributions of individual muscles of the rotator cuff. They determined that contraction of the whole rotator cuff contributed to abducting the arm and subsequently that the deltoid force required for abduction was significantly less ($p<0.0001$) when there was concurrent contraction of the rotator cuff (100±30N compared to 20±21N). Additionally, they found that the magnitude of force produced by the supraspinatus contributing to abduction was similar to the net force produced by the infraspinatus, subscapularis and teres minor. Otis et al. (1994) also demonstrated that the supraspinatus and deltoid are not exclusively responsible for abduction, but that the infraspinatus and subscapularis contribute to abduction in the scapular plane.

2.4 Subacromial Impingement and Subsequent Pain and/or Discomfort

2.4.1 Subacromial Impingement

The subacromial space of the shoulder is located between the humerus and acromion. It is often referred to as the acromio-humeral interval (AHI) (Weiner and MacNab 1970). Specifically, the upper border of the space consists of the acromion, coracoid process and the coracoacromial ligament, while the lower border consists of the superior aspect and greater tuberosity of the humerus. Within this area, there are tissues such as the supraspinatus tendon of the rotator cuff, the biceps tendon and the bursa, which are all at potential risk for injury (Bigliani and Levine 1997). Subacromial impingement occurs when this volume is decreased through acute or cumulative trauma. When this occurs, the interposed tissues become compressed or impinged, which may lead to inflammation or rupture (Bey et al. 2007; Calis et al. 2000; Flatow et al. 1994; McFarland et al. 1999).

2.4.2 Mechanism of Impingement

Superior migration of the humeral head decreases the subacromial space, which can cause impingement. The line of action of the deltoid vector is such that it pulls proximally along the long axis of the humerus. During abduction, if the rotator cuff muscles are unable to maintain compression of the humeral head in the glenoid cavity, the humeral head may be translated superiorly (Weiner and MacNab 1970). Deutsch et al. (1996) stated that the deltoid is not effective at the initiation of abduction, despite being active and thus with the superiorly oriented force vector of the deltoid, it tends to produce superior displacement of the humerus with respect to the glenoid. However, a functioning rotator cuff resists this potential translation.

2.5 Previous Radiographic Measurements of Humeral Head Translation

2.5.1 Evaluation of the Healthy Shoulder

Several researchers have attempted using medical imaging techniques to evaluate changes in the Acromio-humeral interval (AHI) in healthy shoulders during abduction. Golding (1962) performed a radiographic analysis on 150 healthy shoulders in a resting posture (0˚ flexion/abduction) and found the typical AHI was approximately 7-13 millimeters. Cotton and Rideout (1964) later confirmed this range, stating that subjects with no evidence of radiological abnormality had an AHI of approximately 6-14 millimeters. Graichen et al. (1999b) also examined the average width of the AHI, at different angles of arm abduction. Measurements were 4.7±2.4mm, 4.1±2.5mm and 4.8±2.0mm for 60˚, 90˚ and 120˚ of abduction, respectively.

In reports of radiographic examination of the shoulder, differences in measurement techniques and imaging equipment exist. As opposed to measuring AHI, research that is more recent has examined humeral head migration with respect to the glenoid cavity. AHI width can be decreased due to: (1) increased size of the interposed tissues, (2) size and shape of the glenohumeral joint structures (i.e. acromial morphology) and/or (3) lack of dynamic stabilization (Deutsch et al. 1996). As more recent research aimed to examine normal and abnormal motion of the glenohumeral joint and it's affect on the AHI width, the measurement of humeral head migration to evaluate dynamic stabilization has been far more prominent in the literature than simple AHI measurements (which may be solely due to individual geometry) (Chen et al. 1999; Cote et al. 2009; Deutsch et al. 1996; Paletta et al. 1997; Poppen and Walker 1976; Teyhen et al. 2008). For the purpose of this discussion, neutral or 0mm excursion exists when the center of the humeral head is aligned with the center of the glenoid cavity (defined by the midpoint of its limits). Excursions greater than 0mm indicate superior translation of the humeral head with respect to the geometric center of the glenoid cavity; negative excursions indicate inferior translation (Figure 2). Graichen et al. (2000) examined humeral head translation during active and passive abduction (30-150˚) using an MR scanner. Initially, at 30˚ of passive elevation, when muscles were relaxed, the humeral head was positioned approximately 1.58±1.2mm with respect to the glenoid cavity; as the arm was abducted to 150˚, the position continuously decreased to approximately 0.36±1.6mm. During active abduction, the humeral head was initially migrated superiorly, but to a lesser magnitude than under muscle relaxation (passive) (1.0±1.3mm), but decreased to a more central position at 120˚ of abduction. This indicated that the dominance of the superiorly orientated deltoid vector is only present at initial stages of abduction, after which the humeral head returns to a more central position. A study by Nishinaka et al. (2008) measured this translation in vivo during active abduction (0-150˚) using a fluoroscope. Throughout the range of abduction (20° to 150°) the humerus progressively moved superiorly approximately to finish 1.7mm superior to the glenoid center. A study by Beaulieu et al. (1999) determined that a humeral deviation of less than 3mm over the full abducting range of motion represented a 'precisely centered' position in the glenoid fossa. From these conflicting reports, it is apparent that the movement of the humeral head throughout the range of abduction is not well established.

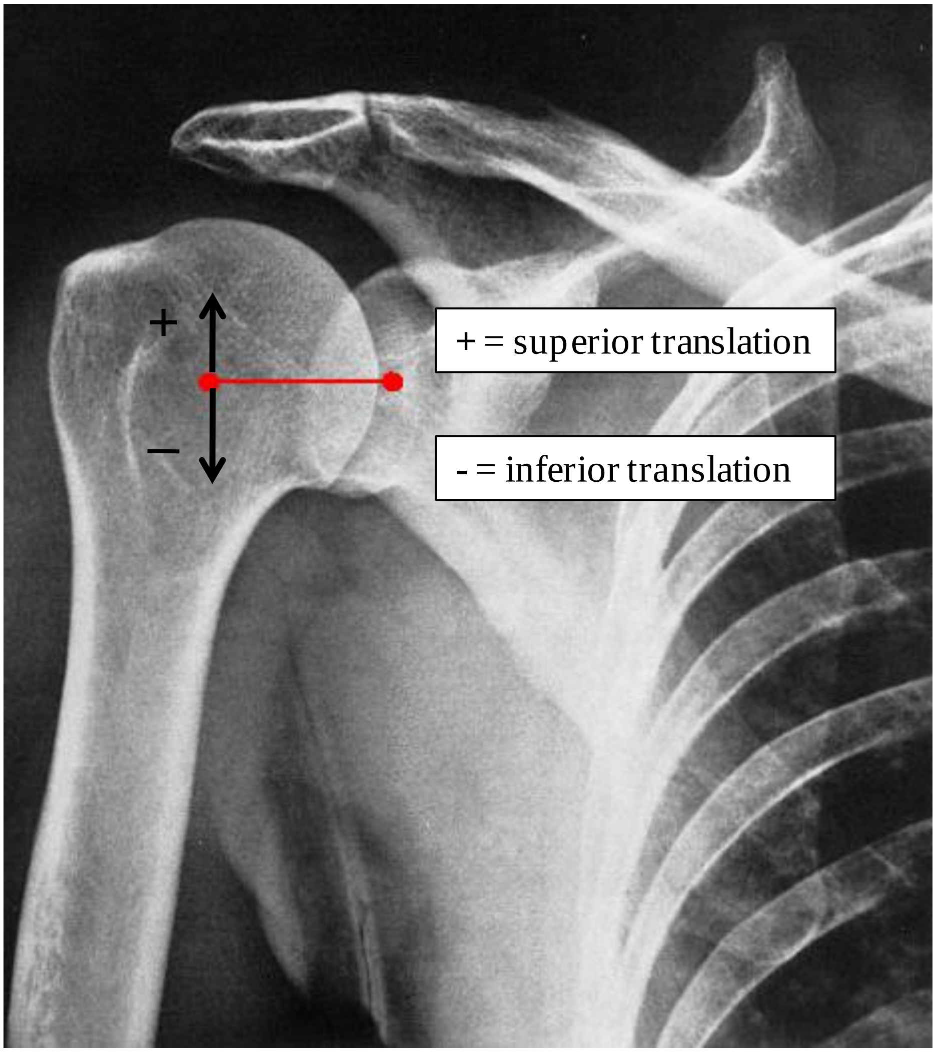

Figure 2. Right anterior-posterior radiograph of the glenohumeral joint (SUNY Downstate Medical Center). Circles represent the centers of the humeral head and the glenoid cavity. Superior (+) and Inferior (-) translation is identified by upward and downward shift of the center of the humeral head with respect to the center of the glenoid cavity.

2.5.2 Evaluation of the Unhealthy Shoulder: Specifically Rotator Cuff Tears

Due to the stabilizing role of the rotator cuff, studies have examined whether a rotator cuff injury influences the magnitude of humeral head migration with postural changes. Weiner and MacNab (1970) were among the first to examine the influence of rotator cuff tears on AHI magnitudes. The AHI measured for healthy subjects was between 7 to 14mm, consistent with past research (Golding 1962; Cotton and Rideout 1964). Conversely, 44% of subjects with surgically proven rotator cuff tears displayed AHI of 5±3.9mm or less, which in combination demonstrate that rotator cuff tears relate to decreased subacromial space. Poppen and Walker (1976) introduced a method of measuring humeral head excursion on radiographs that is still widely accepted today. They examined excursion over seven different abduction angles (0˚, 30˚, 60˚, 90˚, 120˚, 150˚ and maximal) in asymptomatic patients and patients with unstable, torn and/or painful shoulders. The average excursion of the humeral head in asymptomatic patients was 1.09±0.475mm, with most of the movement occurring between 0 to 60˚ of abduction. There was more than double the amount of excursion present for subjects with symptomatic shoulders (2.76±0.88mm).

Further research has compared asymptomatic shoulders with those having a range of injury severity. A study by Deutsch et al. (1996) compared healthy shoulders with those in stages II and III of impingement. They found a significant excursion (1.2mm) in stage II impingement compared to healthy (0.7mm). They also discovered that unlike healthy and less severe impingements, stage III impingements (which include full-thickness rotator cuff tears) had an initial humeral head position superior to the glenoid, with a sharp rise of 1.0mm during the first 20˚ of abduction. Consistent with past research, the average excursion in the two symptomatic groups was significantly more superior than the excursion in the healthy group ($p<0.05$). A subsequent study by the same research team examined healthy patients with those with unstable shoulders and those with rotator cuff tears, both before and after surgery (Paletta et al. 1997). In the healthy shoulder, the humeral head remained at or below the center of the glenoid cavity over all angles of abduction. Before surgery both unstable (39%) and rotator cuff torn (100%) shoulders displayed superior displacement; however after surgical intervention, 100% of previously unstable shoulders remained at or below the center of the glenoid and 86% of shoulders with previous tears exhibited similar displacement decreases. A more recent study evaluated the severity and location of rotator cuff tears and their effect on the magnitude of superior displacement (Bezer et al. 2005). They examined three groups: (1) isolated supraspinatus tears, (2) both supraspinatus and infraspinatus tears, and (3) all of supraspinatus, infraspinatus and subscapularis tears. Although groups 1 (1.4±1.2mm) and 2 (2.0±1.7mm) were not significantly different, the addition of a subscapularis tear (group 3) resulted in significantly higher excursion (4.5±0.5mm). A comparison of the average injured shoulder to uninjured showed that, overall, the humeral head position in injured shoulders was substantially more superiorly located with respect to the center of the glenoid cavity than in uninjured shoulders. Keener et al. (2009) examined the effects of humeral head migration as a function of rotator cuff tear size and location, in both symptomatic and asymptomatic rotator cuff patients. They found that the position of the humeral head with respect to the center of the glenoid cavity in symptomatic patients was migrated more superiorly (0.26±1.6mm) compared to asymptomatic patients (-0.28±1.3mm). Further, superior humeral head migration correlated with rotator cuff tear size. The mean position of the humeral head for patients with supraspinatus tears alone was -0.09±1.5mm, whereas for patients with infraspinatus or infraspinatus and supraspinatus tears, it was 1.01±1.5mm. Thus, it was concluded that tears involving the infraspinatus had more superior humeral head translation than those only isolated to the supraspinatus. Based on this subset of studies, it is evident that the rotator cuff plays a vital role in preventing superior excursion of the humeral head in the glenoid cavity.

2.5.3 Experimentally Disabling the Rotator Cuff

There has been limited research regarding the effect of disabling the rotator cuff on humeral head excursion. Increased superior migration with rotator cuff tears is well documented, as discussed. However, the effect of disrupting the function or fatiguing the rotator cuff has not been thoroughly examined.

Studies have synthesized rotator cuff deficiency by progressive detachment, suprascapular nerve blocks, and 3D modelling of the shoulder in order to examine humeral head translation. Through these methods, muscles of the rotator cuff are rendered completely inactive. Mura et al. (2003) examined abduction torque and superior migration of the humeral head after retracting the supraspinatus and progressively detaching the infraspinatus (by fifths) on a cadaveric shoulder. Tendons were detached using nylon strings sutured to the tendons of the rotator cuff muscles. Although incremental superior translation was present with progressive detachment, a significant change in humeral head position ($p<0.05$) was only present after complete detachment of the infraspinatus and supraspinatus tendons, indicating that both muscles are likely involved in humeral head stabilization. Studies have examined the effect of rotator cuff paralysis via suprascapular nerve block on humeral head translation. In a study by Werner et al. (2006), it was expected that the active rotator cuff musculature prevents translation; thus by deactivating supraspinatus and infraspinatus, large superior translation should be present. Their hypothesis was rejected, as completely disabling supraspinatus and infraspinatus showed no significant translation. Thus, an alternative mechanism inhibiting this migration may be present. Terrier et al. (2007) developed a 3D shoulder model to predict this translation, both in the presence and absence of supraspinatus. Superior migration was seen in both cases, though it was 1.6 times higher with simulated supraspinatus deficiency.

Another approach to examining humeral head translation is by selectively fatiguing different muscles of the rotator cuff. By completing a fatiguing protocol, the muscles are not completely deactivated, but are significantly limited in assisting with shoulder movement. Chen et al. (1999) was the first to examine the effects of fatigue. They examined translation at four abduction angles (0˚, 45˚, 90˚ and 135˚) using radiographs, both before and after a fatiguing protocol. Their protocol aimed to fatigue the supraspinatus, by having subjects lay prone and abducting their arm to 100˚. Initial non-fatigued measurements displayed very minimal changes in humeral head position across abduction angles, whereas fatigued measurements indicated an average superior excursion of 2.5mm. Teyhen et al. (2008) performed a similar protocol to Chen et al. (1999), but fatigued supraspinatus, infraspinatus and teres minor. Post-fatigue excursion measurements increased by 0.79mm on average during abduction. This excursion was far less than that seen in Chen et al. (1999), indicating that the muscles were most likely less fatigued following the fatiguing protocol. In a recent study by Cote et al. (2009), fatiguing exercises were selected based on clinical exercises that have been shown to elicit high muscle activity amplitude in lower and middle trapezius. These exercises had also been found to elicit high activity from supraspinatus and infraspinatus. Humeral translation in the fatigued state was found to be 4.8mm which was much higher than other these previous studies. However, the humeral head position in the pre-fatigued state was 3mm superior to the center of the glenoid. Thus, although peak translation magnitude was much higher, the difference in humeral head position was less than that seen previously. Some of the differences are also potentially due to the measurement techniques used.

2.5.4 Current Limitations

Although contributory, there were many limitations associated with previous attempts to examine the effect of rotator cuff fatigue on humeral head translation. The most obvious consistently acknowledged limitation was the failure to quantify muscle activity and subsequent fatigue (Chen et al. 1999; Cote et al. 2009; Teyhen et al. 2008). As well, these studies used decreased strength and/or inability to complete the fatiguing task as fatigue measures (Chen et al. 1999; Cote et al. 2009; Teyhen et al. 2008). Although force measurement has been used as an indication of fatigue in previous research (Nussbaum et al. 2001), quantifying muscle activity through electromyography gives a more muscle-specific indication of fatigue, as opposed to a measure of total upper extremity fatigue. Another consistent limitation is the lack of realism or real-life applicability of the fatiguing protocol used. Although protocols have incorporated some overhead arm angles, completing isolated exertions lying prone is not a realistic simulation of occupational tasks. Considering a realistic job situation could offer insight into mechanisms creating injury in jobs that incidentally fatigue the rotator cuff; whether it is by internal/external rotation and/or overhead work. Further, the muscles that were selected as having the most influence on humeral head stabilization varied greatly between studies; certain studies only aimed to fatigue the supraspinatus, others fatigued the trapezius. Recalling the study by Bezer et al. (2005), the entire rotator cuff contributes to the stability of the humeral head in the glenoid cavity, thus fatiguing isolated muscles would not emulate a full rotator cuff tear.

This study will use surface electromyography (EMG) to quantify muscle activity and examine changes in both EMG amplitude and mean power frequency (MnPF) to ensure the rotator cuff was fatigued. This will eliminate the possibility of unknowingly fatiguing the surrounding muscles (i.e. deltoid, pectoralis major), while failing to fatigue the rotator cuff. Additionally, the task used aimed to emulate a simple industrial task where the body is not restricted, but the actions will require activation from the four muscles of the rotator cuff.

III. Materials and Methods

3.1 Participants

Twenty healthy, right-hand dominant, male participants (aged 25.3±5.1 years) were recruited to participate in this study. Sample size was calculated by extracting mean excursion measurements (and their associated standard deviations) from previous research (Chen et al. 1999) and performing a paired t-test; twenty subjects were required to obtain an acceptable level (80%) of power (Cohen 1988). Participants were excluded from participation if they self-reported any upper extremity pain or injury within the past year; or any past bone structural damage (humeral head, clavicle or acromion fracture or joint dislocation). All participants had active ranges of motion in both flexion (176.2±5.6˚) and abduction (176.9±4.3˚) that fell within the healthy range, as outlined by Boone and Azen (1979). As well, all participants tested negative on the Neer and Hawkins-Kennedy tests for clinical impingement (Table 1; Park et al. 2005), and had an initial RPE rating of less than 1 on a modified Borg CR-10 Scale (Table 2; Borg 1982).

Table 1. Clinical Impingement Tests (Park et al. 2005)

Impingement Test	Test Procedure	Positive Test (Indicating Impingement)
Neer	The scapula is stabilized by the examiner, and the arm is forward flexed by the examiner until the patient reports pain or until full elevation is reached.	If there is pain in the anterior or lateral part of the shoulder (typically between 90° to 140° of flexion)
Hawkins-Kennedy	Both the shoulder and arm placed in 90° of forward flexion and then gently rotated into internal rotation. The end point for internal rotation is either when the patient felt pain or when rotation of the scapula was felt of observed by the examiner.	If the patient had pain during the test

Table 2. Rate of Perceived Exertion (RPE) Scale (Borg 1982)

Exertion	RPE
Nothing at all	0
Very light	1
Fairly light	2
Moderate	3
Somewhat hard	4
Hard	5
	6
Very Hard	7
	8
	9
Very, very hard	10

3.2 Instrumentation

3.2.1 Radiography

Radiographic examinations were performed at St. Joseph's Healthcare Hamilton, using the Discovery XR650 Digital Radiography System (GE Healthcare, United Kingdom). The effective radiation dosage for the 8 x-rays was 0.08mSv; this is comparable to the natural background radiation experienced in 12 days. The technique factors used for these radiographs were 81kVp and an average of 5 to 8mAs. The senior technologist at St. Joseph's Hospital and his team of technologists positioned the equipment to obtain a clear view of the anterior-posterior glenohumeral joint. Any unclear radiographs in which it was thought that measurements could be difficult or potentially inconsistent between observers were re-taken.

3.2.2 Surface Electromyography

Muscle activity was collected from four muscles of the upper limb. The skin overlying these muscles was shaved and cleansed with alcohol to minimize impedance; then bi-polar Ag-AgCl Noraxon dual surface electrodes with a fixed 2cm spacing (Noraxon, Arizona, USA) were placed over the muscle belly of each muscle. Specifically, electrodes were placed over the supraspinatus, infraspinatus, middle deltoid, and sternal insertion of the pectoralis major, on the right side of the body (Table 3) using published placements (Cram and Kasman 1998; Hintermeister et al. 1998). A ground electrode was placed on the lateral portion of the clavicle. These muscles provided a representation of the rotator cuff (supraspinatus and infraspinatus, demonstrated by Waite et al. (2009)), as well as surrounding shoulder musculature that provides active assistance to movement (middle deltoid, pectoralis major). The muscle activity of the remaining rotator cuff muscles were not examined due to the invasiveness of fine-wire electromyography. Surface electromyographical signals (EMG) were collected using the Noraxon T2000 telemetered system. Raw EMG signals were band pass filtered from 10-500Hz, and differentially amplified (common-mode rejection ratio >100 dB at 60Hz, input impedance 100MΩ) to generate maximum signal amplification in the range of the A/D board. EMG signals were A/D converted at 1500 samples/second using a 16 bit A/D card with a ±3.5V range.

Table 3. Muscle sites monitored with surface electrodes; electrode location and test contraction.

Muscle	**Electrode Position**
Middle deltoid	**Electrode Location:** On the lateral aspect of the arm, approximately 3cm below the acromion, parallel to muscle fibres **Test Contraction:** Abduct the arm to 90° (elbow extended, thumb points forward); abduct against resistance
Pectoralis major,* sternal insertion	**Electrode Location:** Approximately 2cm medial from axillary fold, horizontal **Test Contraction:** Elbow flexed to 90˚, shoulder abducted to 75˚; palm press (push medially)
Supraspinatus*	**Electrode Location:** Midpoint and two finger-breadths anterior to scapular spine **Test Contraction***:* Abduct shoulder to 5° with elbow extended (thumb forward); abduct against resistance
Infraspinatus	**Electrode Location:** Parallel to scapular spine, approximately 4cm below and on the lateral aspect **Test Contraction:** Elbow bent to 90°, external rotation of arm

Cram and Kasman (1998)
* Hintermeister et al. (1998)

3.3 Experimental Protocol

The experimental protocol was completed in a single testing session that took approximately 1 ½ hours; this protocol followed a defined order of events (Figure 3).

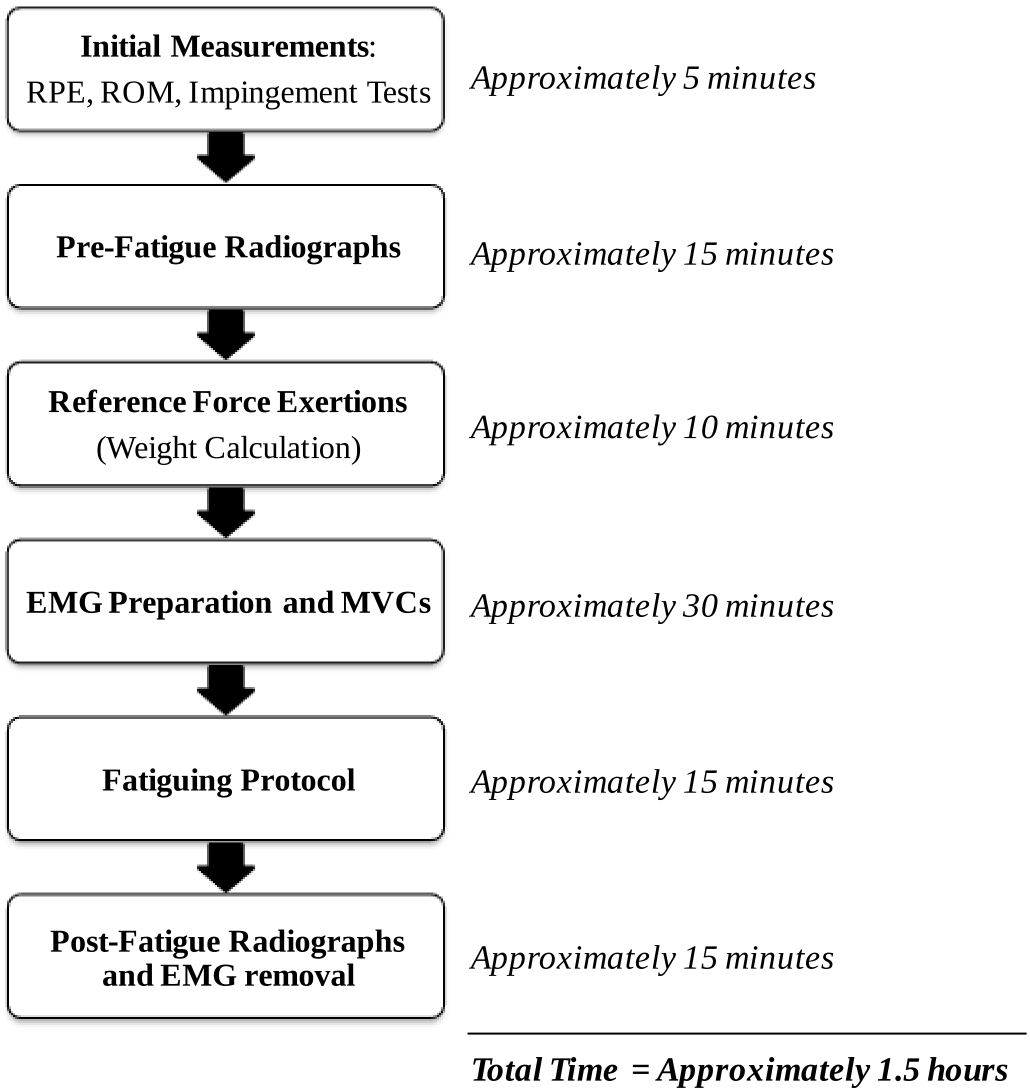

Figure 3. Flowchart outlining the sequence of the experimental protocol.

3.3.1 Radiographs

A series of four radiographs were taken before and immediately after a fatiguing protocol (outlined in Section 3.3.3). With the participant standing, radiographs captured an anterior-posterior view of the glenohumeral joint (Figure 4). Participants held a 1 kg weight while each radiograph was taken, consistent with previous research (Chen et al. 1999; Cote et al. 2009; Teyhen et al. 2008). A goniometer was used to position the participant's arm in four randomized abduction angles (0˚, 45˚, 90˚, 135˚) in the scapular plane, which was set at an angle of 30° to the plane of the x-ray beam (Paletta et al. 1997). Landmarks were drawn on participants' shoulder and arm to ensure proper goniometer placement, thereby ensuring angle consistency (within ±5°). The center of each participant's glenohumeral joint was aligned with the center of an "X" on the board behind them before measurements were made to ensure position was exact both within and between participants. The principle investigator was present for each examination to perform measurements and ensure that consistent testing conditions were enforced. Lead shielding was provided to protect the gonads from radiation.

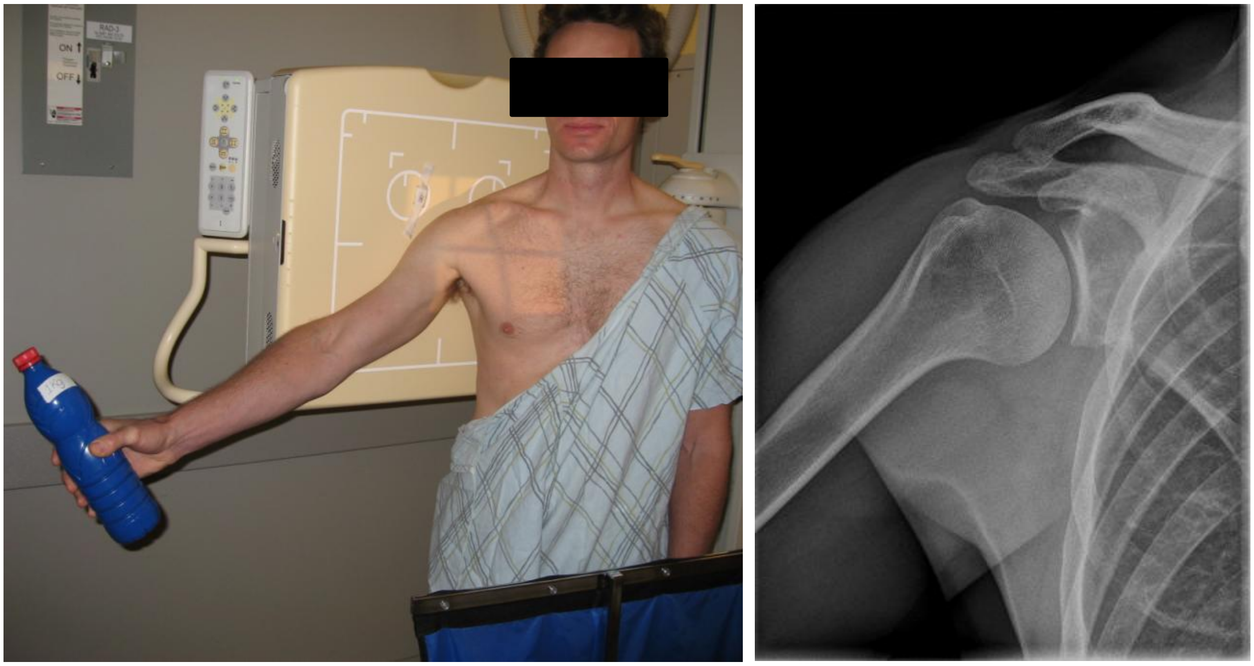

Figure 4. Photograph (left) and matching radiograph (right) of participant positioned at 45˚ of arm abduction.

3.3.2 Reference Value and Normalization Determination

Participants performed two repetitions of two maximal exertions against an ErgoFet 300™ hand dynamometer (Hogan Health Industries, Utah):

(1) shoulder flexion, with the arm positioned at 90˚ of shoulder flexion and 0˚ of horizontal abduction (directly in front of participant) and

(2) horizontal abduction, with arm positioned at 90˚ of shoulder abduction and 90˚ of horizontal abduction (arm out at side).

If the maximal force produced within a posture differed by ±5N, a third exertion was performed. An average of these four exertions served as a representation of the participant's maximal voluntary force, which was then used to set the weight lifted during the fatiguing protocol (Section 3.3.3). If it was necessary to repeat exertions due to dissimilarities in force levels, the two exertions in each posture that were within ± 5N were used to calculate the average.

Participants also performed three repetitions of maximal voluntary contractions (MVCs) for each of the monitored muscles (Table 3). The peak value obtained from these three repetitions was later used to normalize the EMG data collected during the fatiguing protocol (Section 3.3.3).

3.3.3 Fatiguing Protocol

The fatiguing protocol was a simulated job task involving arm elevation above shoulder height as well as internal and external rotation. Specifically, participants lifted a weighted (by lead shot) bottle from a starting position (0˚ of horizontal abduction and at 45˚ of shoulder flexion vertical) up to a second location (135˚ of shoulder flexion). They then lowered the bottle to the starting position, bent their elbow to 90˚ and externally rotated it so that their forearm moved 90˚ in horizontal abduction). They then lifted the bottle vertically up to a third location (135˚ of shoulder flexion) and reversed and repeated this pattern (Figures 5 and 6). This protocol provided a representation of an industrial assembly task. A metronome set at 40 beats per minute was used to set the pace of the task, so that it remained consistent between trials and participants. The weight of the bottle was set to 15% of the participant's maximum voluntary force, as determined by the reference value determination (Section 3.3.2). Lifting 15% of their maximum was expected to cause muscles to fatigue at a moderate rate (approximately 15 minutes to fatigue) (Chaffin et al. 2006). This work task intended to fatigue the entire rotator cuff due to the intentional combination of overhead work (supraspinatus), internal rotation (subscapularis) and external rotation (infraspinatus, teres minor) (Moore and Dalley 2006).

After each minute of the fatiguing protocol, participants performed a 5-second static hold of the weighted bottle at 90˚ of shoulder abduction in the scapular plane, with the elbow fully extended. EMG was collected during these static holds and was used as a reference for fatigue onset. Participants also gave their current rating on a modified Borg's RPE scale (Borg 1982). Due to the close relationship between subjective perception and electromyographic indications of fatigue (Dedering et al. 1999; Hummel et al. 2005), this rating was used to determine the next step in the protocol:

1) If this rating was below 10, they completed the 5-second static hold and then continued the fatiguing protocol for another minute.
2) If this rating was equal to 10, they completed the 5-second static hold and then proceeded to have their second series of radiographs taken.

There were a few instances in which post-fatigue radiographs could not be taken at the instant of max RPE rating; to prevent fatigue recovery subjects continued the fatiguing protocol to the best of their ability.

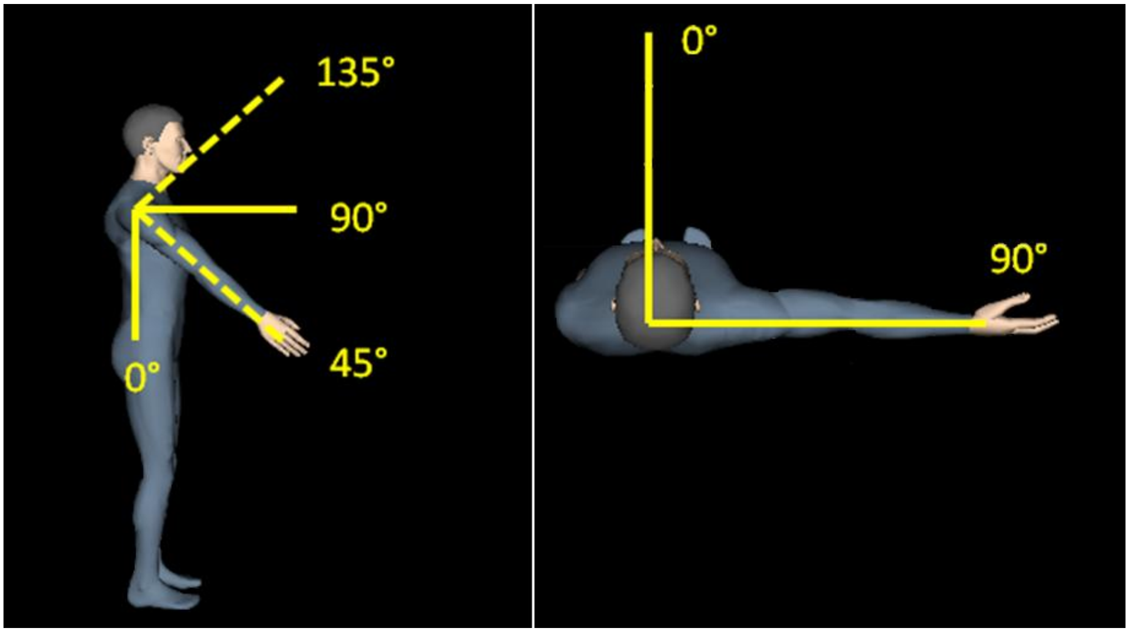

Figure 5. Arm angles involved in fatiguing task; shoulder flexion angles of 45˚ and 135˚ (left) and horizontal abduction angles of 0˚ and 90˚ (right).

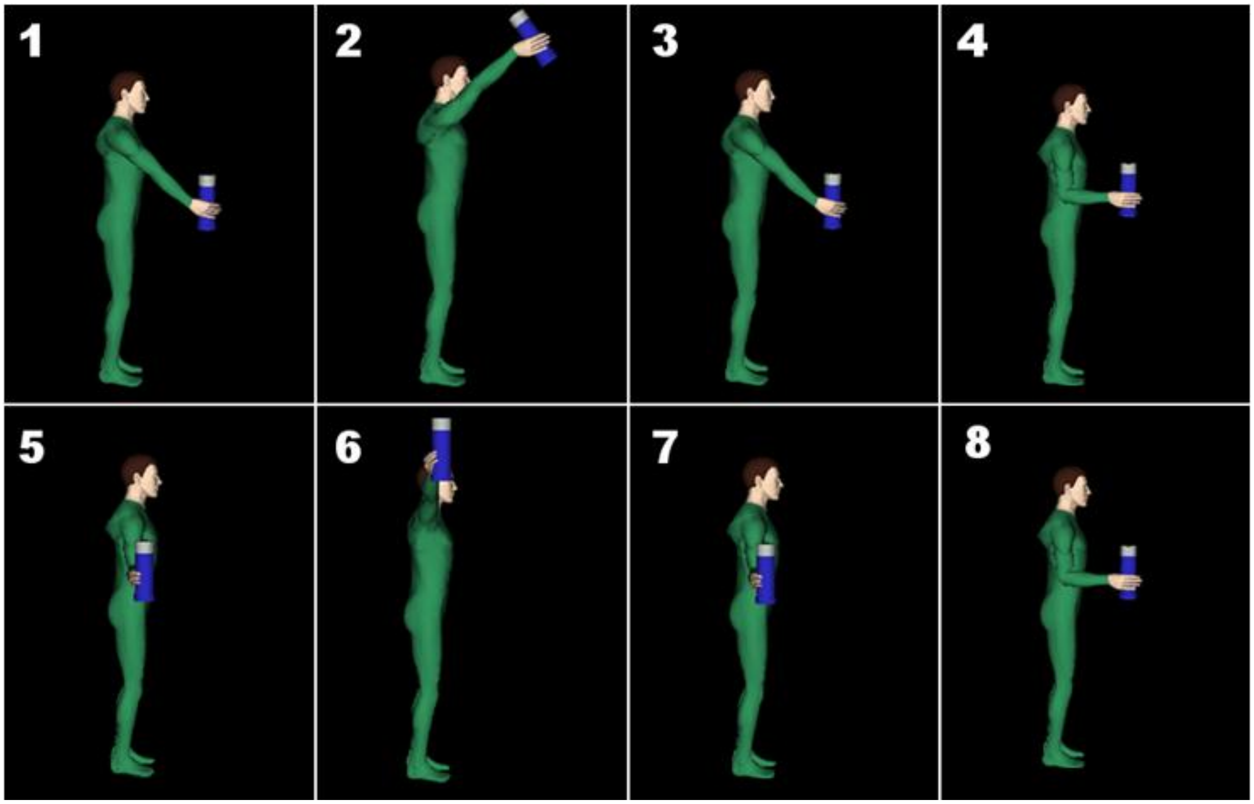

Figure 6. Steps/Positions of fatiguing task: **(1)** 0˚ of horizontal abduction, 45˚ shoulder flexion vertical (START); **(2)** 0˚ horizontal abduction, 135˚ shoulder flexion; **(3)** START; **(4)** elbow bent to 90˚, 0˚ horizontal abduction; **(5)** elbow bent to 90˚, external rotation/horizontal abduction 90˚; **(6)** 90˚ horizontal abduction, 135˚ shoulder flexion; **(7)** position (5); **(8)** elbow bent to 90˚, internal rotation/horizontal abduction 0˚. These steps were repeated for a minute at a pace of 40 beats per minute.

3.4 Laboratory-based Fatiguing Task Evaluation

In addition to field collection, a sample of three participants performed the fatiguing task in a lab-based setting to evaluate the muscular demand of the fatiguing task. The participants performed a series of maximal voluntary contractions (section 3.3.2) before beginning the fatiguing protocol; surface electromyography was collected throughout (section 3.2.2). To evaluate the fatiguing protocol, each participant performed five trials of a complete cycle of the fatiguing protocol (section 3.3.3). The average and peak demand of each muscle, normalized to respective MVCs, was examined (summarized in section 3.5.3).

3.5 Data Analysis

3.5.1 Radiographic Measurement: Humeral Head Translation

Radiographs were measured using GE PACS software (GE Healthcare, United Kingdom). Films were measured to determine the position of the humeral head with respect to the glenoid cavity, using the method outlined by Poppen and Walker (1976) and subsequently used in more recent research (Chen et al. 1999; Cote et al. 2009; Deutsch et al. 1996; Paletta et al. 1997; Teyhen et al. 2008). One aim of this research was to provide a more thorough explanation of these measurement instructions to ensure easy and efficient repeatability of the experiment. Measurement definitions are as follows:

<u>3. 5.1A Center of Humeral Head</u>

The geometric center of the humeral head (C_H) was determined first by drawing a circle (in which the radius from any point on the circle to the center is equal) around the superior and medial contours of the humeral head (Figure 7). Depending on individual bone geometry, a variable area of lateral portions of the bone was included. Despite this discrepancy, the researchers wanted to maintain consistency with previous methods. Second, the maximum/outermost points of the circle were landmarked by using the built-in coordinate system of the program; a horizontal and a vertical line were drawn to connect these points (Figure 8). These lines should be identical in length; if not, the circle was adjusted accordingly, remembering to ensure the superior and medial contours were still included; this was to ensure that the center of the circle was correctly identified. Each of these lines was measured to the nearest 0.1mm; thus the estimated error was ±0.05mm for line. The geometric center of the humeral head was defined as the interception of these lines. To ensure the center was obtained correctly, four lines of identical length were drawn from the interception point (proposed center) to the circumference in each of the four quadrants; if the lines were not equal the center was adjusted accordingly (Figure 9). The estimated error for measuring the center of the circle was 0.071mm [Equation 1].

$$Error_{CH} = \sqrt{Error_{vertical}{}^2 + Error_{horizontal}{}^2}$$ **[Equation 1]**

Where $Error_{CH}$ is the error associated with measuring the center of the humeral head; $Error_{vertical}$ is the error associated with drawing the vertical maximum to minimum points (0.05mm) and $Error_{horizontal}$ is the error associated with drawing the horizontal maximum to minimum points (0.05mm).

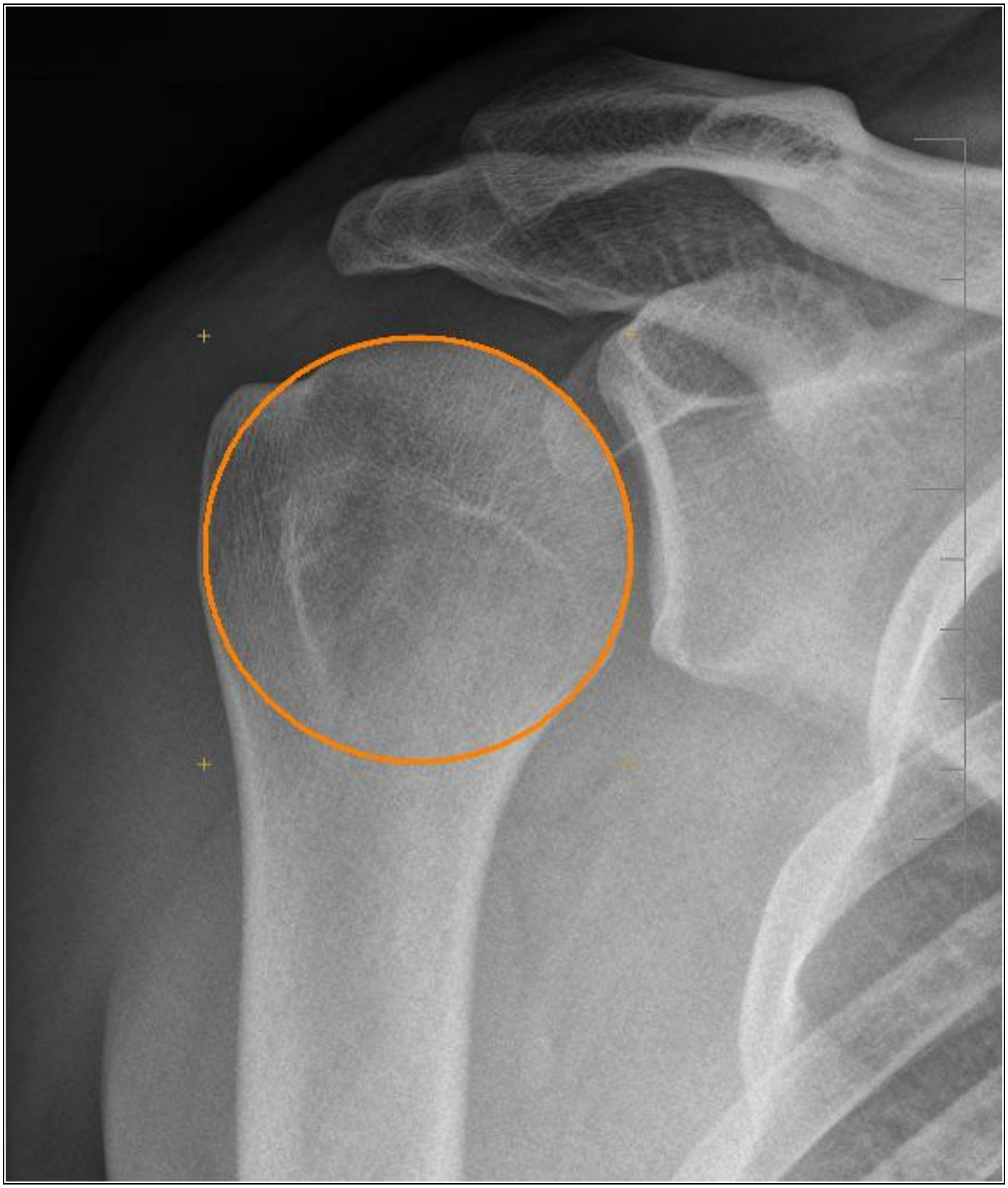

Figure 7. Step 1 of defining center of humeral head: draw a circle around the humeral head incorporating both its superior and medial contours. [Figures drawn in eFilm Workstation™ software (v 3.0, Merge Healthcare, Milwaukee, USA)].

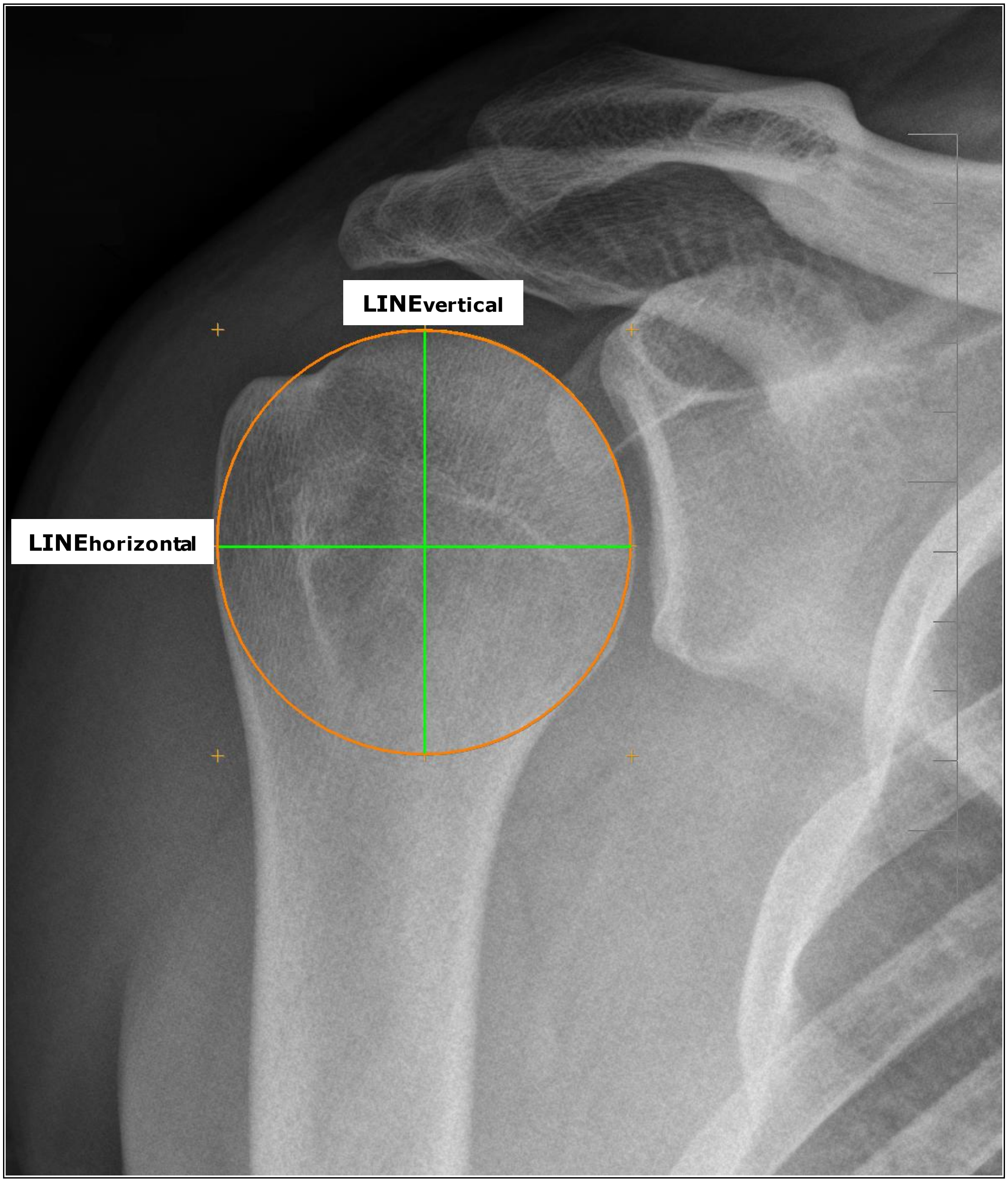

Figure 8. Step 2 of defining center of humeral head: use the built-in coordinate system to find the outer most points of the circle. Draw two lines: $\mathrm{LINE}_{vertical}$ and $\mathrm{LINE}_{horizontal}$: to connect the most superior/inferior points and medial/lateral points respectively [Figures drawn in eFilm Workstation™ software (v 3.0, Merge Healthcare, Milwaukee, USA)].

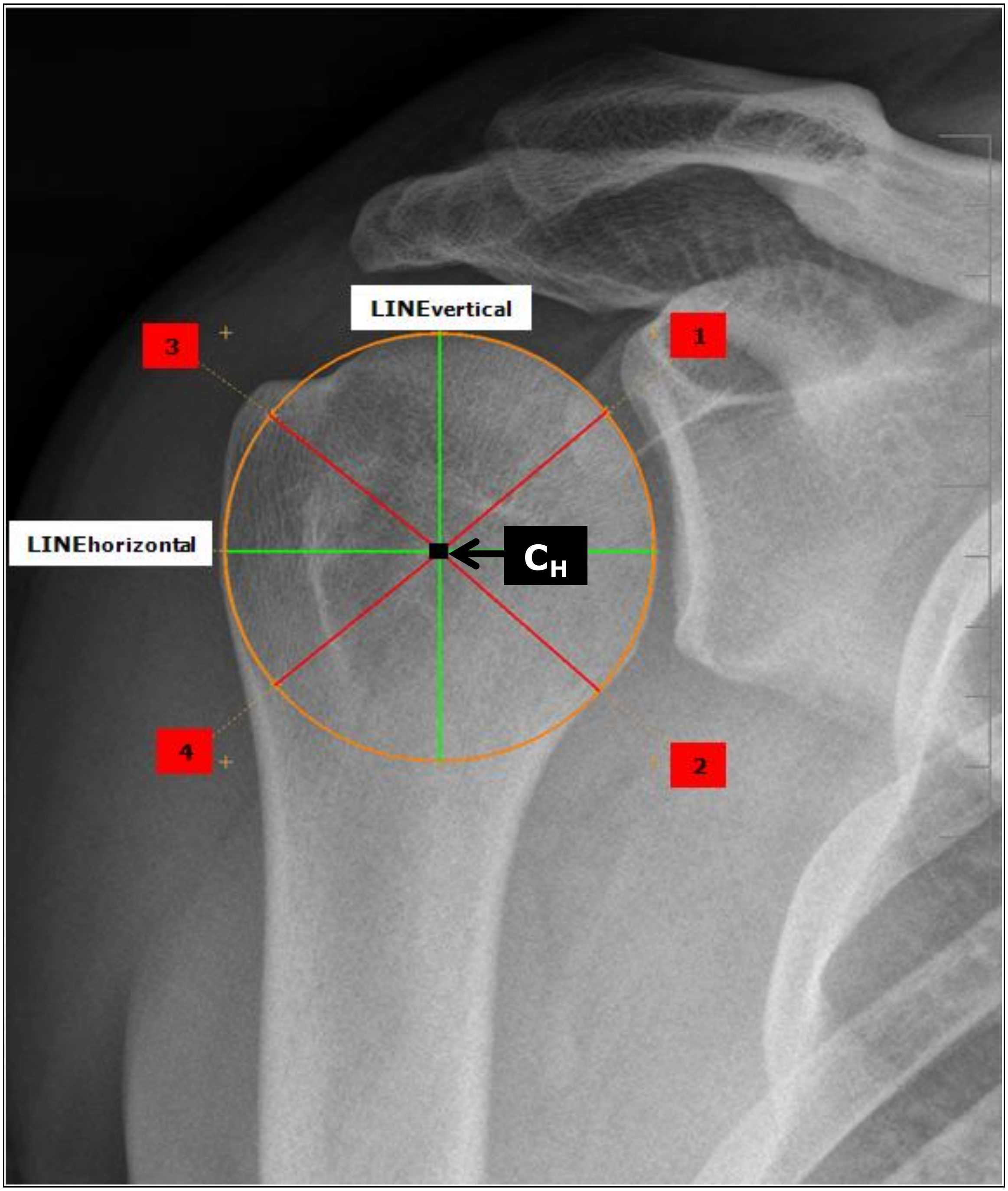

Figure 9. Step 3 of defining center of humeral head: ensuring that the intersection was in fact the center. Draw four lines from C_H (the proposed center) to the circumference in each of the four quadrants (1, 2, 3 and 4 in figure); these lines should be equal [Figures drawn in eFilm Workstation™ software (v 3.0, Merge Healthcare, Milwaukee, USA)].

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3.5.1B Center of Glenoid Cavity

The center of the glenoid cavity (C_G) was measured by landmarking the most superior and inferior points of the anterior articular margin. Due to the position in which the x-rays were taken, it was important to ensure that the anterior, and not the posterior, aspect of glenoid cavity was being measured. The anterior margin was determined by following the curvature of the margin to the endpoints of the glenoid cavity; the anterior margin appears in the form of a curved white border easily definable in all x-rays (Figure 10). A line was drawn connecting these endpoints and the center of this line, determined by drawing a parallel second line of half the length, was defined as the center of the glenoid cavity (Figure 11). The error associated with determining the center of the glenoid is 0.11mm [Equation 2].

$$Error_{CG} = \sqrt{Error_{limits}^{\ 2} + Error_{midpoint}^{\ 2}} \qquad \textbf{[Equation 2]}$$

Where $Error_{CG}$ is the error associated with measuring the center of the glenoid cavity; $Error_{limits}$ is the error associated with determining the superior and inferior limits (0.1mm) and $Error_{midpoint}$ is the error associated with drawing the horizontal maximum to minimum points (0.05mm).

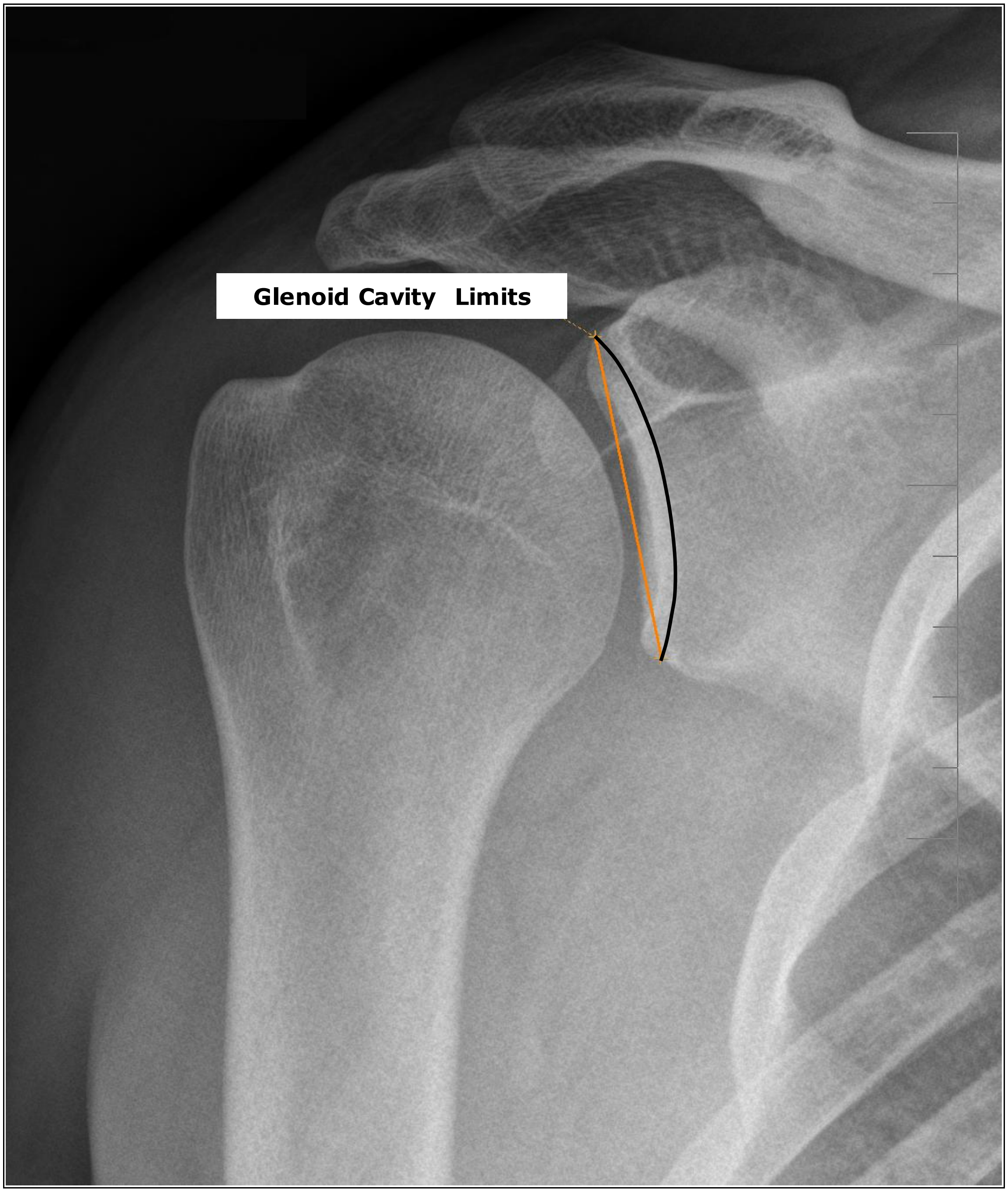

Figure 10. Step 1 of defining center of glenoid cavity: draw a line connecting the end points of the anterior margin of the glenoid cavity; curved line follows the curvature of the anterior margin (appears bright white on x-ray) [Figures drawn in eFilm Workstation™ software (v 3.0, Merge Healthcare, Milwaukee, USA)].

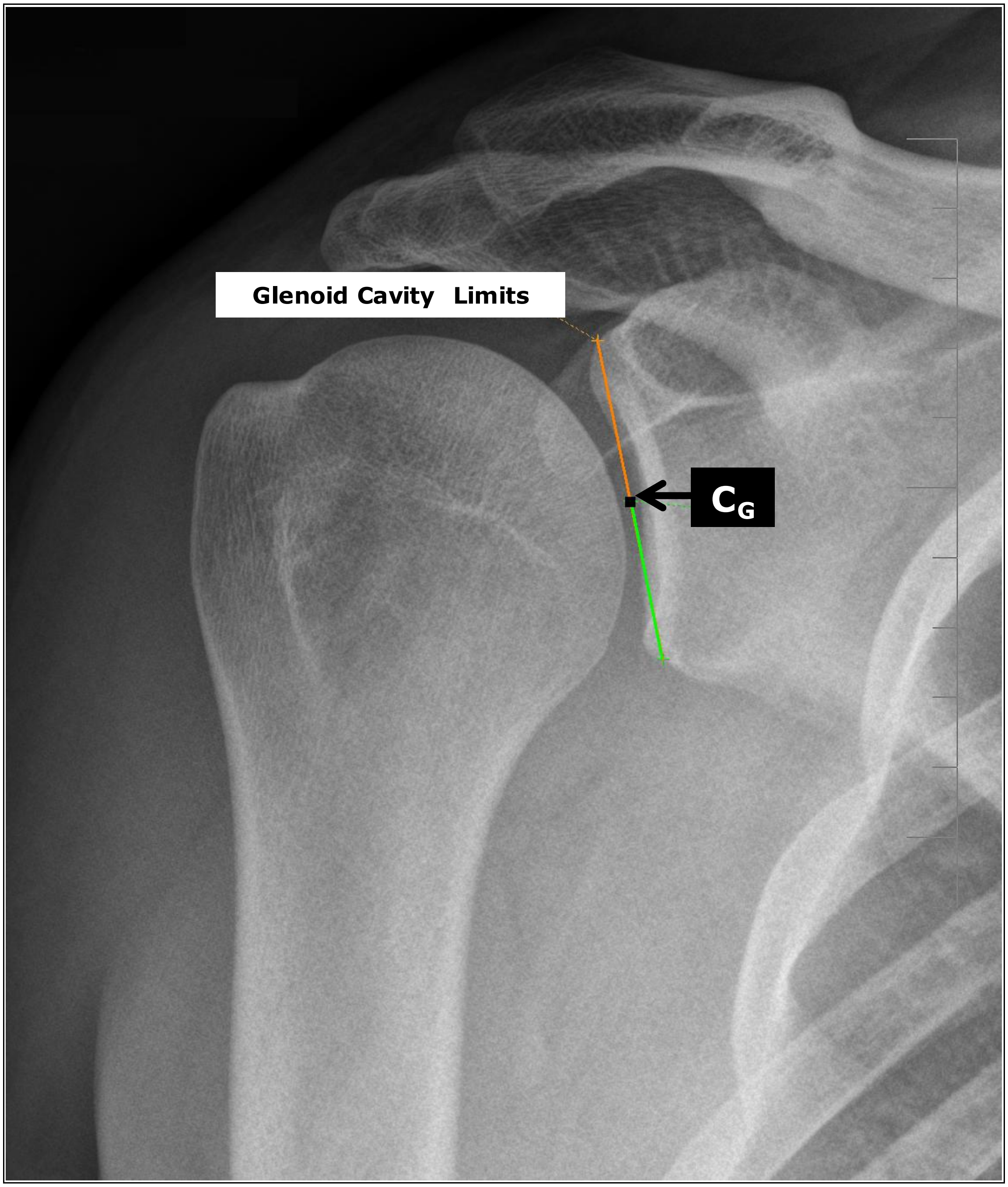

Figure 11. Step 2 of defining center of glenoid cavity: draw a line half the length of the original glenoid line; this point is the center of the glenoid cavity [Figures drawn in eFilm Workstation™ software (v 3.0, Merge Healthcare, Milwaukee, USA)].

3.5.1C Humeral Head Translation

The measure of excursion (E) was defined as the perpendicular difference between the center of the humerus and the center of the glenoid cavity. This was determined first by drawing a perpendicular line from the center of the humeral head to the line connecting the limits of the glenoid cavity (Figure 12). The difference between the pre-determined C_G and the extension of C_H along the glenoid axis was the excursion measurement (E) (Figure 13). If C_H was positioned superior to C_G, then the excursion was positive; inferior movement was documented as a negative value. The error associated with measuring the excursion is 0.05mm ($Error_E$).

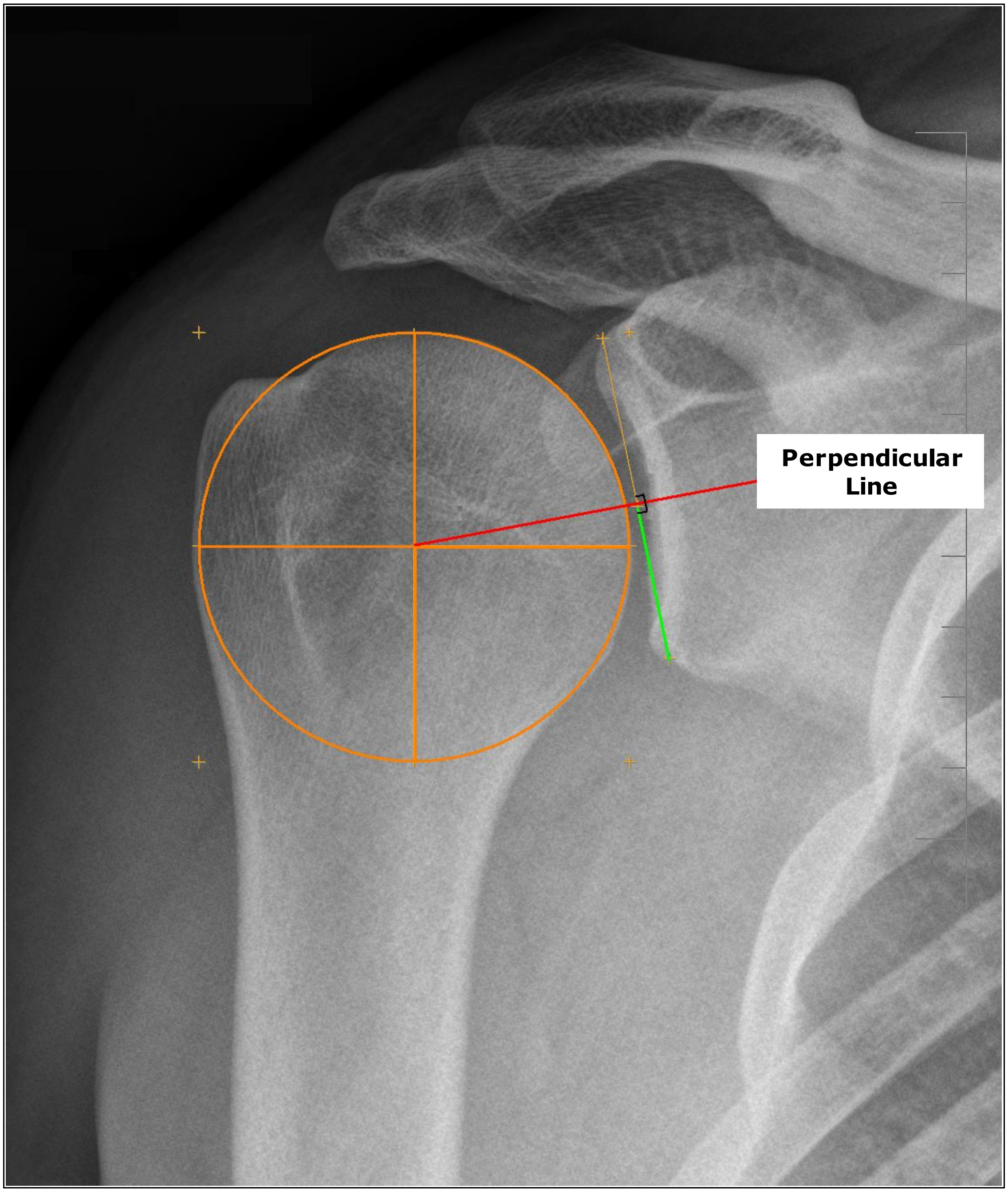

Figure 12. Step 1 of determining humeral head excursion: draw a perpendicular line from the center of the humeral head to the glenoid line [Figures drawn in eFilm Workstation^{TM} software (v 3.0, Merge Healthcare, Milwaukee, USA)].

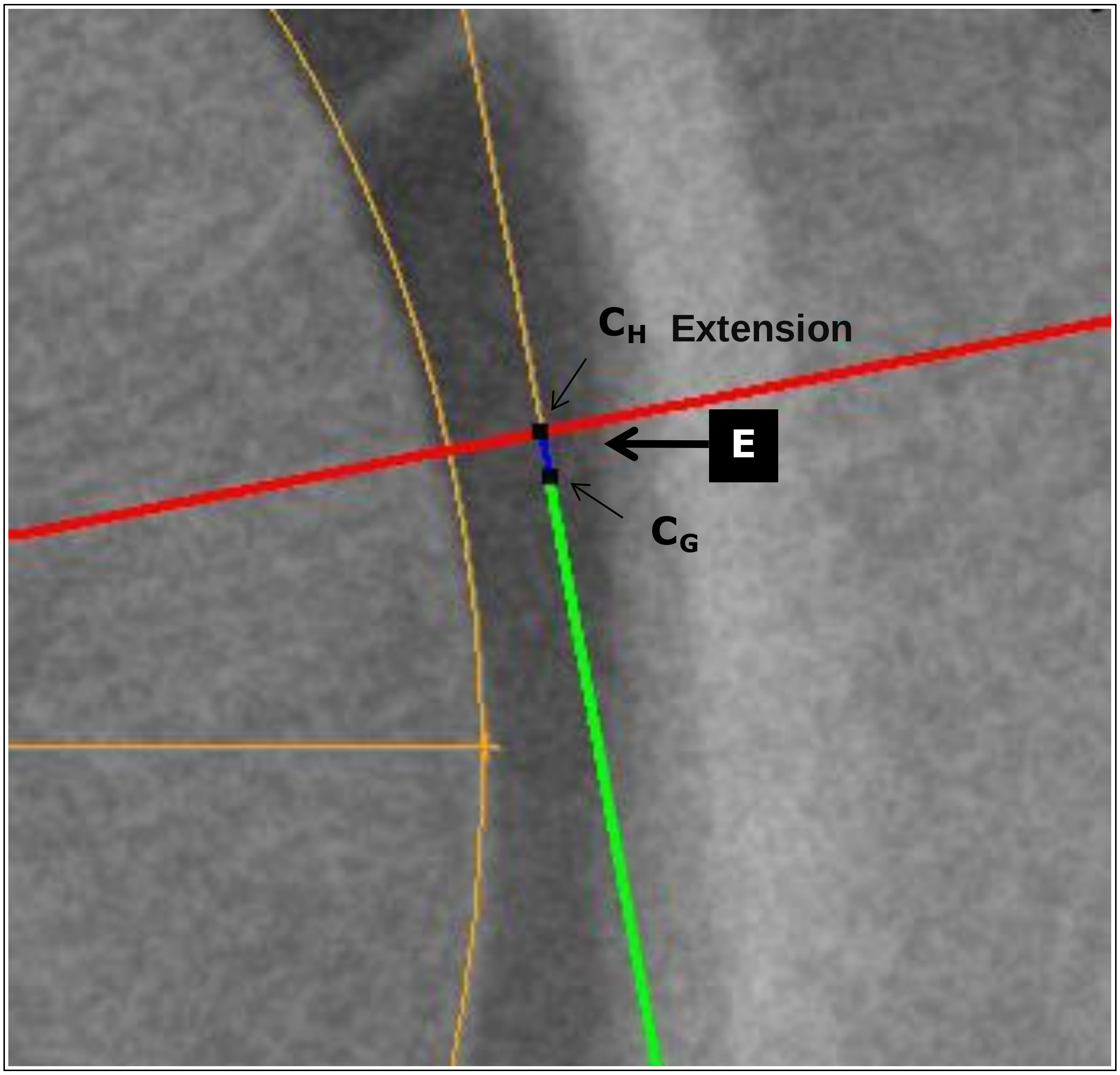

Figure 13. Step 2 of determining humeral head excursion: measure the difference between center of the glenoid cavity (C_G) and the extension from the center of the humeral head (C_H Extension) along the glenoid axis; this value is the excursion (E) **Note: If C_H Extension is above C_G there is positive excursion, if C_H Extension is below C_G there is negative excursion.** [Figures drawn in eFilm Workstation™ software (v 3.0, Merge Healthcare, Milwaukee, USA)].

The total error in the measurement is 0.14mm [Equation 3]. Thus, excursions determined should be greater than 0.14mm to be considered significant.

$$Error_T = \sqrt{Error_{CH}^{\;2} + Error_{CG}^{\;2} + \; Error_E^{\;2}} \qquad \textbf{[Equation 3]}$$

Where $Error_T$ is the total error associated with the measurement; $Error_{CH}$ is the error associated with measuring the center of the humeral head (0.071mm); $Error_{CG}$ is the error associated with measuring the center of the glenoid cavity (0.11mm); $Error_E$ is the error associated with measuring the excursion (0.05mm).

3.5.2 Radiographic Measurement: Acromio-Humeral Intervals (AHI)

Acromio-humeral intervals (AHI) were also measured to determine individual capacity for excursion. This distance was measured by drawing a vertical line from the most superior point on the humeral head (consistent with Section 3.4.1A), to the most inferior point on the acromion (Figure 14). This measurement was made on both pre- and post-fatigue radiographs in a neutral position (0˚); the anterior-posterior glenohumeral view prevents accurate measurement of the acromio-humeral interval at variations of abduction away from a neutral position. As well, certain geometric glenohumeral joint structures of certain individuals may prevent accurate measurement; thus only x-rays with clear measurements were used for analysis. The error associated with measuring the AHI in a clear x-ray is 0.13mm [Equation 4].

$$Error_{AHI} = \sqrt{Error_{CH}^{\;2} + \; Error_{SubSpace}^{\;2}} \qquad \textbf{[Equation 4]}$$

Where $Error_{AHI}$ is the total error associated with the AHI measurement; $Error_{CH}$ is the error associated with measuring the center of the humeral head (0.071mm); $Error_{SubSpace}$ is the error associated with measuring the vertical distance from the superior border of the humeral head to the most inferior point on the acromion (0.11mm).

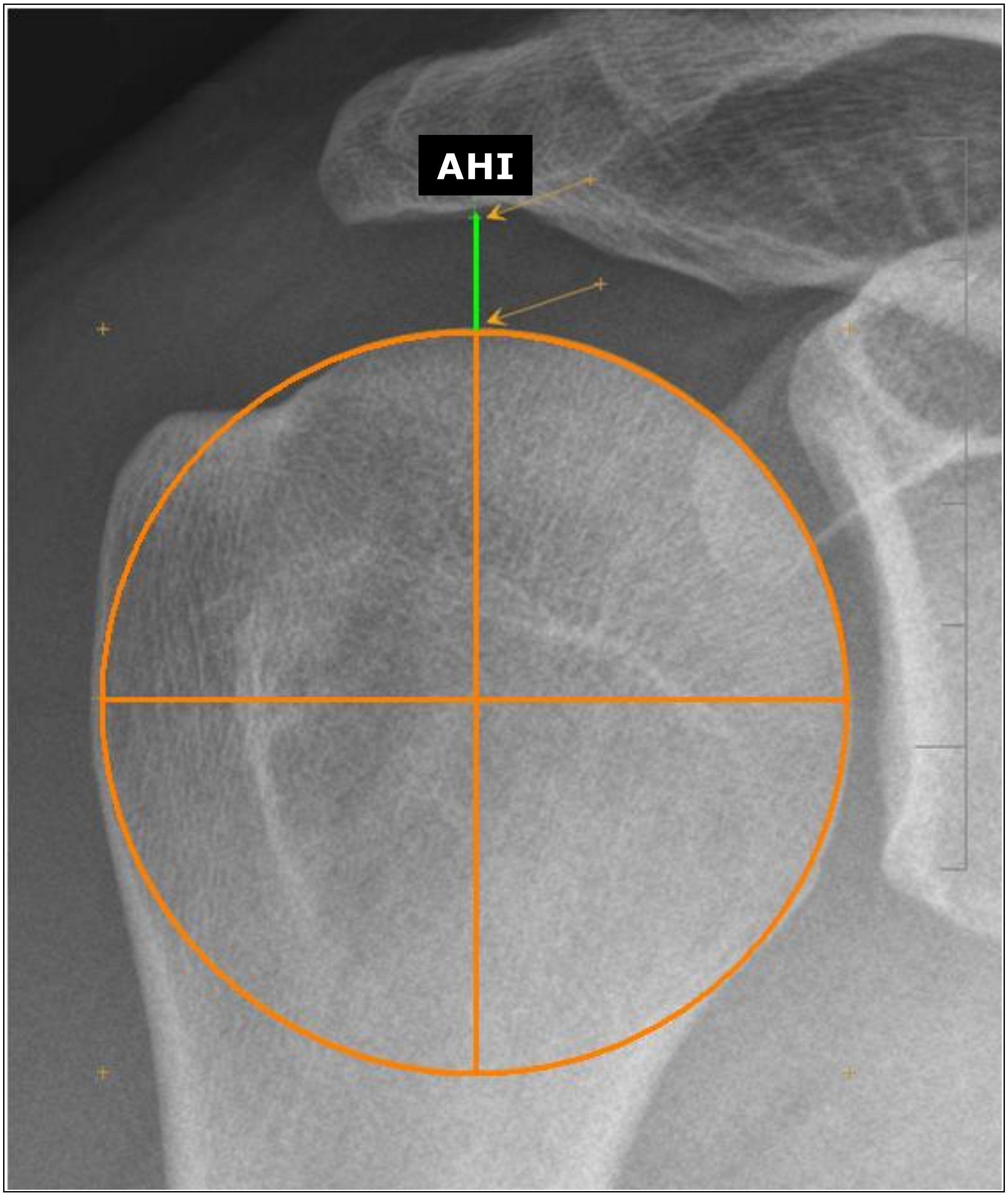

Figure 14. Acromio-humeral interval measurement; from most superior point of humeral head, vertically upwards to the lowest point on the inferior acromion.

3.5.3 EMG Processing

EMG was analyzed both in the time and frequency domains. In the time domain, EMG signals were full wave rectified and low pass filtered at 4Hz (Mathiassen et al. 1995) using a second order dual pass Butterworth filter. A trial is considered to be each 5-second static hold of the weighted bottle following each minute of the fatiguing protocol; thus each participant would have a different number of trials depending on how many minutes they could perform the fatiguing task. For trial EMG and MVCs, a 500 msec moving average was applied, and a peak value was obtained from the resulting curve (Fischer et al. 2009). Trial EMG was normalized to the maximal value obtained from MVCs to allow comparison of results across subjects (Chopp et al. 2009a; Knutson et al. 1994). To analyze the effects of fatigue, the first (pre-exercise) trial was compared to the last (fatigued) trial. In the frequency domain, a Fourier Transform was performed on raw EMG signals for each muscle of every trial. Heart rate contamination was removed using a 30Hz high pass filter (Drake and Callaghan 2006). Mean power frequency (MPF) was calculated from each 500 msec window, from which the average MPF value was determined (Oberg et al. 1994). To compare across subjects MPF values were normalized to the initial (pre-exercise) MPF value; thus subsequent measurements were reported as a percentage of this starting value. To analyze the effect of fatigue, the first (pre-exercise) trial was compared to the last (fatigued) trial. A muscle will be considered fatigued if there is a negative shift in MPF greater than 8% (Oberg et al. 1990; Szucs et al. 2009).

3.5.4 Statistical Analysis

A two-way repeated measures ANOVA was used to determine the effects of fatigue (pre-fatigue and post-fatigue) and arm angle (0˚, 45˚, 90˚, 135˚) on humeral head excursion. Two one-way repeated measures ANOVAs were used to determine the effect of fatigue (pre-fatigue and post-fatigue) on EMG amplitude and on AHI. Also, two-tailed paired t-tests were used to compare the pre-fatigue and post-fatigue humeral head position at each arm angle. A p-value of 0.05 was used to determine significance. Interactions were examined using post-hoc Tukey tests with Bonferroni adjustments to ensure a strict p-value, and reduce the risk of type 1 error. All statistical analyses were performed using JMP 8.0 software (SAS Institute, North Carolina, USA).

To assess reliability in the measurement, both inter- and intra- observer reliability were assessed. A random sample of 20 radiographs (including all four angles of arm abduction) was given to an experienced musculoskeletal radiologist; excursion was measured on each radiograph using the method outlined in Section 3.5.1; this sample was compared to the measurements performed by the student/principle investigator used to assess inter-observer reliability. The student/principle investigator performing all initial measurements also received a separate random sample of 20 radiographs and re-measured excursion; this sample was used to assess intra-observer reliability. Intraclass correlation coefficients with a 95% confidence interval were used to assess inter- and intra- observer reliability (Ludewig and Cook 2002; Keener et al. 2009; Teyhen et al. 2008).

IV. Results

The position of the humeral head with the respect to the glenoid cavity was significantly affected both by arm angle and fatigue state. A fatigue-arm angle interaction effect was tested but not found to be significant, thus only main effects will be discussed. Further, although the time at which it occurred was highly variable, infraspinatus and middle deltoid had conclusive evidence of fatigue in 95% of participants following the job simulated task. Acromial-humeral interval changes were not significant.

4.1 Radiographic Examination

4.1.1 Humeral Head Excursion: Mean Differences

The position of the humeral head with respect to the glenoid cavity was significantly affected ($p<0.0001$) by arm angle [$F(3,133) = 29.59$]. As the arm was abducted (45˚, 90˚ or 135˚) from the 0˚ resting position, there was an overall significant ($p<0.0001$) mean excursion of approximately 2.01-2.21±1.57mm (Figure 15). Specifically, at the 0˚ arm angle, the position of the humeral head was an average of -0.42 ± 1.3mm, which indicates that the center of the humeral head was 0.42mm lower than the center of the glenoid cavity. The median excursion at this angle was -0.29mm with 25th and 75th percentiles at -2.15mm and 1.18mm respectively. At the 45˚ arm angle, the position of the humeral head was an average of 1.59±1.42mm; thus the center of the humeral head showed significant upwards migration of approximately 2.01mm with respect to the 0˚ resting position. The median excursion at this angle was 1.45mm with 25th and 75th percentiles at 0.66mm and 2.38mm respectively. At the 90˚ arm angle, the position of the humeral head was an average of 1.79±1.84mm. This position was significantly higher than the 0˚

resting position, but was statistically similar to the 45˚ arm angle. The median excursion at this angle was 1.95mm with 25th and 75th percentiles at 1.18mm and 2.60mm respectively. At the 135˚ arm angle, the position of the humeral head was an average of 1.72±1.46mm. This position was significantly higher than the 0˚ resting position, and although lower than at the 90˚ arm angle, it was statistically similar to both the 45˚ and 90˚ arm angles. The median excursion at this angle was 1.85mm with 25th and 75th percentiles at 0.65mm and 2.55mm respectively. Outliers were present at the 45˚ and 90˚ arm angles, indicating some extreme excursions, which were both positive and negative.

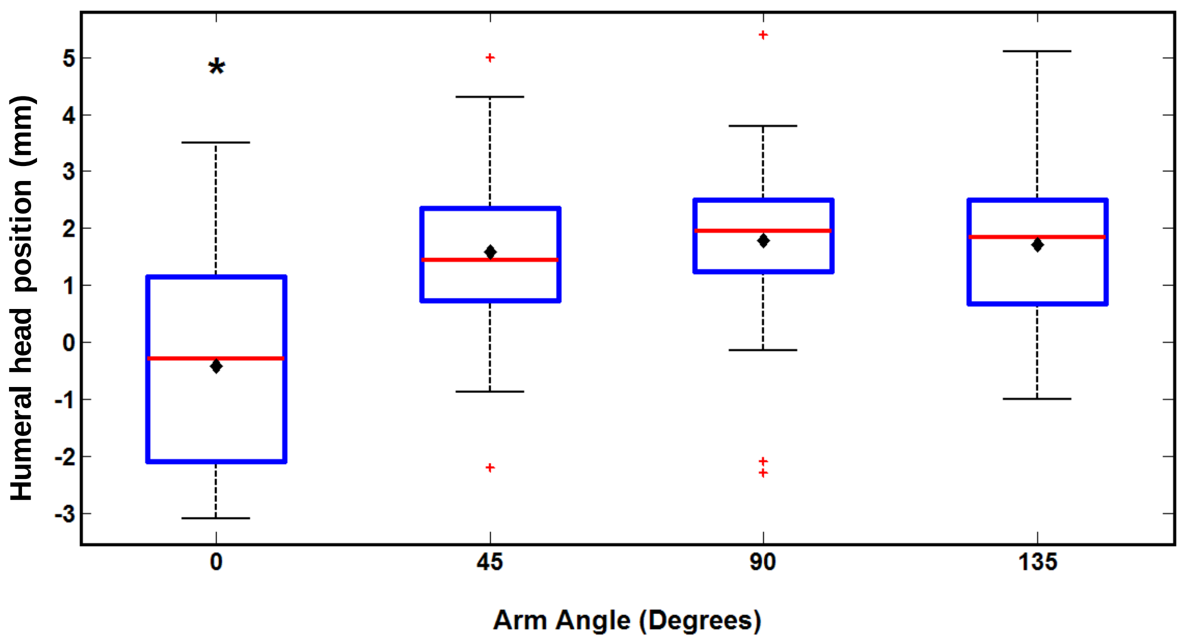

Figure 15. Box plot of humeral head excursion at different arm angles. Edges of boxes indicate 25th and 75th percentiles, center lines indicate median, diamonds indicate mean and small plusses indicate outliers. The star (*) identifies the zero angle as significantly lower than all other angles.

The position of the humeral head with respect to the glenoid cavity was significantly affected ($p<0.0017$) by fatigue state [$F(1,133) = 10.27$] (Figure 16). The effect size of this measure was determined to be approximately 0.4, which indicated a medium effect between pre-and post- fatigue states (Cohen 1988). In the pre-fatigue state, the mean position of the center of the humeral head was 0.858±1.8mm above the center of the glenoid cavity, while the median excursion at this angle was 1.15mm with 25th and 75th percentiles at -0.11mm and 2.28mm respectively. In the post-fatigue state, the mean position of the center of the humeral head was 1.485±1.72mm above the center of the glenoid cavity, giving a mean excursion measure of approximately 0.63±1.76mm; the median excursion at this angle was 1.60mm with 25th and 75th percentiles at 0.47mm and 2.30mm respectively. Outliers were present in the post-fatigue state, indicating some extreme excursions, both positive and negative.

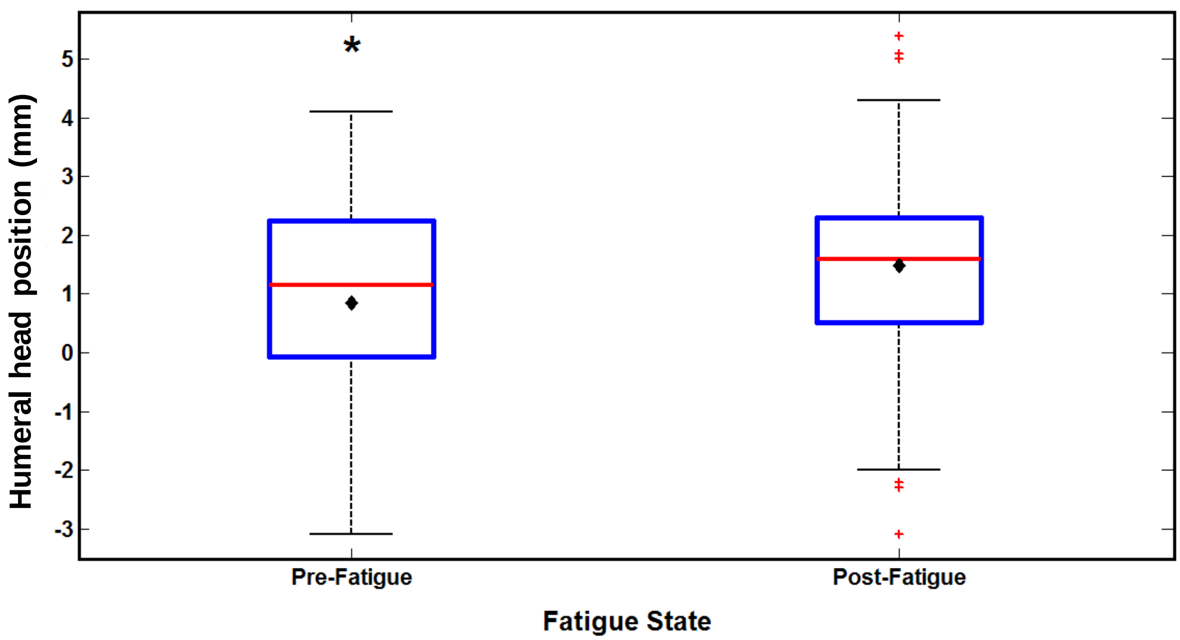

Figure 16. Box plot displaying changes in humeral head excursion with fatigue state. Edges of box indicate 25th and 75th percentiles, center line indicates median, center of diamond indicates mean. Star (*) indicates that the excursion in the pre-fatigued state is significantly lower than it is in the post-fatigued state ($p<0.05$).

Changes in humeral head position were recorded in both the pre-fatigue and post-fatigue states and paired t-tests were used to compare excursion at each arm angle (Table 4). In the pre-fatigued state, the humeral head position was initially inferior to the center of the glenoid cavity.

A significant upward excursion occurred with arm abduction, and then a minor downward excursion as the arm was further abducted to 135˚. Positions of the humeral head at 45˚, 90˚ and 135˚ were not statistically different from one another. In the post-fatigue state, the humeral head position was centered with respect to the glenoid cavity; as the arm was abducted there was an upward excursion to a position of 2.21±1.25mm. There was a similar level of excursion over the range of abduction within each fatigue state, with pre-fatigue having 2.09±2.36mm of excursion from 0˚ to 135˚ and post-fatigue excursion having 2.20±2.11mm of excursion from 0˚ to 135˚. However, the overall position of the humeral head was superiorly located after the fatiguing task, as indicated by the 0° humeral head position. Paired t-tests indicated that was significant upward excursion (0.97±1.29mm) from the pre-fatigue to post-fatigue state at 135˚; as well, an effect size calculation determined this to be a large effect (0.74) (Cohen 1988). At 0˚ and 90˚ there was an upward excursion of approximately 0.85±2.16mm and 0.62±1.55mm respectively; this was not a significant excursion, although the effect size was determined to be moderate. At 45˚ neither the excursion nor effect size was deemed significant; thus this angle appeared to be uninfluenced by fatigue.

Table 4. Humeral head position with respect to arm angle reported in both the pre-fatigue and post-fatigue states. Star (*) indicates that the post-fatigue state humeral head position at a specific arm angle was statistically different from the pre-fatigue state humeral head position at the same arm angle ($p<0.05$).

Arm Angle	Pre-Fatigue State	Post-Fatigue State
0°	-0.85 ± 1.92mm	0.01 ± 1.70mm
45°	1.56 ± 1.13mm	1.63 ± 1.77mm
90°	1.48 ± 1.59mm	2.10 ± 1.19mm
135°	1.24 ± 1.37mm	2.21 ± 1.25mm*

4.1.2 Humeral Head Excursion: Individual Differences

With the presence of outliers in both main effects (arm angle and fatigue state), individual excursion values for each subject between pre- and post-fatigue states were compared for each of the four arm angles.

In a resting position of 0˚, 13 out of 20 participants displayed positive humeral head excursion in the post-fatigue radiograph (Table 5). The mean difference/excursion in humeral head position between pre- and post- fatigue states was 0.85±2.16mm, with the maximum excursion being 4.60mm and the minimum being a negative/inferior excursion of -2.60mm.

Table 5. Individual humeral head positions in the pre- and post-fatigue state and their respective excursion measurements at 0˚ of arm abduction.

Participant	Pre-Fatigue Position (mm)	Post-Fatigue Position (mm)	Excursion (mm)	Positive Excursion?
1	-0.87	0.00	0.87	Y
2	-1.20	-1.70	-0.50	N
3	-2.60	2.00	4.60	Y
4	0.29	1.10	0.81	Y
5	-2.50	0.14	2.64	Y
6	-0.58	-1.80	-1.22	N
7	-1.20	-0.87	0.33	Y
8	-3.10	-2.20	0.90	Y
9	-2.80	1.50	4.30	Y
10	0.00	-2.00	-2.00	N
11	-2.40	-2.30	0.10	Y
12	2.60	0.00	-2.60	N
13	3.50	1.50	-2.00	N
14	-1.80	0.00	1.80	Y
15	-2.00	1.30	3.30	Y
16	2.30	1.90	-0.40	N
17	0.00	2.60	2.60	Y
18	0.43	0.88	0.45	Y
19	-2.80	1.20	4.00	Y
20	-2.20	-3.10	-0.90	N
Average	-0.85	0.01	**0.86**	
Std Dev	1.92	1.70	**2.16**	

At 45˚ of arm abduction, 12 out of 20 participants displayed positive humeral head excursion in the post-fatigue radiograph (Table 6). The mean difference/excursion in humeral head position between pre- and post- fatigue states was 0.07±1.39mm, with the maximum excursion being 2.40mm and the minimum being a negative/inferior excursion of -2.78mm. Of the four arm angles examined, 45˚ displayed the most variable results with respect to humeral head position in the glenoid cavity.

Table 6. Individual humeral head positions in the pre- and post-fatigue state and their respective excursion measurements at 45˚ of arm abduction.

Participant	**Pre-Fatigue Position (mm)**	**Post-Fatigue Position (mm)**	**Excursion (mm)**	**Positive Excursion?**
1	-0.87	0.43	1.30	Y
2	2.40	-0.32	-2.72	N
3	1.00	-0.32	-1.32	N
4	1.00	1.20	0.20	Y
5	1.60	1.50	-0.10	N
6	0.58	1.00	0.42	Y
7	2.60	0.93	-1.67	N
8	0.58	-2.20	-2.78	N
9	2.30	4.30	2.00	Y
10	1.70	0.93	-0.77	N
11	0.29	0.58	0.29	Y
12	1.90	1.70	-0.20	N
13	3.90	4.10	0.20	Y
14	1.40	2.20	0.80	Y
15	1.20	0.85	-0.35	N
16	3.30	3.80	0.50	Y
17	0.60	2.20	1.60	Y
18	2.60	5.00	2.40	Y
19	0.87	1.50	0.63	Y
20	2.20	3.20	1.00	Y
Average	1.56	1.63	**0.07**	
Std Dev	1.13	1.77	**1.39**	

At 90˚ of arm abduction, 13 out of 20 participants displayed positive humeral head excursion in the post-fatigue radiograph (Table 7). The mean difference/excursion in humeral head position between pre- and post- fatigue states was 0.62±1.55mm, with the maximum excursion being 4.40mm and the minimum being a negative/inferior excursion of -2.66mm.

Table 7. Individual humeral head positions in the pre- and post-fatigue state and their respective excursion measurements at 90˚ of arm abduction.

Participant	Pre-Fatigue Position (mm)	Post-Fatigue Position (mm)	Excursion (mm)	Positive Excursion?
1	-0.14	1.90	2.04	Y
2	1.70	1.50	-0.20	N
3	0.32	0.72	0.40	Y
4	1.60	2.90	1.30	Y
5	1.90	2.30	0.40	Y
6	1.50	2.00	0.50	Y
7	2.80	0.14	-2.66	N
8	-2.30	0.41	2.71	Y
9	1.40	2.00	0.60	Y
10	2.10	1.40	-0.70	N
11	2.30	1.60	-0.70	N
12	0.65	2.70	2.05	Y
13	3.30	5.40	2.10	Y
14	2.20	1.10	-1.10	N
15	2.00	1.70	-0.30	N
16	3.80	3.30	-0.50	N
17	-2.10	2.30	4.40	Y
18	3.20	3.60	0.40	Y
19	1.10	2.20	1.10	Y
20	2.30	2.80	0.50	Y
Average	1.48	2.10	**0.62**	
Std Dev	1.59	1.19	**1.55**	

At 135˚ of arm abduction, 17 out of 20 participants displayed positive humeral head excursion in the post-fatigue radiograph (Table 8). The mean difference/excursion in humeral head position between pre- and post- fatigue states was 0.97±1.29mm, with the maximum excursion being 3.30mm and the minimum being a negative/inferior excursion of -1.80mm. This angle displayed the greatest percentage of those having positive humeral head excursion following fatigue.

Table 8. Individual humeral head positions in the pre- and post-fatigue state and their respective excursion measurements at 135˚ of arm abduction.

Participant	Pre-Fatigue Position (mm)	Post-Fatigue Position (mm)	Excursion (mm)	Positive Excursion?
1	0.00	2.20	2.20	Y
2	0.00	1.10	1.10	Y
3	0.62	2.30	1.68	Y
4	2.60	5.10	2.50	Y
5	2.70	2.90	0.20	Y
6	0.21	2.20	1.99	Y
7	4.10	2.30	-1.80	N
8	-0.62	0.41	1.03	Y
9	1.70	2.80	1.10	Y
10	1.30	3.00	1.70	Y
11	0.72	0.41	-0.31	N
12	-1.00	2.30	3.30	Y
13	1.60	2.90	1.30	Y
14	3.40	1.60	-1.80	N
15	2.30	4.30	2.00	Y
16	1.70	2.00	0.30	Y
17	-0.72	-0.41	0.31	Y
18	1.10	2.30	1.20	Y
19	1.70	2.00	0.30	Y
20	1.40	2.40	1.00	Y
Average	1.24	2.21	**0.97**	
Std Dev	1.37	1.25	**1.29**	

4.1.3 Acromio-Humeral Interval

Acromio-humeral interval was reported for participants whose subacromial space was clearly measureable. In approximately half of the participants, there was difficulty accurately assessing the under surface of the acromion, given the anterior-posterior view of the glenohumeral joint. However, in participants with clear measurements, the results were inconclusive; some participants displayed the expected decrease to the AHI after fatigue, whereas some showed a contrasting increase (Figure 17). Statistical analysis determined changes in the AHI to be insignificant (p=0.7275) and inconsistent in direction across participants.

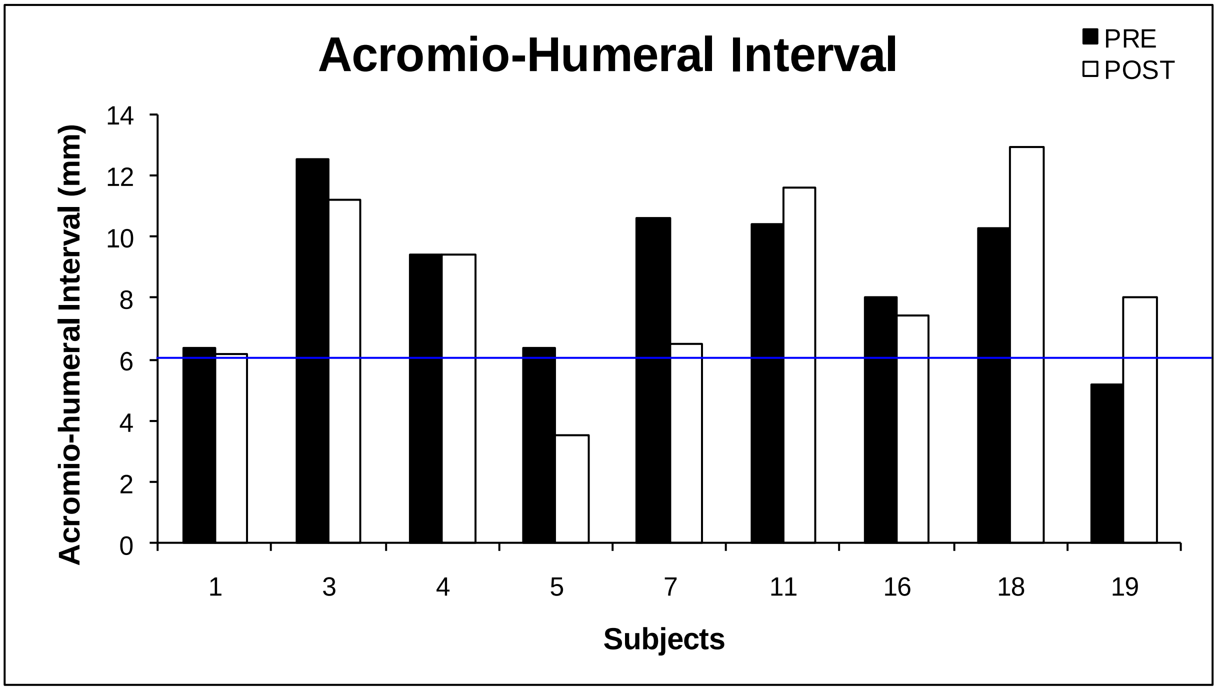

Figure 17. Acromio-humeral interval measurements, pre- and post- fatigue, for participants whose radiographic measurement could be clearly assessed; horizontal line at 6mm indicates a healthy AHI width (as defined by Cotton and Rideout 1964).

4.2 Quantification of Fatigue

Changes in EMG amplitude and Mean Power Frequency (MPF) (as well as subjective analysis [section 4.3]) throughout the fatiguing task were used as indicators of muscle fatigue. As well, an initial analysis of the fatiguing task was evaluated in terms of the average and peak muscle activity required of each muscle during the task. It was determined that supraspinatus and infraspinatus (as well as middle deltoid) were activated an average of 10-15% MVC; further, the peak activation was approximately 25-35% MVC. Pectoralis major was only activated approximately 5% MVC.

4.2.1 EMG Amplitude Changes

Changes in EMG amplitude resulting from the fatiguing exertion were quantified for each muscle examined: supraspinatus, infraspinatus, middle deltoid and pectoralis major. Three of the four muscles displayed significant increases in EMG amplitude in the post-fatigue state (Figure 18). EMG amplitude of pectoralis major also increased in the post-fatigue state, but was not statistically higher. Supraspinatus EMG amplitude increased an average of 13.49±9.87% MVC, with a maximum increase of 39.58% MVC and a minimum increase of 1.34% MVC. Infraspinatus EMG amplitude increased an average of 19.03±12.72% MVC, with a maximum increase of 49.21% MVC and a minimum increase of 1.33% MVC. Deltoid EMG amplitude increased an average of 18.80±11.45%, with a maximum increase of 39.14% MVC and a minimum increase of 0.46% MVC. For each of these three muscles, all 20 participants displayed an EMG amplitude increase in the post-fatigue state. Pectoralis major, despite not showing a significant increase in EMG amplitude, still increased a magnitude of 2.85±4.38%MVC with a maximum increase of 14.39% MVC and a maximum decrease of -1.26% MVC. In two of the 20 participants, a decrease in EMG amplitude was present for the pectoralis major. Individual changes in EMG amplitude are presented in Appendix A.

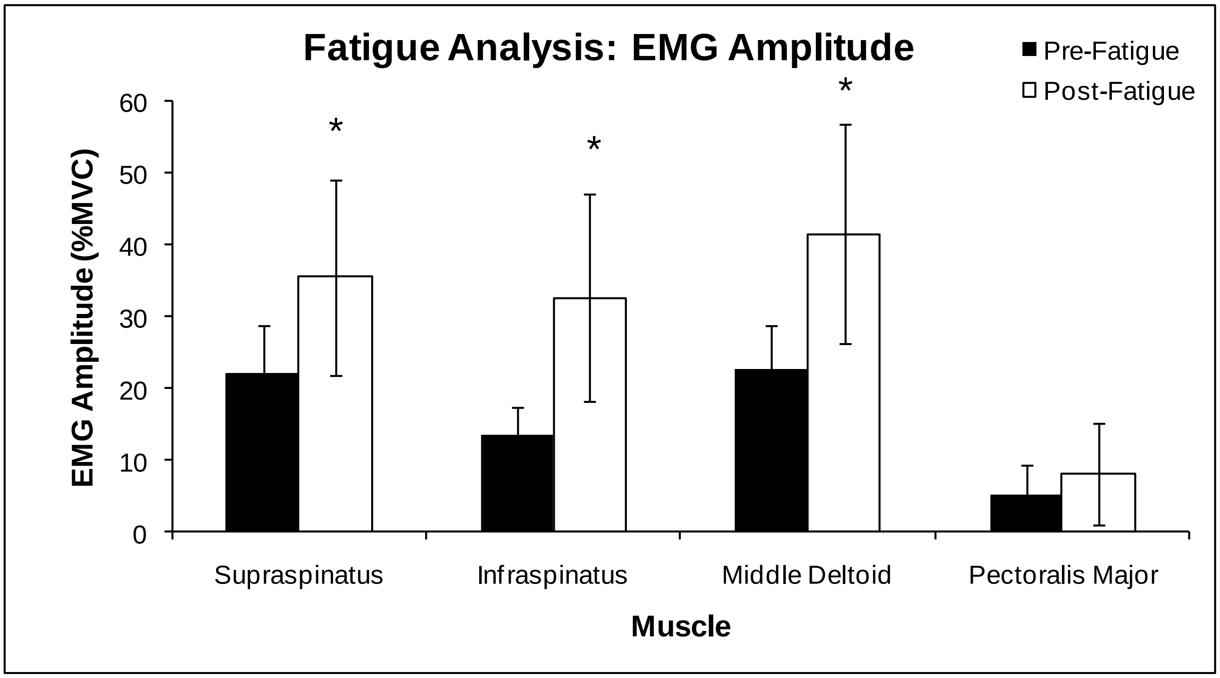

Figure 18. EMG amplitude changes for the supraspinatus, infraspinatus, middle deltoid and pectoralis major, in the pre- and post-fatigue state. Star (*) indicates significance ($p<0.05$).

4.2.2 Mean Power Frequency Changes

Shifts in mean power frequency (MPF) from the pre-fatigue to post-fatigue states were examined for each of the muscles monitored: supraspinatus, infraspinatus, middle deltoid and pectoralis major. Statistically significant negative shifts in MPF existed for the infraspinatus and middle deltoid (Figure 19). Infraspinatus displayed an average negative shift of 23.70±10.3%PreMPF in the post-fatigue state; middle deltoid displayed a similar negative shift of 16.29±7.54. In both of these muscles, all participants displayed this negative MPF shift, with a range from -9.88 to -42.10%PreMPF and -4.74to -31.93%PreMPF for infraspinatus and middle deltoid respectively. Two participants experienced a negative MPF shift in middle deltoid that was not considered significant (less than 8%). Supraspinatus and pectoralis major displayed statistically similar MPF values for pre- and post-fatigue states; with supraspinatus showing an average increase of 0.02±8.15%PreMPF and pectoralis major an average decrease of 7.47±17.76%PreMPF. For supraspinatus, 9 of 20 participants displayed the characteristic negative MPF shift present in the post-fatigue state; the range of MPF shift between participants was -18.85 to 10.18%PreMPF. However, only 2 out of 20 participants displayed a significant negative shift (greater than 8%). For pectoralis major, 15 of 20 participants displayed a negative shift in the post-fatigue state with a wide range of -41.08 to 38.00%PreMPF. However, only 11 out of 20 participants displayed a significant negative shift (greater than 8%). Individual changes in MPF are presented in Appendix B.

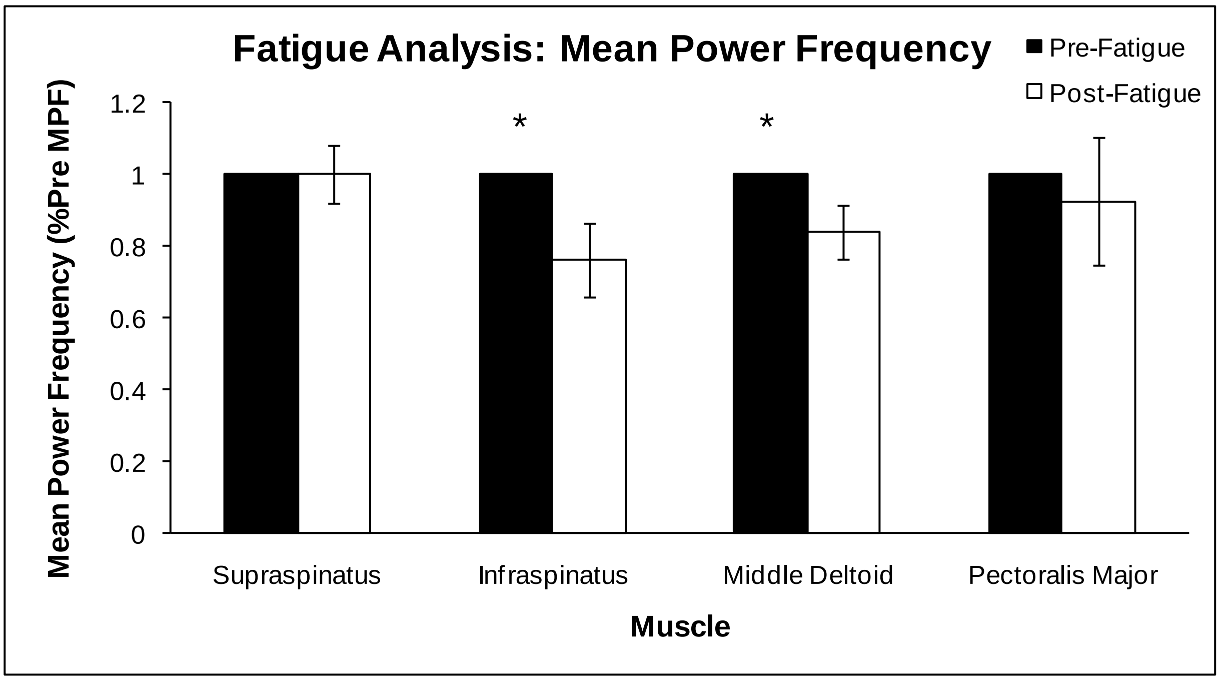

Figure 19. Mean power frequency changes for the supraspinatus, infraspinatus, middle deltoid and pectoralis major, in the pre- and post-fatigue state. Star (*) indicates a frequency decrease of greater than 8%.

4.3 Subjective Results

Psychophysical analyses and observation during the fatiguing task indicated high variability between participants for measures such as bottle weight lifted, time to fatigue and average rate of perceived exertion (RPE) ratings. As stated, the anthropometrically scaled bottle lifted during the fatiguing task was dependent upon the four maximal exertions performed on the hand dynamometer. The average bottle weight lifted was 16.5±3.27N (1.68 ±0.33kg), which coincided with 15% of the participants' maximal voluntary force (average 110.01±21.80N). This scaled weight caused participants to fatigue after performing a minimum of 4 to a maximum of 15 minutes of the fatiguing task (Figure 20); the average time to fatigue was 7.85 ± 3.42min. Due to the high variability in time performing the fatiguing task, the rate of perceived exertion (RPE) after each minute also varied substantially for each participant (Figure 21). The biggest drop off of participants was between the 5 to 7 minute marks, with over half of the participants (12) unable to continue after 8 minutes. Participants continuing the exercise over 11 minutes indicated RPE values of 9 or 10 for the remaining 1-4 minutes; this decreased the suspicion of participants dropping out sooner than they should have. Each participant reported a RPE of 10 and verbally indicated they were too fatigued to continue, before proceeding to the second set of radiographs.

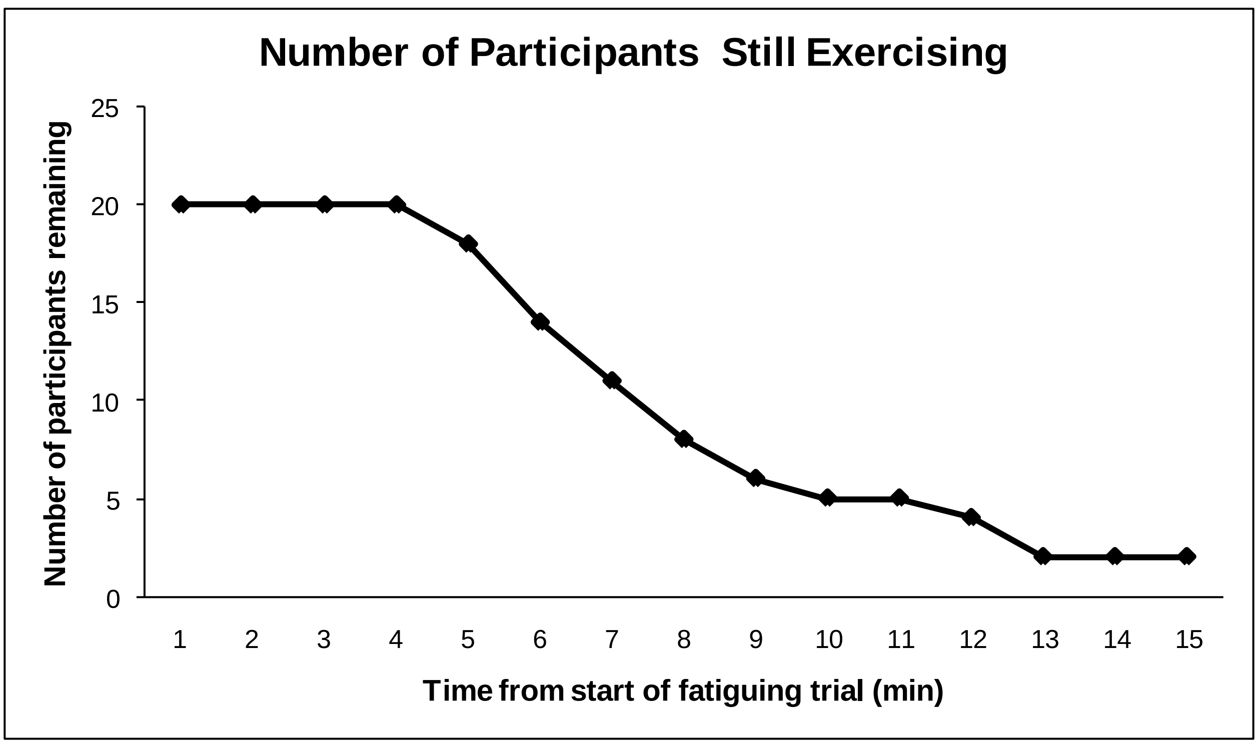

Figure 20. Number of participants still exercising after each minute of the fatiguing task.

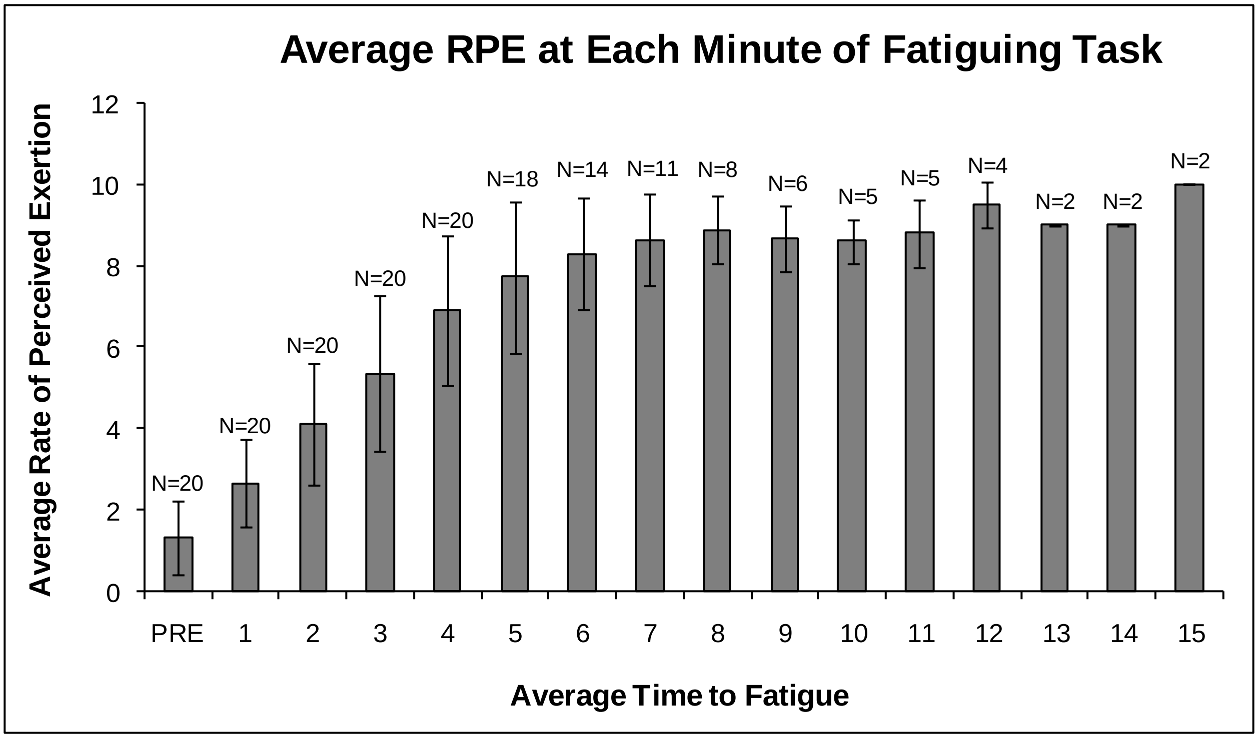

Figure 21. The average rate of perceived exertion (RPE) reported after each minute of performing the fatiguing task; N is the number of subjects remaining after each minute of the fatiguing task.

4.4 Inter- and Intra- observer Reliability

Intraclass correlation coefficients were calculated to assess inter- and intra- observer reliability of excursion measurements (SPSS software, Illinois, USA). Both inter- and intra- observer analysis were determined to have excellent agreement, with correlations of 0.92 (95%CI = 0.82 to 0.97) and 0.93 (95%CI = 0.84 to 0.97) respectively.

V. Discussion

Results from this study accept two out of three research hypotheses initially stated for this study. The first hypothesis of this research was that the humeral head center would migrate superiorly with respect to the center of the glenoid cavity following fatigue. Experimental data supported this hypothesis implying that industrial jobs requiring overhead and/or repetitive work may cause upper extremity musculoskeletal disorders, particularly impingement. The second hypothesis was that this superior migration would be at a magnitude similar to those reported for patients with full thickness rotator cuff tears. Further, it was hypothesized that the changes in acromio-humeral interval in the pre- and post- fatigue states would resemble those determined from healthy participants and those with rotator cuff tears, respectively. The magnitudes of excursion measured was found to be less than those documented in patients will full thickness rotator cuff tears of the supraspinatus, infraspinatus and subscapularis, but similar to the excursion present in patients with tears of the supraspinatus and infraspinatus (Bezer et al. 2005). The significant decrease in acromio-humeral interval present in rotator cuff patients was not present after participants were fatigued (Golding 1962). The third hypothesis regarding the trend of excursion as an effect of arm angle was supported by the data; in the pre-fatigued shoulder there was an upward excursion at low angles of abduction followed by a downward excursion at high angles, whereas in the fatigued shoulder there was continuous upward excursion.

5.1 Evaluation of Results with Respect to Previous Research

Case-control studies for healthy shoulders versus those with varying degrees of shoulder injuries examined excursion as a function of arm angle elevation. Unfortunately, there is no way to assess pre- and post- injury excursion at individual angles of abduction. However, studies, such as the current one, that examined healthy and ‘facilitated’ injury, by means of fatigue, were able to compare pre- and post- excursion measurements at each arm angle, as well as excursion as an effect of arm angle within fatigue states.

5.1.1 Direction of Excursion

Results indicated that the majority of participants displayed superior humeral head excursion as an effect of both arm angle and fatigue. With respect to arm angle, a characteristic trend for excursion existed as healthy patients abducted their arm above 0˚. Graichen et al. (2000) examined humeral head excursion during active and passive abduction, and found that during active abduction, an initial superior migration was present, but at 90˚ and further at 120˚ of abduction, the humeral head had migrated inferiorly to a more central position (Figure 22); this finding was consistent with that of Poppen and Walker (1976). The theory regarding superior translation was that the upward pull of the deltoid muscle during the first stages of abduction was strong enough to overcome the resistive or stabilizing effect of the rotator cuff muscles. However, in a healthy shoulder, above 90˚ of abduction, the centralizing effect of the rotator cuff muscles was more active; thus causing an inferior translation (Graichen et al. 2000). Yanagawa et al. (2008) supported this by finding that the abducting force of the middle deltoid increased significantly until 75˚ of abduction, then decreased; thus so did the upward pull. This same trend of initial superior translation followed by inferior translation was also present in these results (Figure 23). The main effect of angle, although only showing the superior translation to be significant, began to show this downward shift in humeral head position as the arm was abducted above 90˚ (Figures 15 and Figure 23). Although, by looking at pre- and post-fatigue states separately, this trend was only present in the pre-fatigue state (Table 4, Figure 23). Thus, this late centralizing effect generated by the rotator cuff, present in the healthy shoulder was apparently reduced due to muscular fatigue, and consequently, continuous superior translation was present (Figure 23).

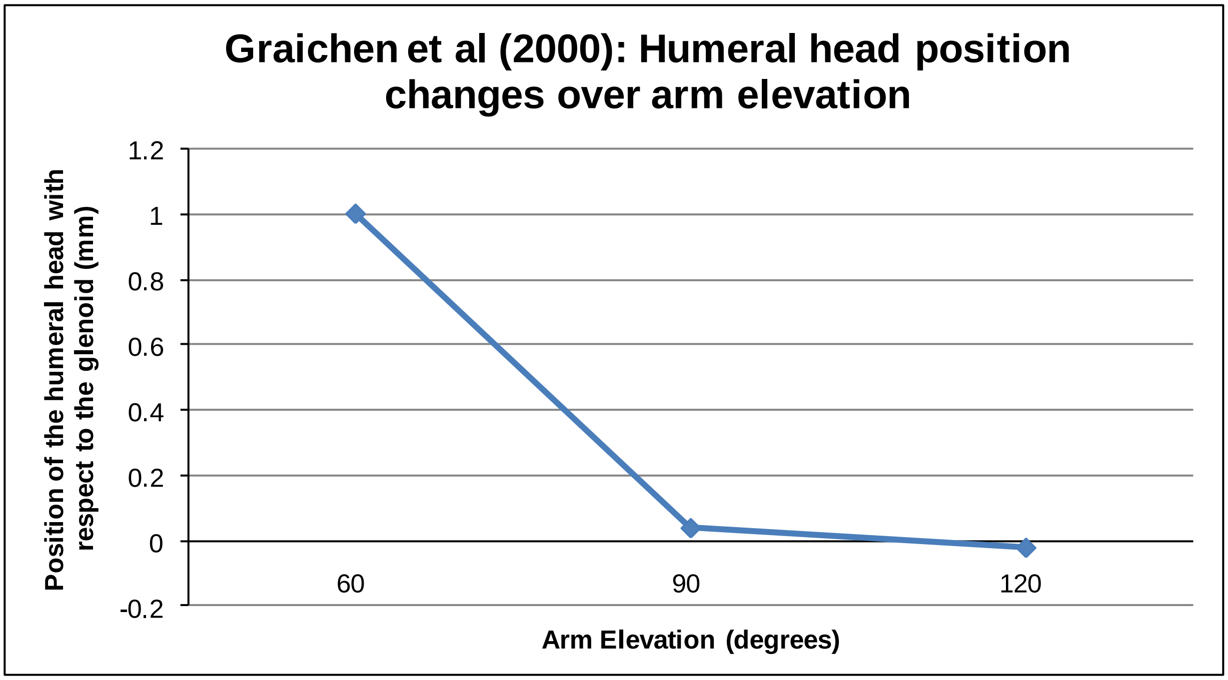

Figure 22. Graph from Graichen et al. (2000) displaying changes in humeral head position with respect to arm elevation in 15 healthy participants.

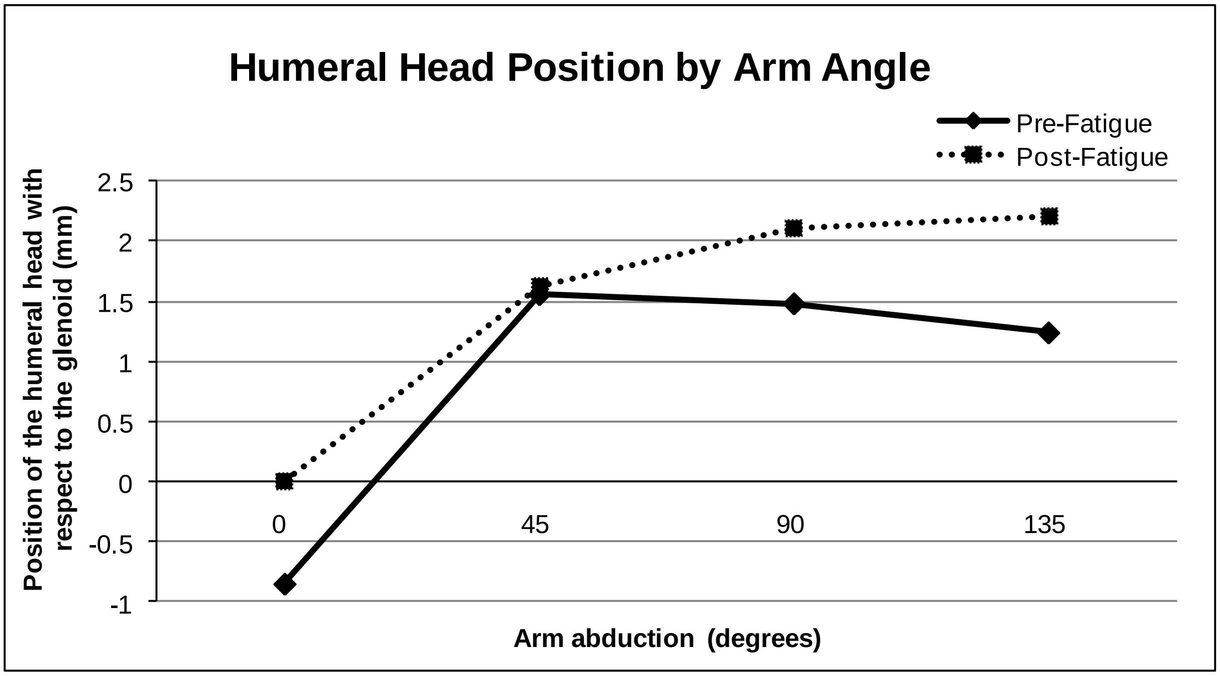

Figure 23. Graph showing humeral head position as the arm was abducted away from neutral; solid line indicates the position in the pre-fatigued state, dashed line indicates the position in the post-fatigued state.

In studies where a pre- and post- or a case-control measurement of excursion was evaluated at a specific arm angle, there was a characteristic superior excursion present at each angle of abduction following fatigue or injury (Bezer et al. 2005; Cote et al. 2009; Chen et al. 1999; Teyhen et al. 2008). One explanation for this translation centers on the inability of the fatigued rotator cuff muscles to resist the upward pull of the deltoid muscle, which thus allows superior translation of the humeral head. In our study, approximately 70% of the post-fatigue radiographs displayed this superior excursion; 65% at 0˚ arm angle, 60% at 45˚, 65% at 90˚ and 85% at 135˚. However, across all arm angles, there was an average of 30% in which inferior translation was present (Tables 5-8). Previous work identified mean negative excursions in healthy or uninjured participants (Bezer et al. 2005; Keener et al. 2009) at 30˚ of abduction. These findings coincided with data from the current investigation at a 45˚ arm abduction angle, which had the highest percentage of negative excursion (40%). A proposed theory for the inferior excursion present at the low levels of abduction (45˚) is that the deltoid was fatigued in addition to, or instead of the rotator cuff; thus the level of upward pull would also be less than the resistance/downward pull of the rotator cuff muscles. In all participants at the 45˚ arm angle, where negative excursion was present, the deltoid had a decline in MPF greater than 8%, characteristic of fatigue (Oberg et al. 1990). Further, when negative excursion occurred along with deltoid fatigue, the supraspinatus was not fatigued 50% of the time (using amplitude increases greater than 15% as criteria for fatigue) and 88% of the time (using decreases in MPF as criteria for fatigue). Thus, these data support the proposed theories, as rotator cuff fatigue was indicative of humeral head excursion. However, deltoid fatigue, in addition to or in the absence of rotator cuff fatigue, may limit the superior translation or even result in inferior translations.

5.1.2 Magnitude of Excursion

The magnitude of humeral head excursion, with respect to fatigue and arm angle, displayed some unexpectedly low and high results, respectively. Overall, there was an expected statistically significant superior excursion in the post-fatigue state, with a mean magnitude of 0.63±1.76mm. As well, there was a significant effect of arm angle, with mean excursion of 2.09±2.36mm in the pre-fatigue state and 2.20±2.11mm in the post-fatigue state as the arm was abducted from 0˚ to 135˚. Although the excursion levels were statistically significant, the magnitudes of post-fatigue excursions at each arm angle individually were slightly less than in several previous studies of rotator cuff muscle fatigue (Cote et al. 2009; Chen et al. 1999; Teyhen et al. 2008). However, the magnitude of excursion as a function of arm angle was much larger than those previously found (Deutsch et al. 1996; Graichen et al. 2000; Poppen and

Walker 1976). Humeral head excursion occurs on a very small scale (fractions of millimeters); thus, although the magnitudes were generally smaller than expected, the magnitude of excursion reported in the literature has a wide range that includes our findings.

Other work that experimentally disabled the rotator cuff through fatigue provide a more direct method to compare humeral head excursions at individual arm angles, as well as over the abducting range. The few research studies available have found similar trends; though the magnitudes of excursion at individual arm angles display some differences (Cote et al. 2009; Chen et al. 1999; Teyhen et al. 2008). Three research studies in addition to this current study measured humeral head excursion on radiographs of the anterior-posterior view of the glenohumeral joint; radiographs were taken at the same four angles of abduction, both before and after a variable fatiguing protocol and measurements were performed using the same technique (Table 9).

Table 9. Comparison of humeral head excursion measurements at each examined arm angle for four research studies, including this current study.

	Current Study	**Chen et al (1999)**	**Teyhen et al (2008)**	**Cote et al (2009)**
Arm Angle	**Excursion (mm)**	**Excursion (mm)**	**Excursion (mm)**	**Excursion (mm)**
0°	0.86 (± 2.16)	1.2 (± 0.67)	1.09 (± 2.51)	0.08
45°	0.07 (± 1.39)	0.4 (± 0.89)	1.17 (± 1.88)	1.45
90°	0.62 (± 1.55)	1.3 (± 0.72)	1.05 (± 2.77)	1.43
135°	0.97 (± 1.29)	1.0 (± 0.64)	-0.15 (± 3.35)	1.92

Though each of the four previous studies found significant excursion due to rotator cuff fatigue, excursion magnitudes were highly variable. Excursion over the abducting range (0˚ to 135˚) was also examined in each fatigue state, for each of the four studies (Table 10). However, in these studies, excursion was computed by comparing only the 0˚ arm position to the 135˚ arm position in each of the fatigue states. This method of evaluating total excursion is limited due to non-uniform translation throughout the range of abduction. This may result in neglecting group effects and masking of the true excursion findings. The current study measured a rather modest 0.11±3.17mm (or nil) excursion from pre- to post-fatigue states when comparing the excursion change between the ends of the abduction range in each fatigue state (Table 10). However, by evaluating humeral head position both between and within fatigued states, it was shown that the initial position of the humeral head was shifted upwards due to fatigue and thus, subsequent measurements within that group were also shifted upwards. Thus, it is important to report changes that occur both within as well as between arm abduction angles and fatigue states, in order to report a complete picture of the findings.

Table 10. Comparison of humeral head excursion in the pre- and post- fatigue states over the arm abduction range; four research studies are compared, including this current study.

	Current Study	**Chen et al (1999)**	**Teyhen et al (2008)**	**Cote et al (2009)**
Fatigue	**Excursion (mm)**	**Excursion (mm)**	**Excursion (mm)**	**Excursion (mm)**
PRE	2.09 (± 2.36)	0.3 (± 0.5)	1.7 (± 2.82)	3.0
POST	2.20 (± 2.11)	1.3 (± 0.6)	0.46 (± 3.11)	4.8

Results from this study were similar to those examining patients with varying degrees of rotator cuff injuries. Excursion measured in the pre-fatigued state was greater than those commonly reported for healthy patients; however, post-fatigue excursion was similar to that reported in injured patients. Again, it is important to note that excursion values reported between studies were extremely variable, including those reported for healthy patients. Studies by Poppen and Walker (1976), Deutsch et al. (1996), Bezer et al. 2005 and Keener et al. (2009) found mean excursion values ranging from -2.0mm to 1.09mm for healthy patients and 0.26mm to 4.5mm for patients with varying degrees of rotator cuff tears. Bezer et al. (2005) examined three injury groups: (1) isolated supraspinatus tears, (2) supraspinatus and infraspinatus tears and (3) supraspinatus, infraspinatus and subscapularis tears, and found excursion values of 1.4±1.2mm, 2.0±1.7mm and 4.5±0.5mm, respectively. Thus, based on this data, the post-fatigue excursion measurement, determined to be 2.20±2.11mm would be indicative of fatiguing only the supraspinatus and infraspinatus. This finding indicates one of two possibilities: (1) the fatiguing task was not capable of fatiguing the subscapularis, (2) even when muscles were fatigued they were still capable of resisting superior humeral head translation; whereas physical injury inhibited this ability. Subscapularis was not monitored in the present study due to its deep placement and the difficulty of placing indwelling EMG electrodes in this muscle. Additionally, the invasiveness of these electrodes may have influenced the performance of the fatiguing task by participants, and the wires may have limited the effectiveness of the radiographs. An interesting similarity between the findings of Deutsch et al. (1996) and this current research was, that despite reporting a small pre- to post- excursion change, they found that the initial resting position (0˚) of the humeral head was shifted upwards in the fatigued state, similar to that seen in the current study (Table 4). This further reinforces the importance of examining both between and within group changes in order to document the entire effect of injury or fatigue.

Therefore, based on past research, there are no concrete magnitudes for excursion following injury or a fatiguing protocol due to variability in individual geometry. However, magnitude comparison between research studies allows evaluation of trends in humeral position. Further, these results need to be interpreted by means of clinical significance, rather than individual magnitude comparisons to previous findings.

5.1.3 Acromio-humeral Interval

A narrowed acromio-humeral interval (AHI), which is the space between the humeral head and the acromion, is considered evidence of impingement, as decreased width of this space may cause compression of the interposed tissues and subsequent injury. AHI provides an alternate method to humeral head excursion for examining the altered mechanics of the shoulder due to fatigue or injury. No specific AHI width corresponds to injury likelihood definitively. However, there are guidelines based on large scale studies on healthy and rotator cuff patients that provide width measurements indicative of injury. Generally, the AHI width of a healthy shoulder is above 6mm (Cotton and Rideout 1964; Golding 1962; Weiner and MacNab 1970). Cotton and Rideout (1964) measured AHI width in patients with full-thickness rotator cuff tears and found values that ranged from 1 to 4mm. Thus, a grey area between 4 and 6mm exists where injury diagnosis based solely on the AHI width measurement was unclear. For some radiographs in this study, it was difficult to clearly identify the undersurface of the acromion and still have a clear view of the joint center in order to perform excursion measurements. Thus, AHI width was only reported for those radiographs where the landmarks were clearly identifiable. Results were inconsistent and showed no trends related to fatigue. Only one patient had a pre-fatigue measurement that fell within the "healthy" range (6.4mm) and a post-fatigue measurement that fell within the "injured" range (3.5mm) (Figure 17). It was expected that in radiographs showing excursion, decreased AHI widths would be present, however this was not always the case.

Difficulty in assessing the AHI width can be explained by the known interpersonal variability in acromial morphology. Bigliani et al. (1991) classify acromial shape with three different types: (1) flat, (2) curved, and (3) hooked (Figure 24). Although acromial morphology was not examined in this research, the shape of the acromion has implications for measurement of the subacromial space. AHI measurements were straightforward for some participants (Figure 25) and problematic for others (Figure 26). Their radiographs demonstrate that this difficulty may be largely attributed to differences in acromial orientation and morphology. Fehringer et al. (2008) reported that small changes in arm position and radiographic beam orientation can affect AHI measurements. However, by comparing the pre- and post- fatigue radiographs of each participant, the measurement difficulty was subject specific and therefore not likely due to positioning, but rather due to intrinsic geometry. In order to identify both the acromial shape and AHI width, radiographs should be taken using a lateral or “supraspinatus outlet” view (Bigliani et al. 1991; Bright et al. 1997; Jacobson et al. 1995). However, this view would preclude humeral head excursion measurements. Acromial shape influences rotator cuff disorders, as a hooked acromial shape is associated with a higher incidence of tears (Bigliani et al. 1991). It can be argued that, AHI width and acromial morphology are more important than glenohumeral mechanics in discriminating between healthy and injured shoulders. In this study, however, all participants were evaluated and determined to be healthy; thus mechanical changes following the fatiguing protocol were considered more germane to the research questions addressed by this study.

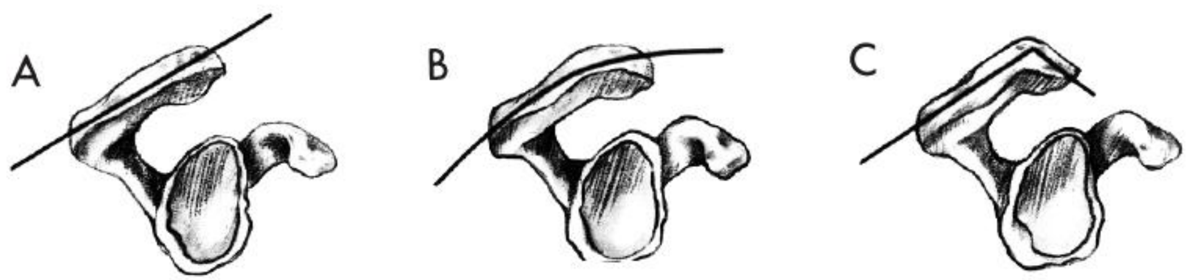

Figure 24. Classification of acromial morphology according to Bigliani et al. 1986 (Figure from Bright et al. 1997): (A) Type I: flat; (B) Type II: curved; (C) Type III: hooked.

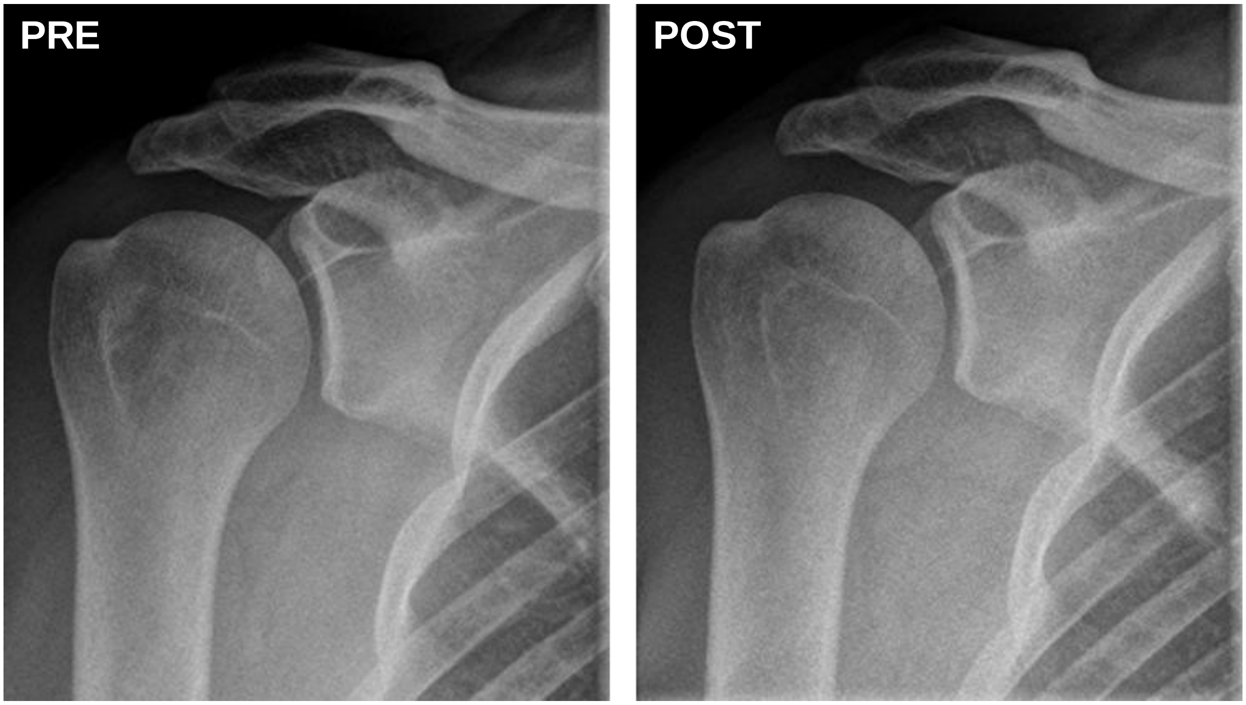

Figure 25. Pre-fatigue and Post-fatigue radiographs of a participant whose AHI was clearly measureable.

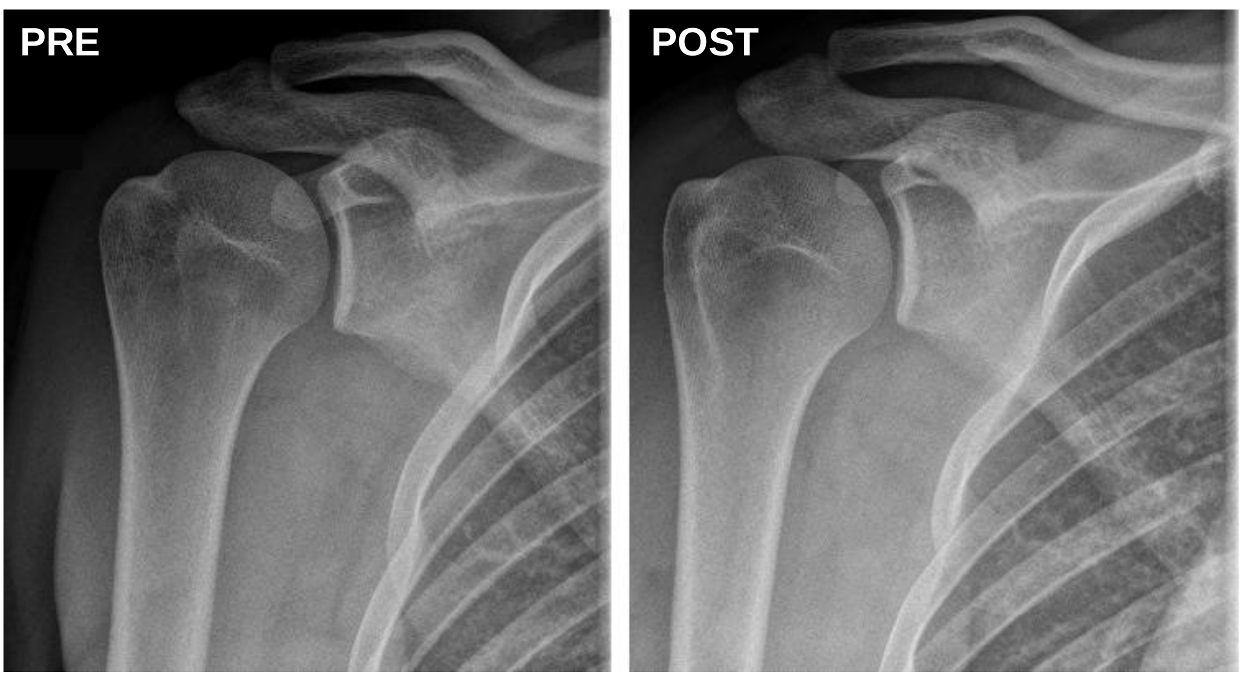

Figure 26. Pre-fatigue and Post-fatigue radiographs of a participant whose AHI was clearly not measureable and therefore not reported.

5.2 Affirmation of Rotator Cuff Fatigue

Results from EMG data supported psychophysical reports that participants were in fact fatigued, particularly for the infraspinatus. Infraspinatus is the primary rotator cuff muscle active in resisting the upward translation of the humeral head in the glenoid cavity (Keener et al. 2009); thus, it was particularly important to debilitate this muscle during the fatiguing task. Two physical indicators from EMG were examined for each of the four muscles (supraspinatus, infraspinatus, middle deltoid and pectoralis major) measured: amplitude and mean power frequency.

EMG amplitude was reported in terms of percentage of maximum capability, by means of normalizing EMG to maximum voluntary contractions; this allowed comparison between subjects and trials (Chopp et al. 2009a; Knutson et al. 1994). Initial EMG measurements for each muscle were compared to EMG measurements of each participant's last or 'fatigued' trial, and changes in amplitude were examined. Infraspinatus, middle deltoid and supraspinatus showed significant average amplitude increases over 10%MVC, providing evidence of fatigue. Pectoralis major showed a statistically insignificant increase of less than 5% indicating that the muscle was most likely not fatigued (Figure 18). Although an increase in EMG amplitude is not a direct measure of fatigue, significant bursts or increases in mean EMG amplitude have been associated with fatigue onset (Potvin 1997; Viitasalo and Komi 1977). Further, there is no explicit cut off value indicative of fatigue; Potvin (1997) found increases in biceps EMG amplitude of 34.6% MVC and 10.5% MVC after repetitive elbow flexion and extension respectively, and deemed these increases to be significant. EMG amplitude increases found in this study for the supraspinatus, infraspinatus and middle deltoid were larger than the low-end of those determined significant by Potvin (1997); thus according to the criteria used in past research, these three muscles with significant amplitude increases can be considered fatigued.

Mean power frequency (MPF) was also used to quantify muscle fatigue. Like EMG amplitude, there is no specific cut off value indicating that muscles are definitely fatigued; however, a decrease in MPF of 8% or more has been recommended as indicative of fatigue (Oberg et al. 1990; Szucs et al. 2009). Based on this criterion, the infraspinatus indicated fatigue in all participants and middle deltoid in all but two participants; however, on average, the supraspinatus and pectoralis major muscles did not show the characteristic MPF decline that is typically seen when fatigued (Figure 19).

Thus based on these results, there was conclusive evidence that the infraspinatus and middle deltoid were fatigued by performing this task. They had both a significant increase in EMG amplitude and a significant decrease in MPF. Supraspinatus showed inconclusive evidence for fatigue, as the characteristic amplitude increase was present, but not the decline in MPF. Pectoralis major showed conclusive evidence against fatigue; characteristic signs for fatigue were not present in EMG amplitude or mean power frequency.

5.3 Shoulder Mechanics and Individual Geometry

5.3.1 Mechanics of the Rotator Cuff Muscles Affecting Translation

The simplified mechanism of superior humeral head translation is well-established. In a neutral posture, the line of action of the deltoid is positioned to pull the humeral head superiorly. The rotator cuff functions to prevent this upward pull, while also compressing the humeral head in the glenoid cavity (Figure 27; Deutsch et al. 1996). If the rotator cuff is dysfunctional, superior translation of the humeral head and subsequent impingement may occur (Weiner and

MacNab 1970). Historically, the deltoid vector has been drawn vertically upwards when the arm is positioned at neutral (0˚ of abduction) (Figure 27; Deutsch et al. 1996). This simplified free body diagram of the shoulder excludes some aspects of shoulder muscle mechanical function (i.e. deltoid wrapping). Further, this simplification does not consider effects of arm abduction on the moments and lines of action of the deltoid and rotator cuff muscles. Thus, in order to fully understand at which arm postures a person is at greater risk for superior humeral head translation, these concepts need to be more carefully addressed.

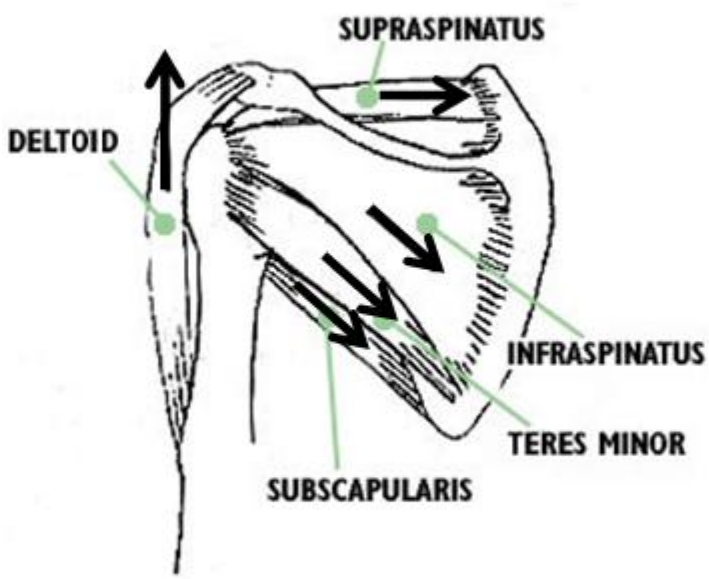

Figure 27. Diagram displaying a posterior view of the rotator cuff; simplified depiction of the lines of action of each muscle has been indicated with black arrows (PreventDisease.com).

The humeral head is often assumed to be spherical. Thus, as the arm is abducted, the moment arm of the deltoid remains relatively unchanged due to its modeled tangency to the humeral sphere. This has been shown experimentally (Figure 28; Kuechle et al. 1997). Thus, the muscle force required to achieve a given abduction moment also remains unchanged, as the moment is the cross product of the force and moment arm. However, due to the changes in the deltoid line of action, the superior shear and compressive components change as the arm is abducted, explaining the different magnitudes of superior humeral translation at different arm abduction angles. Ackland and Pandy (2009) measured the muscle lines of action of 18 different upper extremity muscles including multiple sub-regions of the deltoid and the rotator cuff muscles. These lines of actions were computed during scapular-plane abduction (similar to this research) and sagittal plane flexion using a musculoskeletal model. They found that with respect to the glenoid axis, the lines of action of the rotator cuff muscles remained relatively unchanged through the range of abduction. The deltoid line of action, however, changed from superior to inferior as the arm was abducted in the scapular plane. Thus, changes in humeral head translation may be best explained by changes in the deltoid line of action throughout the range of abduction.

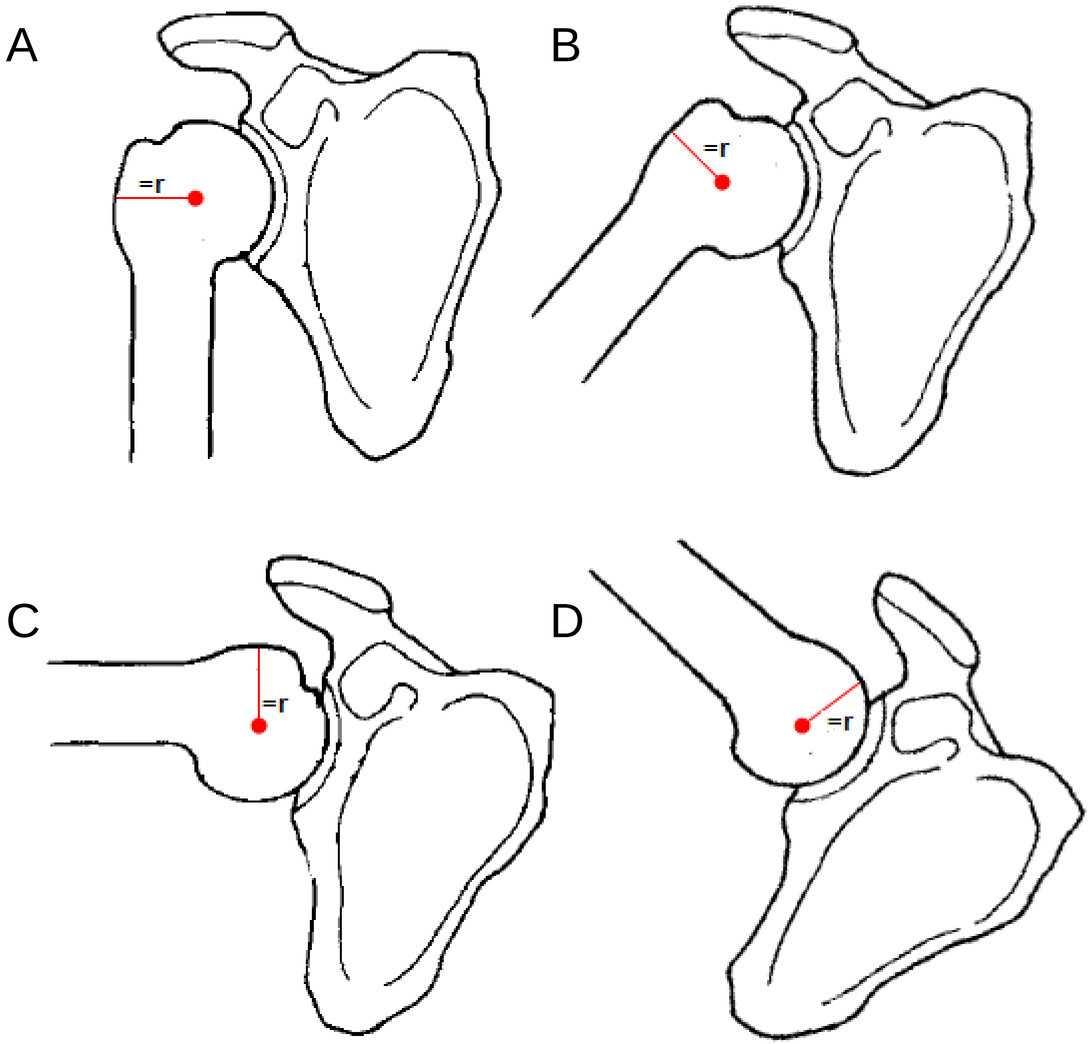

Figure 28. Diagram depicting the deltoid moment arm (r) throughout the range of abduction; (A) 0˚ abduction, (B) 45˚ abduction, (C) 90˚ abduction, (D) 135˚ abduction.

The directional change of the deltoid line of action as the arm is abducted away from neutral is primarily responsible for differences in humeral head translation. In a neutral posture with the arm at 0˚ of abduction, the deltoid is directed such that the superior shear component is substantially larger than the compressive component; thus acting to pull the humeral head superiorly (Figure 29). As the arm is abducted to 45˚ and then to 90˚, this shear component begins to decrease, and the deltoid starts acting more compressively with respect to the glenoid cavity (Figures 30 and 31). At 135˚ of arm abduction, the deltoid line of action is directed more inferiorly (with respect to a global, gravity-based reference system) (Figure 32). Further, as the arm is abducted from neutral, the line of action of the rotator cuff muscles with respect to the changing glenoid axis remains constant (Note: consistent θ in Figures 29-32) (Poppen and Walker 1978). Thus, at neutral and at initial phases of abduction, the rotator cuff muscles have difficulty overcoming the large shear component of the deltoid, and superior humeral head translation is more likely. As the arm is abducted to 90˚, the deltoid orientation becomes more favourable for glenohumeral stabilization and therefore, the decreasing upward shear component of the deltoid coupled with the consistent inferior direction of the rotator cuff allows resistance to upward translation. As the arm is abducted to 135˚ the deltoid's line of action acts to pull in an inferior direction; thus with less superior shear of the deltoid to resist, the rotator cuff is able to pull the humeral head to a more inferior position (Figure 32). This provides an explanation as to why, in a healthy shoulder, superior humeral head excursion primarily exists until 90˚, followed by inferior excursion at higher abduction angles (Figure 22; Graichen et al. 2000).

Examining glenohumeral mechanics solely with respect to a global, gravity-based reference system is limited, as the scapula also rotates as a function of humeral elevation. It is important to note that although the scapulohumeral rhythm is not 1:1, the scapula does rotate as a function of arm angle. The ratio of humerus to scapula movement is approximately 2:1, with the scapula moving 1˚ for every 2˚ of humeral elevation above 30˚ (Ackland and Pandy 2009). Thus, at high arm angles, it may not necessarily be a superiorly oriented deltoid shear component that is responsible for creating subacromial impingement; but rather a more compressively oriented vector. Nonetheless, the orientation of the deltoid vector is directed more towards the lateral surface of the acromion rather than the glenoid cavity at low arm abduction angles and thus, the incidence of superior humeral head migration should still be more prevalent at low abduction angles than at high (in a healthy shoulder). However, in the presence of rotator cuff fatigue and/or tears, the more favourable orientation of the deltoid alone (at high arm angles) may be insufficient to maintain enough inferior pull as occurs in a healthy shoulder; and superior translation persists as the arm is abducted above 90˚. Our current data supports this mechanical explanation. In the presence of rotator cuff fatigue, the late centering (inferior translation) effect generated by the rotator cuff that was present in the healthy, un-fatigued shoulder was reduced and consequently, continuous superior translation existed (Figure 23).

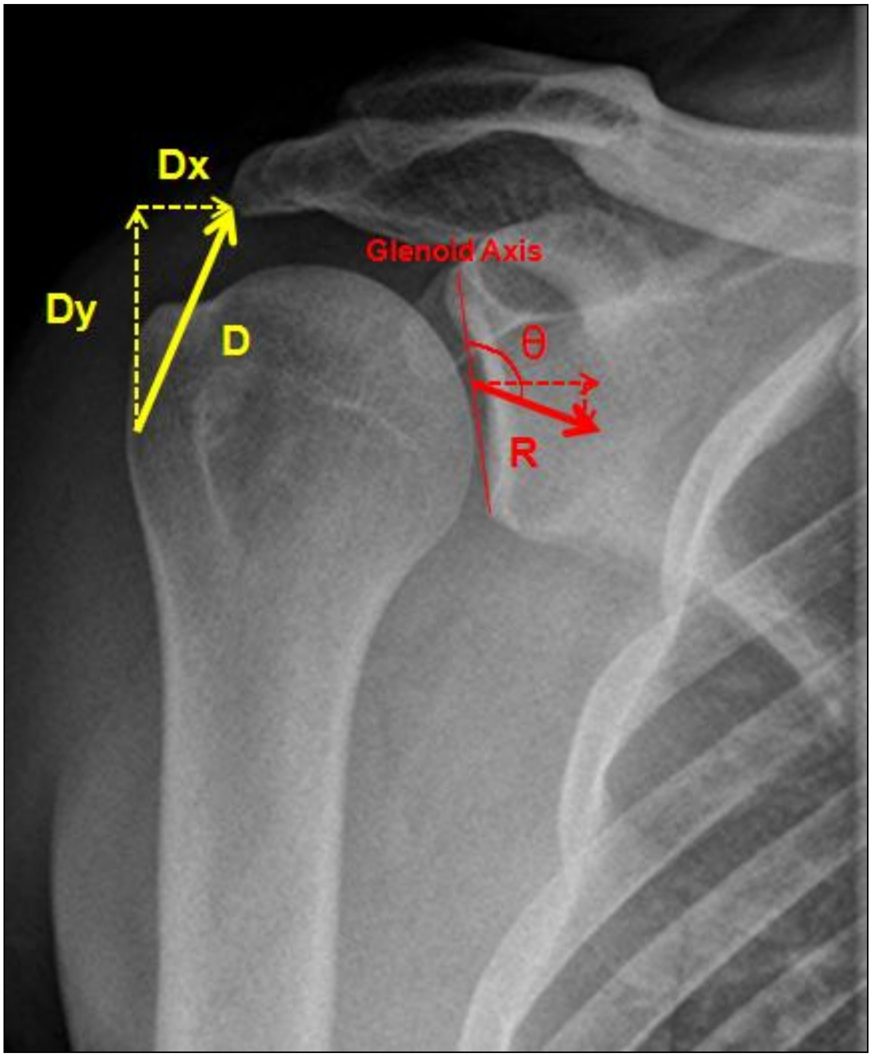

Figure 29. Radiographs depicting the force vector and respective lines of action of the deltoid (D) and the net rotator cuff muscles (R) at 0˚ of arm abduction; θ is the angle between the glenoid axis and the rotator cuff line of action.

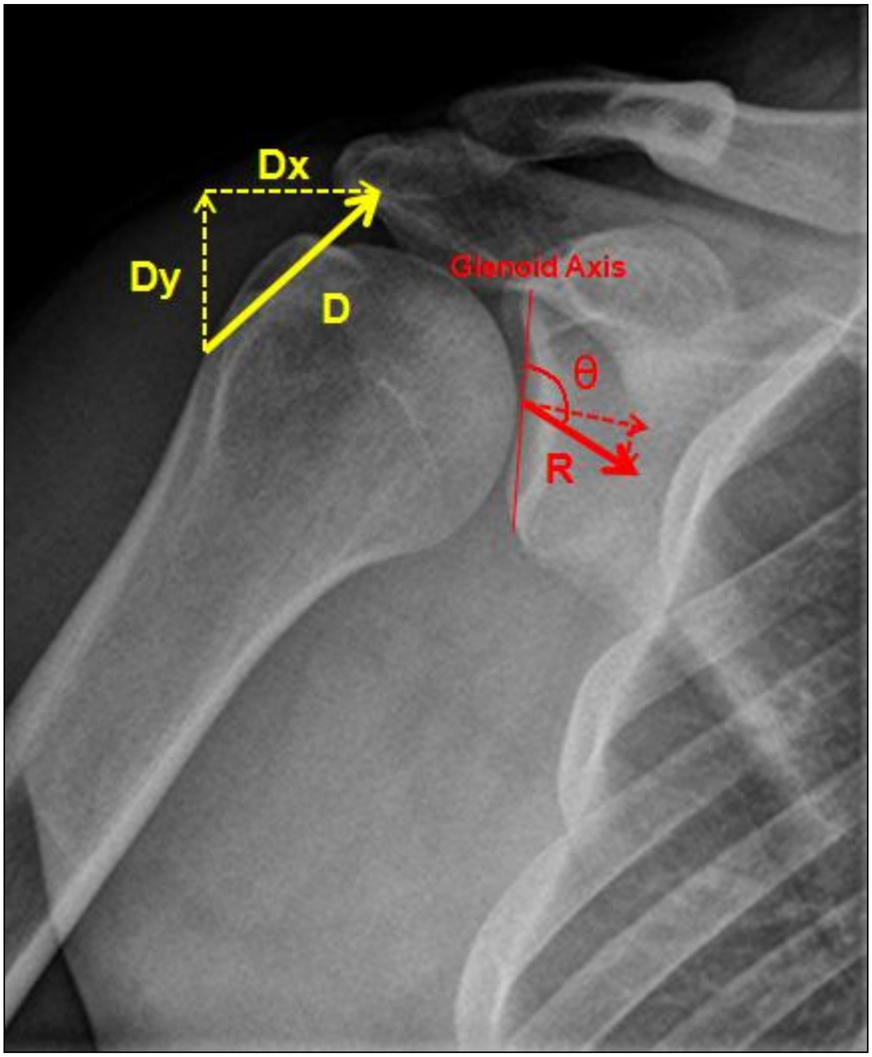

Figure 30. Radiographs depicting the force vector and respective lines of action of the deltoid (D) and the net rotator cuff muscles (R) at 45˚ of arm abduction; θ is the angle between the glenoid axis and the rotator cuff line of action.

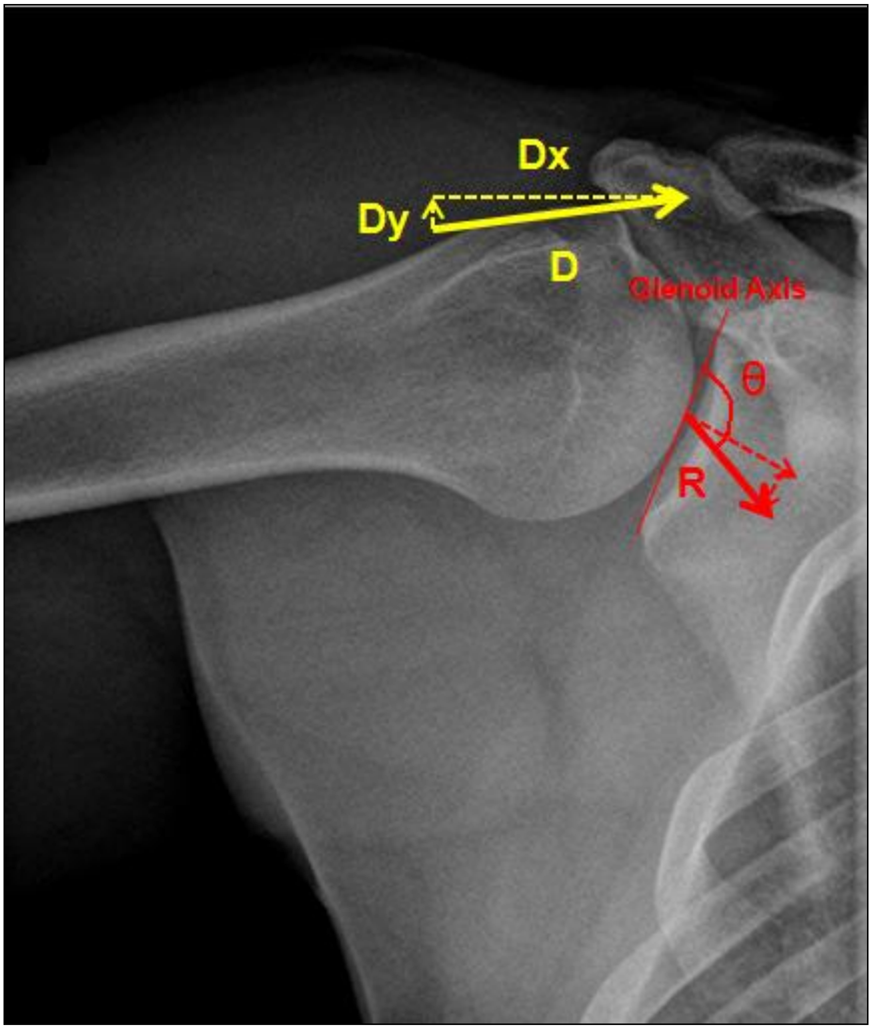

Figure 31. Radiographs depicting the force vector and respective lines of action of the deltoid (D) and the net rotator cuff muscles (R) at 90˚ of arm abduction; θ is the angle between the glenoid axis and the rotator cuff line of action.

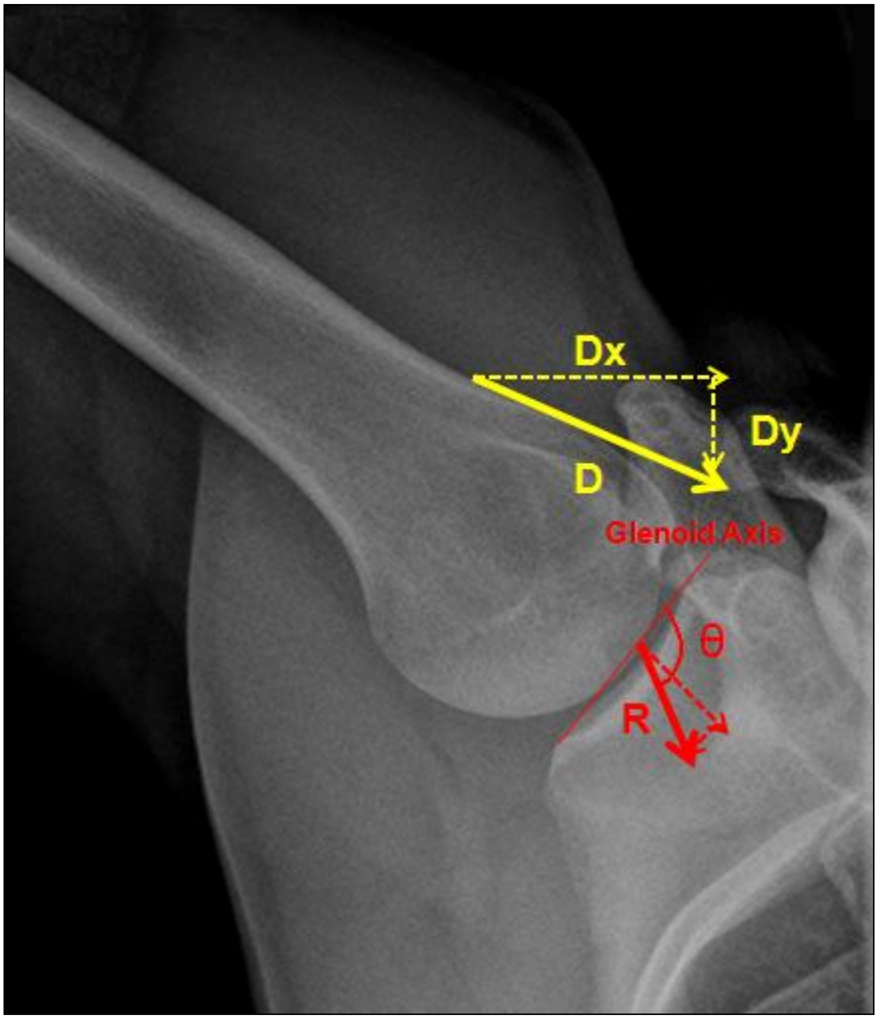

Figure 32. Radiographs depicting the force vector and respective lines of action of the deltoid (D) and the net rotator cuff muscles (R) at 135˚ of arm abduction; θ is the angle between the glenoid axis and the rotator cuff line of action.

In this study, excursion existed with inconclusive evidence of entire rotator cuff fatigue. For instance, if the supraspinatus was not fatigued, it is possible that individual muscles of the rotator cuff act differently on the humeral head or stabilize more or less than others. Keating et al. (1993) studied the relative strength of the rotator cuff muscles and determined that the force generating capacity of the subscapularis was 53% of the cuff moment, the infraspinatus was 22%, the supraspinatus was 14% and the teres minor was 10%. Thus, the subscapularis was the strongest muscle of the rotator cuff, followed by the infraspinatus; whereas the supraspinatus and teres minor have relatively low potential for contribution. This was supported by Yanagawa et al. (2008) who determined that the middle deltoid, infraspinatus and subscapularis were the only muscles of the eleven examined in their model that developed significant forces during abduction, and further that the infraspinatus exerted a small adduction torque which functioned to pull the humeral head inferiorly. If the lines of action of the rotator cuff muscles are examined it can be seen that, in an anatomical position, the supraspinatus is oriented to compress the humeral head into the glenoid cavity (Ackland and Pandy 2009), however, the infraspinatus (and subscapularis anteriorly) is directed inferiorly, thus actively resisting the upward pull of the deltoid (Figure 27). These lines of action, coupled with the muscle strength provide an explanation as to why infraspinatus fatigue, in the absence of supraspinatus fatigue, would still cause the humeral head to translate superiorly. The subscapularis similarly acts inferiorly on the humerus. These findings are supported by later work (Keener et al. 2009) that documented that patients with tears in the infraspinatus alone, or the infraspinatus and supraspinatus had significantly higher humeral head translation than those with only supraspinatus tears. Thus, with respect to preventing subacromial impingement, the infraspinatus as well as the subscapularis appear to be far more active in resisting humeral head translation than the supraspinatus, unlike previous belief (Chen et al. 1999).

5.3.2 Individual Geometry and High Variability

From examining individual differences, and then referring to the group means for both main effects, arm angle and fatigue (Figures 15 and 16), there is evidence to suggest that individual geometry influenced humeral head excursion. By examining the humeral head position in both the pre-fatigued and post-fatigued shoulder at each arm angle, it could be seen that there is a high level of variability between participants for this measure (Tables 5-8).

Previous research efforts have determined that there is a high variability in humeral head excursion between individuals. In this study, the mean excursion was 0.63mm with a standard deviation of 1.60mm; a variability of 2.5 times the excursion measurement. Teyhen et al. (2008), found mean excursion following fatigue of 0.79mm, with a standard deviation 2.63mm. This variability is over 3 times the excursion measurement. Similar findings with respect to the magnitude of variability were present in those examining excursion with respect to arm angle for injured and uninjured patients (Keener et al. 2009). There were studies that did not report the standard deviation (Cote et al. 2009), or rather found that the variability was lower than the excursion (Bezer et al. 2005; Chen et al. 1999). However, due to the small magnitude of changes, and the variation with respect to individual shoulder geometry, even in a healthy shoulder, high variability in this measure can be expected. This variability has the potential to mask changes with respect to injury or fatigue; thus having a quantifiable measure for injury or fatigue (such as ultrasound or EMG) is important to help identify whether there is an explanation regarding outliers.

Aside from the variability between participants within the same study, there was a high variability in the mean humeral head position reported between research studies. Chen et al. (1999) and Cote et al. (2009), while evaluating excursion after rotator cuff fatigue, reported similar excursion differences between pre- and post- fatigue. However, the mean excursion within each state was substantially different between studies. Chen et al. (1999) had a mean pre-fatigue excursion of approximately 0.3mm and post-fatigue excursion of 2.5mm; Cote et al. (2009) had a mean pre-fatigued excursion of 3mm and post-fatigued excursion of 4.8mm. Thus, although fatigue had a similar effect in the two studies (approximately 2mm more excursion in the post-fatigue state) the actual excursion magnitudes within each fatigue state differed greatly.

The humeral head excursion in the pre-fatigue state found by Cote et al. (2009) was 0.5mm more than the post-fatigue humeral head excursion found by Chen et al. (1999). This high magnitude of excursion found by Cote et al. (2009) far exceeds that of the current study and past research (Chen et al. 1999; Teyhen et al. 2008). Although between-study variability was expected, these substantially high excursion values, coupled with not reporting standard deviation metrics, raise concerns over the consistency of the measurement technique with other studies.

5.4 Statistical versus Clinical Significance of Excursion

Many studies have discussed acromio-humeral interval (AHI) widths in terms of "healthy" or "unhealthy" magnitudes using a specific cut-off value. As previously mentioned, Golding (1962) found that a healthy AHI ranged from 7 to 13mm; Cotton and Rideout (1964) found a slightly wider healthy range of 6mm to 14mm. Weiner and MacNab (1970) measured healthy and injured patients and found a healthy range to be between 7 to 14mm and an injured range to be indicative of less than 5mm. Although these ranges are generally agreed upon in the literature, the variability of shoulder geometry and the individual responses to mechanical changes of the shoulder prevent there from being a comprehensive aforementioned "cut-off" value between healthy and injured. Thus, a grey area exists in the literature between 4mm and 6mm where in some instances, patients had diagnosed rotator cuff tears and in others, patients had no evidence of injury. With this large "grey" area between healthy and injured, coupled with humeral head excursion measurements taken on such a small scale, a persistent discrepancy exists regarding the significance of humeral head excursion. Although two measurements are deemed statistically different, the difference may not necessarily have clinical significance. Unfortunately, no current literature has examined humeral head excursion in terms of clinical significance. However, approximate widths of the tissues within the subacromial space could be compared to the defined healthy ranges, to determine whether small excursion values could be deemed clinically significant.

The size of these subacromial tissues relative to the total space (AHI) is important in determining how much excursion is associated with tissue impingement and subsequent injury. Girometti et al. (2006) quantified the morphology of the tissues in the subacromial space in overhead athletes and healthy controls in a neutral posture. They found the bursal thickness was an average of 1.43±0.34mm, the tendon thickness was an average of 2.30±0.43mm and the subacromial space was an average of 8.55±0.85mm (average of both shoulders of all participants). Thus, in this position, the tissues occupied approximately 44% of the subacromial space. However, evidence suggests that AHI width decreases as arm abduction increases. Bey et al. (2007) measured the width of the AHI during shoulder elevation in 5˚ increments from 10˚ to 75˚ of elevation. The AHI had an inverse relationship with elevation. In asymptomatic patients, the AHI width ranged from 7.1mm to 1.2mm at 10˚ and 65˚ of elevation respectively. Graichen et al. (1999a) determined that the maximum AHI occurred at 30˚ of elevation (7.0±1.6mm) and the minimum at 120˚ of elevation (3.9±1.8mm). In a subsequent study, they also found that the AHI width was lower than 5mm over 60˚ of abduction (Graichen et al. 1999b). Thus, with the tissues occupying approximately 3.7mm of the subacromial space, when the arm is abducted, excursion magnitudes less than 1mm could create risk for subacromial impingement and injury.

5.5 Study Limitations and Sources of Error

Despite being conducted very methodically, there was still a potential for error in this study collection. The one criterion that was vital to achieving the purpose of this study was that the rotator cuff was fatigued. Although this study was able to better quantify muscle fatigue than past research through the use of electromyography (Chen et al. 1999; Cote et al. 2009; Teyhen et al. 2008), participant compliance was still a potential limiting factor. Participants subjectively chose when they felt their shoulder was fatigued using a psychophysical scale. A second potential limitation was, although participants were positioned consistently for each x-ray, following the fatiguing trial some participants had difficulty maintaining arm elevation postures for the x-ray. Radiographs were repeated if their arm shifted between arm positioning and the taking of the x-ray, but errors may have occurred regardless.

As well as study protocol limitations, there are other sources of error that stem from errors or inconsistencies with past research. Sample size was calculated prior to study collection in order to ensure high statistical power. Although, 20 participants were adequate for 80% power, this calculation is dependent on past research and thus could be incorrect if improper study methods were previously used.

Measurement errors are a possible source of error in studies that measure on such a small scale. However, a strict measuring protocol was used to ensure repeatability within and between observers. Thus, although there are certain subjective aspects of the process, this protocol was over 90% repeatable both within and between observers.

5.6 Future Directions and Open Questions

The findings of this study are extendable towards future, potentially fruitful, research projects. Alterations of the fatiguing task and monitoring different muscles are two primary ways of extending this research. The fatiguing protocol was intended to simulate a job task that involves overhead working conditions due to previously confirmed increased upper extremity risks when working in overhead postures (Bernard 1997; Chopp et al. 2009b; Grieve and Dickerson, 2008). However, the infraspinatus and subscapularis muscles appear to be the most important for resisting the upward translation of the humerus. Thus, a pick-and-place type task, involving solely internal and external rotation until fatigued, may provide more specificity in terms of muscle interactions with humeral head positioning. This task may also prevent deltoid fatigue, which could enhance the upward pull of the humerus. This would magnify the upward shift of humeral head position, if present. A further extension of this project would be using indwelling electromyography to monitor subscapularis, a rotator cuff muscle that is immeasurable using surface electromyography. Since this muscle is identified as the strongest rotator cuff muscle, and one that has a large effect (over two-fold) on the magnitude of excursion (Bezer et al. 2005; Keating et al. 1993), monitoring this muscle while also assessing the infraspinatus may give more insight into whether internal and external rotators play a larger role in resisting humeral head excursion than previously suspected.

VI. Conclusions

Industrial jobs requiring overhead and/or repetitive work that lead to fatigue appear to put workers at greater risk for superior humeral head translation. Although the magnitude of humeral translations are not as large as for patients with rotator cuff tears, continuous overhead work is known to create rotator cuff fatigue, which inhibits the muscles' ability to resist upward translation of the humerus. Exacerbating this situation, the size of the subacromial space decreases as the arm is elevated to an overhead working condition. Thus, when this is coupled with superior humeral head translation, the total available space for the underlying tissues decreases substantially, putting the worker at risk for subacromial impingement and subsequent injury. The effects of this translation may have been more pronounced without deltoid fatigue.

However, the current findings support trends previously documented for the healthy shoulder, and provide an extension for the fatigued shoulder. In a healthy shoulder, superior translation is typically present until 90˚ of abduction; after this point, when the workers' arms are in an overhead position, the humeral head moves to a more centralized position. If the rotator cuff is unable to compress the humeral head in the glenoid cavity due to injury or fatigue, the head continues to migrate superiorly, even at higher abduction angles. Thus, workers should be aware that although a single overhead working task may not put them at risk of injury, continually working in these postures can result in rotator cuff fatigue. This study is the first to show that a simulated job task that induces muscle fatigue may inhibit the ability to maintain healthy shoulder biomechanics, at which point impingement or further injury is likely.

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Appendices

Appendix A: Individual EMG amplitude changes

Table A1. Individual EMG amplitude changes for the supraspinatus in the pre- and post-fatigue state and the overall change in %MVC.

Participant	Pre-Fatigue EMG Amplitude (%MVC)	Post-Fatigue EMG Amplitude (%MVC)	Percentage Change (%MVC)
1	18.32	34.90	16.59
2	41.14	72.13	30.99
3	14.80	16.78	1.98
4	19.26	34.26	15.00
5	18.25	43.93	25.68
6	19.45	20.79	1.34
7	24.20	35.37	11.17
8	20.61	35.67	15.06
9	21.37	60.95	39.58
10	14.03	29.46	15.43
11	20.36	25.96	5.60
12	29.09	33.20	4.11
13	17.80	21.67	3.87
14	13.77	26.69	12.92
15	25.54	38.23	12.70
16	19.25	22.37	3.13
17	24.10	39.35	15.25
18	33.48	51.61	18.13
19	25.89	39.78	13.89
20	21.33	28.75	7.42
Average	22.10	35.59	**13.49**
Std Dev	6.65	13.67	**9.87**

Table A2. Individual EMG amplitude changes for the infraspinatus in the pre- and post-fatigue state and the overall change in %MVC.

Participant	**Pre-Fatigue EMG Amplitude (%MVC)**	**Post-Fatigue EMG Amplitude (%MVC)**	**Percentage Change (%MVC)**
1	12.16	61.37	49.21
2	18.51	51.57	33.07
3	13.00	21.80	8.80
4	15.87	26.56	10.69
5	11.85	28.65	16.80
6	14.99	16.32	1.33
7	14.36	24.18	9.82
8	11.31	29.95	18.64
9	9.24	37.74	28.51
10	9.64	17.33	7.69
11	10.27	35.00	24.73
12	22.52	54.88	32.36
13	5.95	11.39	5.44
14	18.32	40.62	22.30
15	17.25	57.36	40.11
16	17.24	31.19	13.95
17	13.62	34.46	20.84
18	10.61	31.07	20.46
19	13.79	26.10	12.31
20	12.25	15.70	3.46
Average	13.64	32.66	**19.03**
Std Dev	3.88	14.37	**12.72**

Table A3. Individual EMG amplitude changes for the middle deltoid in the pre- and post-fatigue state and the overall change in %MVC.

Participant	**Pre-Fatigue EMG Amplitude (%MVC)**	**Post-Fatigue EMG Amplitude (%MVC)**	**Percentage Change (%MVC)**
1	24.68	59.03	34.36
2	23.01	44.48	21.48
3	21.37	36.36	14.99
4	16.61	24.76	8.15
5	19.23	45.15	25.92
6	21.47	21.93	0.46
7	19.30	23.11	3.81
8	11.09	21.99	10.91
9	31.04	70.18	39.14
10	16.20	43.28	27.08
11	15.87	29.20	13.33
12	25.42	55.30	29.87
13	29.48	41.66	12.18
14	34.41	69.12	34.72
15	27.58	40.33	12.74
16	20.25	43.34	23.09
17	27.74	47.76	20.02
18	29.57	59.92	30.35
19	18.72	28.84	10.12
20	22.81	26.03	3.22
Average	22.79	41.59	**18.80**
Std Dev	5.94	15.31	**11.45**

Table A4. Individual EMG amplitude changes for the pectoralis major in the pre- and post-fatigue state and the overall change in %MVC.

Participant	Pre-Fatigue EMG Amplitude (%MVC)	Post-Fatigue EMG Amplitude (%MVC)	Percentage Change (%MVC)
1	4.77	8.28	3.51
2	2.22	3.68	1.46
3	5.50	5.89	0.39
4	4.47	6.81	2.34
5	7.11	5.85	-1.26
6	1.07	1.20	0.13
7	3.05	4.02	0.97
8	2.11	2.79	0.68
9	1.51	2.14	0.63
10	3.35	5.99	2.64
11	1.47	1.52	0.05
12	2.45	5.44	2.99
13	2.37	2.05	-0.32
14	2.70	5.62	2.92
15	13.53	27.91	14.39
16	2.42	10.93	8.51
17	12.03	13.49	1.46
18	9.32	23.29	13.98
19	10.91	12.46	1.55
20	13.39	13.41	0.02
Average	5.29	8.14	**2.85**
Std Dev	4.22	7.13	**4.38**

Appendix B: Individual Mean Power Frequency changes

Table B1. Individual Mean Power Frequency (MPF) changes for the supraspinatus in the pre- and post-fatigue state and the overall change in MPF.

Participant	**Pre-Fatigue MPF (%PRE MPF)**	**Post-Fatigue MPF (%PRE MPF)**	**Percentage Change**
1	100.00	105.67	5.67
2	100.00	107.06	7.06
3	100.00	106.32	6.32
4	100.00	102.01	2.01
5	100.00	93.92	-6.08
6	100.00	107.95	7.95
7	100.00	110.18	10.18
8	100.00	99.18	-0.82
9	100.00	82.52	-17.48
10	100.00	81.15	-18.85
11	100.00	110.00	10.00
12	100.00	98.44	-1.56
13	100.00	102.07	2.07
14	100.00	106.42	6.42
15	100.00	95.79	-4.21
16	100.00	92.83	-7.17
17	100.00	96.99	-3.01
18	100.00	100.37	0.37
19	100.00	105.47	5.47
20	100.00	96.11	-3.89
Average	100.00	100.02	**0.02**
Std Dev	0.00	8.15	**8.15**

Table B2. Individual Mean Power Frequency (MPF) changes for the infraspinatus in the pre- and post-fatigue state and the overall change in MPF.

Participant	**Pre-Fatigue MPF (%PRE MPF)**	**Post-Fatigue MPF (%PRE MPF)**	**Percentage Change**
1	100.00	77.33	-22.67
2	100.00	72.34	-27.66
3	100.00	74.83	-25.17
4	100.00	73.66	-26.34
5	100.00	88.21	-11.79
6	100.00	83.65	-16.35
7	100.00	78.11	-21.89
8	100.00	90.12	-9.88
9	100.00	59.75	-40.25
10	100.00	66.89	-33.11
11	100.00	57.90	-42.10
12	100.00	89.46	-10.54
13	100.00	61.63	-38.37
14	100.00	78.50	-21.50
15	100.00	65.83	-34.17
16	100.00	79.48	-20.52
17	100.00	78.53	-21.47
18	100.00	89.67	-10.33
19	100.00	89.36	-10.64
20	100.00	70.75	-29.25
Average	100.00	76.30	**-23.70**
Std Dev	0.00	10.30	**10.30**

Table B3. Individual Mean Power Frequency (MPF) changes for the middle deltoid in the pre- and post-fatigue state and the overall change in MPF.

Participant	**Pre-Fatigue MPF (%PRE MPF)**	**Post-Fatigue MPF (%PRE MPF)**	**Percentage Change**
1	100.00	93.00	-7.00
2	100.00	87.64	-12.36
3	100.00	79.73	-20.27
4	100.00	87.58	-12.42
5	100.00	89.54	-10.46
6	100.00	87.50	-12.50
7	100.00	70.99	-29.01
8	100.00	71.43	-28.57
9	100.00	73.26	-26.74
10	100.00	68.07	-31.93
11	100.00	82.93	-17.07
12	100.00	86.99	-13.01
13	100.00	84.43	-15.57
14	100.00	88.50	-11.50
15	100.00	88.53	-11.47
16	100.00	87.82	-12.18
17	100.00	84.38	-15.62
18	100.00	95.26	-4.74
19	100.00	86.80	-13.20
20	100.00	79.88	-20.12
Average	100.00	83.71	**-16.29**
Std Dev	0.00	7.54	**7.54**

Table B4. Individual Mean Power Frequency (MPF) changes for the pectoralis major in the pre- and post-fatigue state and the overall change in MPF.

Participant	**Pre-Fatigue MPF (%PRE MPF)**	**Post-Fatigue MPF (%PRE MPF)**	**Percentage Change**
1	100.00	82.83	-17.17
2	100.00	114.93	14.93
3	100.00	87.70	-12.30
4	100.00	138.00	38.00
5	100.00	97.00	-3.00
6	100.00	58.92	-41.08
7	100.00	87.46	-12.54
8	100.00	77.97	-22.03
9	100.00	94.36	-5.64
10	100.00	80.09	-19.91
11	100.00	111.62	11.62
12	100.00	92.86	-7.14
13	100.00	92.04	-7.96
14	100.00	102.62	2.62
15	100.00	87.26	-12.74
16	100.00	63.98	-36.02
17	100.00	85.35	-14.65
18	100.00	91.16	-8.84
19	100.00	112.47	12.47
20	100.00	91.94	-8.06
Average	100.00	92.53	**-7.47**
Std Dev	0.00	17.76	**17.76**

Appendix C: Information and Consent Form

Title of Study: Radiographic Examination of Humeral Head Migration after Selectively Fatiguing the Rotator Cuff.

Principle Investigator:	Jaclyn Chopp, BSc University of Waterloo, Department of Kinesiology 519-884-4567 Ext. 36162
Local Principal Investigator:	Dr. John O'Neill, MD MSK Radiologist St. Joseph's Healthcare Hamilton, Department of Diagnostic Imaging 905-522-1155
Co-Investigator:	Clark Dickerson, PhD Assistant Professor University of Waterloo, Department of Kinesiology 519-884-4567 Ext. 37844

Sponsor: Natural Sciences and Engineering Research Council of Canada.

You are being invited to participate in a research study conducted by Jaclyn Chopp because you are a healthy, right-hand dominant male (18-35 years old) with no history of shoulder pain or injuries. This is a student thesis project conducted under the supervision of Dr. Clark Dickerson. The study will offer insight into injury mechanisms in the shoulder, particularly for those with jobs requiring overhead and/or repetitive tasks.

In order to decide whether or not you want to be a part of this research study, you should understand what is involved and the potential risks and benefits. This form gives detailed information about the research study, which will be discussed with you. Once you understand the study, you will be asked to sign a consent form if you wish to participate. Please take your time to make your decision. Feel free to discuss it with your friends and family.

St. Joseph's Healthcare Hamilton and the local investigator Dr. John O'Neill are under contract with the investigators of this study and are receiving compensation to cover the costs of conducting the study.

WHY IS THIS RESEARCH BEING DONE?

Past research has shown that abnormal postures and repetitive tasks in the workplace lead to upper extremity discomfort. Specifically, shoulder flexion or abduction over 90° for more than 10% of the work cycle has been associated with shoulder disorders. Furthermore, repetitive internal and external rotation is a strong predictor (OR = 9.3) of workplace musculoskeletal disorders. Through examination of muscular activity, strong associations have also been made between awkward postures, repetitive tasks and muscle fatigue.

Clinical research focusing on the rotator cuff has determined that a decrease to the subacromial space (area between the top of the upper arm bone and the top of the shoulder) may injure the underlying tissues (which include the supraspinatus tendon of the rotator cuff). A possible mechanism for this damage to the rotator cuff is an upward shift of the humeral head (upper arm bone) with respect to the glenoid cavity (socket).

Although both workplace factors (awkward posture and repetition) and altered shoulder mechanics (impingement) have been associated with pain, there has been minimal research examining the link between these two. The aim of this study is to examine humeral head migration after selectively fatiguing the rotator cuff. Results from this study will offer insight into injury mechanisms in the shoulder, particularly for those with jobs requiring overhead and/or repetitive tasks.

WHAT IS THE PURPOSE OF THIS STUDY?

The purpose of this project is to measure whether the head of the humerus (upper arm bone) shifts upwards in the glenoid cavity (socket) as a result of fatiguing shoulder muscles. It is hypothesized that this upward shift of the upper arm bone will occur after the rotator cuff (group of shoulder muscles) is fatigued. This will provide a direct link between workplace factors (awkward postures, repetitive tasks) and injury, with fatigue as a facilitator.

WHAT WILL MY RESPONSIBILITIES BE IF I TAKE PART IN THE STUDY?

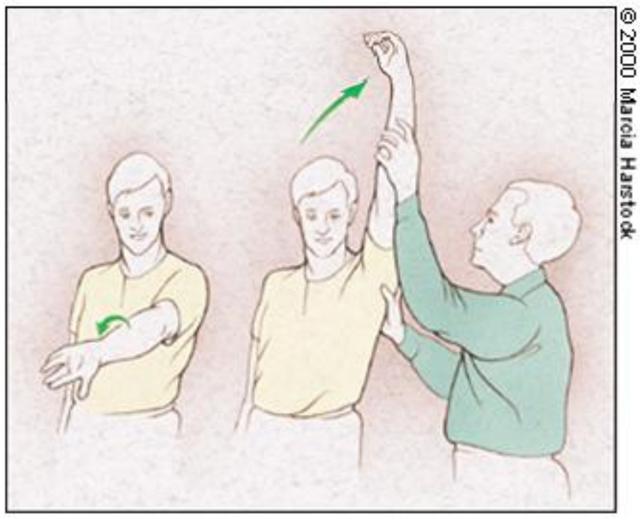
If you volunteer to participate in this study, we will ask you to do the following things:

1.0 Prior to collection

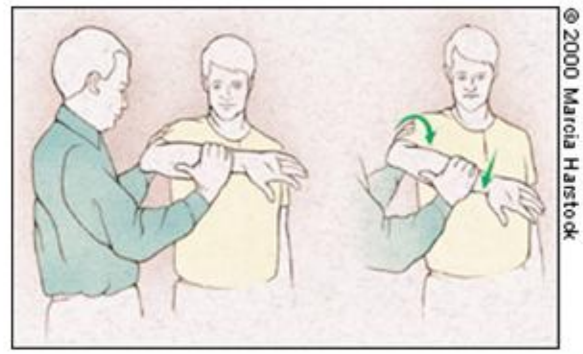
1.1 Prior to commencing the study, there will be preliminary measures to help insure you have no previous shoulder pain/discomfort. All measures/tests are non-invasive. Measures include:

- Current rating on Borg’s Rate of Perceived Exertion Scale.
- Active (pain-free) range of motion
- Neer and Hawkins manual muscle tests (Figure 1)

1.2 Prior to commencing the study, you (male participants) will also be advised that you will be asked to remove your shirt during the study.



Neer's test for impingement of the rotator cuff tendons under the coracoacromial arch. The arm is fully pronated and placed in forced flexion.



Hawkins' test for subacromial impingement or rotator cuff tendonitis. The arm is forward elevated to 90 degrees, then forcibly internally rotated.

Figure 1. Explanation of manual muscle tests; Neer (left), Hawkins (right)

2.0 First Set of Radiographs

2.1 You will be brought into a room containing x-ray equipment. The student investigator and x-ray technician will position your arm into one of four varying abduction angles (0°, 45°, 90°, 135°) in the scapular plane (arm not directly out to the side but at a comfortable angle [30˚ forward]) with the use of a goniometer (large hand-held protractor-type device).

2.2 Holding a 1kg weight, an x-ray will be taken of your shoulder.

2.3 “Section 2.1 and 2.2” will be repeated for each of the four angles of abduction. Angles will be in a random order.

2.4 With your consent, photographs will also be taken of your shoulder for each angle to use as a reference/comparison to x-rays during presentations/papers.

3.0 EMG Preparation

3.1 Four surface adhesive electrode pairs will be placed on the skin overlying four muscles on the dominant side of the upper extremity. As well, one additional electrode will be placed on a bony landmark (likely the clavicle) as a ground electrode. These electrodes will record electrical activity of muscles in the upper limb in order to evaluate fatigue.

3.2 Prior to electrode placement, the skin will be shaved and cleansed with alcohol (so that the electrode has good contact with the skin). A new disposable razor is used for each participant. Over 500 participants have undergone this procedure in the Kinesiology department, and to date no participants have been cut.

3.3 Specific muscles examined will be the supraspinatus, infraspinatus, middle deltoid and sternal insertion of pectoralis major (Figure 2). Some participants may experience mild skin irritation/redness from the tape used to attach the instrumentation to the skin, as well as the electrodes themselves. This is similar to the irritation that may be caused by a bandage and typically fades within 1-3 days. The occurrence of this skin irritation is rare, but participants will be made aware of this risk prior to placing the electrodes.

4.0 Reference Force Values & Maximal Voluntary Contractions

4.1 You will be asked to perform two maximal exertions:

(1) Shoulder flexion with the arm positioned at 90˚ of shoulder flexion and 0˚ of horizontal abduction (directly in front of participant).
(2) Horizontal abduction with arm positioned at 90˚ of shoulder abduction and 90˚ of horizontal abduction (arm out at side).

An average of these two exertions will be the representation of your maximal voluntary force, which will be used to choose the appropriate weight to use during fatiguing protocol.

4.2 You will also perform maximal voluntary contractions (MVCs) for each of the four monitored muscles. An average of the three repetitions of each MVC will be used to normalize EMG data collected during the fatiguing protocol.

4.3 You will also be asked to lay face down on a bench while remaining as relaxed and still as possible. This resting EMG trial will be used to remove bias in the signal.

5.0 Fatiguing Protocol

5.1 You will be performing a job simulated task involving arm elevation above shoulder height as well as internal and external rotation. Specifically you will be picking up a weighted bottle from a basket located directly in front of you (0˚ of horizontal abduction) and at 45˚ of shoulder flexion. You will alternate touching the bottle to targets located at their end range of motion at two different positions:

(1) Position #1: Directly in front (0˚ of horizontal abduction) and at 135˚ of shoulder flexion

(2) Position #2: To the side (90˚ of horizontal abduction) and at 135˚ of shoulder abduction

The weight of the bottle will be 15% of your maximum voluntary force exertion (Section 4.1). A metronome will be set at a comfortable pace for you so that the rate at which you perform the task remains consistent.

5.2 Every minute you will be asked to give a rate of perceived exertion on the Borg RPE scale:

(1) If this rating is below 10, you will continue the protocol. Furthermore, before continuing the task, you will be asked to hold the weight statically, with the arm abducted to 90 degrees, and elbow straight. You will hold this for 5 seconds while EMG is collected.

(2) If this rating is equal to 10, you will perform the 5 second EMG trial and move to "Section 6.0: Second Set of Radiographs"

The goal is for the arm to feel fatigued (tired), but not to the point of any pain or major discomfort. The value of 10 will indicate that you are very fatigued and cannot continue comfortably, but do not feel any extreme comfort or pain.

5.3 You may experience mild discomfort after the fatiguing protocol. This discomfort is similar to that experienced after a workout.

6.0 Second Set of Radiographs

6.1 When you are completely fatigued, as indicated by a rating of equal to 10 on the Borg RPE scale, the second set of radiographs will be taken.

6.2 Repeat “Section 2.0: First Set of Radiographs”.

This study will take approximately 1.5 hours of your time.

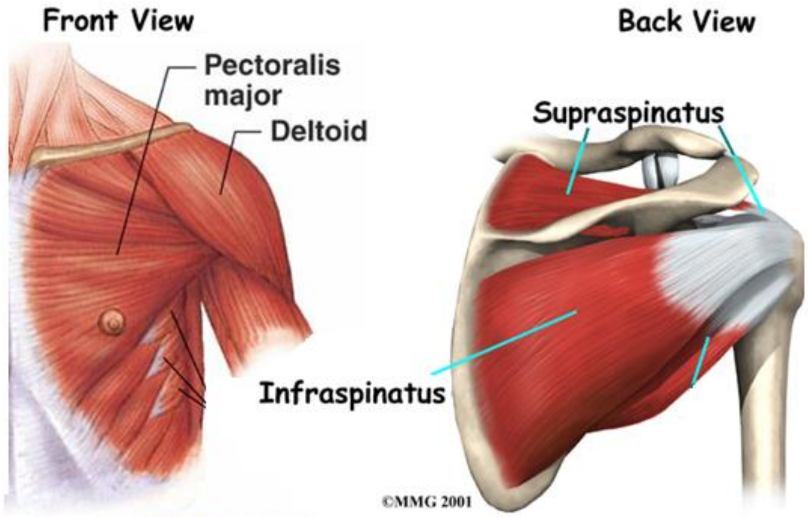


Figure 2. Diagram of shoulder muscles of interest (Medical Multimedia Group).

WHAT ARE THE POSSIBLE RISKS AND DISCOMFORTS?

- With the 8 x-rays, you will experience a total level of radiation exposure comparable to the natural background radiation you are exposed to in 12 days (0.08mSv). Natural radiation includes radiation from natural sources (cosmic rays, etc) and manmade sources (emission from fossil fuels from power plants, improper disposal of radioactive material, etc)
- There is always a risk of muscle, joint or other injury in any physical work. However, the risks in this study are not anticipated to be greater than those required to move personal belongings from one apartment to another or those encountered in an exercise program or recreational activity that requires brief maximum muscular efforts.
- During the fatiguing protocol, you may experience soreness in the upper extremity. The stiffness and/or soreness may develop or persist for two or three days following the study if you are unaccustomed to this type of work. This soreness/stiffness is normal and usually disappears in a few days. If it does not go away within a few days, you should contact the researcher.
- Some individuals may experience mild skin irritation from the tape used to attach the electrodes to your skin or the gel used to moisten the electrode. This is similar to the irritation that may be caused by a bandage and typically fades within 2 to 3 days.
- If you are allergic to rubbing alcohol, you should not participate in this study.
- The portable part of the electrical recording system is battery operated and isolates you from the main electrical lines. There is no risk of electrical shock.
- You will be instructed to monitor your level of discomfort on the Borg RPE scale. In addition, you will be advised to terminate the testing session if you experience severe discomfort or at any time you feel that you can no longer continue.

HOW MANY PEOPLE WILL BE IN THIS STUDY?

Twenty male participants will participate in this study.

WHAT ARE THE POSSIBLE BENEFITS FOR ME AND/OR FOR SOCIETY?

By participating in this study, you may further your knowledge and understanding of experimental procedures commonly used in clinical biomechanics/ergonomics research. There are no other expected benefits to you.
Results from this study will provide a mechanical explanation for the upper extremity pain and disorders that result from awkward postures and repetitive tasks in the workplace. This project will provide a mechanical explanation for upper extremity pain and disorders and offer scientific reinforcement for job interventions and/or rehabilitation programs.

HOW DO I INDICATE THAT I DO NOT WANT TO TAKE PART IN THE STUDY OR WISH TO WITHDRAWAL?

It is important for you to know that you can choose not to take part in the study. Furthermore, you may withdraw from this study at any time without penalty. To do so, indicate this to the researcher or one of the research assistants by saying, "I no longer wish to participate in this study". As well, you may choose to decline answering any questions that may be asked throughout the collection.

WHAT INFORMATION WILL BE KEPT PRIVATE?

To ensure the confidentiality of individuals' data, each participant will be identified by a participant identification code known only to the principle investigator and her research assistants. Photographs will be stored indefinitely in a secure area. A separate consent will be requested in order to use photographs and x-rays for teaching, for scientific presentations, or in publications of this work. No personnel outside of the research team and St. Joseph's Healthcare Hospital Research Ethics Board will have access to any personal information. You have the right to ask the researcher about the data being collected about you for the study and about the purpose of this data. You also have the right to ask the investigator to let you see your personal information and to make any necessary corrections to it.
If the results of the study are published, your name will not be used and no information that discloses your identity will be released or published without your specific consent to the disclosure.

WILL I BE PAID TO PARTICIPATE IN THIS STUDY?

If you agree to take part, we will reimburse you $50 for study related expenses.
In the event that you cannot complete the requirements of the study, you will receive a pro-rated amount at the rate of $20 per hour/session.

WILL THERE BE ANY COSTS?

Your participation in this research project will not involve any additional costs to you.

WHAT HAPPENS IF I HAVE A RESEARCH-RELATED INJURY?

If you are injured as a direct result of taking part in this study, all necessary medical treatment will be made available to you at no cost. Financial compensation for such things as lost wages, disability or discomfort due to this type of injury is not routinely available.

However, if you sign this consent form it does not mean that you waive any legal rights you may have under the law, nor does it mean that you are releasing the investigator(s), institution(s) and/or sponsor(s) from their legal and professional responsibilities.

IF I HAVE ANY QUESTIONS OR PROBLEMS, WHOM CAN I CALL?

If you have any questions about the research now or later, please contact Dr. Clark Dickerson, 519-888-4567 ext.37844

I would like to assure you that this study has been reviewed and received ethics clearance through the St. Joseph’s Healthcare Hamilton Research Ethics Board and the Office of Research Ethics at the University of Waterloo. However, the final decision about participation is yours. If you have any comments or concerns resulting from your participation in this study, you may contact the office of the Chair of the Research Ethics Board, St. Joseph's Healthcare Hamilton, 905-522-1155 Ext. 33537 or Dr. Susan Sykes, Director ORE (University of Waterloo), at (519) 888-4567 ext. 36005.

CONSENT STATEMENT

SIGNATURE OF RESEARCH PARTICIPANT

I have read the information presented in the information letter about the study: "Radiographic Examination of Humeral Head Migration after Selectively Fatiguing the Rotator Cuff" being conducted by Jaclyn Chopp (Student Investigator), Dr. John O'Neill (Local Principle Investigator) of the Department of Diagnostic Imaging at St. Joseph's Healthcare Hamilton and Dr. Clark Dickerson (Faculty Supervisor) of the Department of Kinesiology at the University of Waterloo. I have had the opportunity to ask any questions related to this study, to receive satisfactory answers to my questions, and any additional details I wanted. I am aware that I may withdraw from the study without penalty at any time by advising the researchers of this decision.

This project has been reviewed by, and received ethics clearance through, the University of Waterloo's Office of Research Ethics (ORE) as well as the Research Ethics Board of St. Joseph's Healthcare Hamilton. I was informed that if I have any comments or concerns resulting from my participation in this study, I may contact Dr. Susan Sykes (Director, ORE) at (519) 888-4567 ext. 36005.

I agree to participate in this study. I understand that I will receive a signed copy of this form.

____
Name of Participant

____ _______________
Signature of Participant Date

Consent form administered and explained in person by:

____
Name and title

____ _______________
Signature Date

Signature of Witness to Consent Interview

My signature as a witness, certifies that I witnessed the participant voluntarily sign this consent form in my presence.

Signature Date

SIGNATURE OF INVESTIGATOR:

In my judgement, the participant is voluntarily and knowingly giving informed consent and possesses the legal capacity to give informed consent to participate in this research study.

Signature of Investigator Date

CONSENT TO USE PHOTOGRAPHS AND X-RAYS IN TEACHING, PRESENTATIONS, and/or PUBLICATIONS

Sometimes a certain photograph or x-ray clearly demonstrates a particular feature or detail that would be helpful in teaching or when presenting the study results at a scientific conference or in a publication.

I agree to allow photographs and x-rays in which I appear to be used in teaching, scientific presentations and/or publications with the understanding that I will not be identified by name. I am aware that I may withdraw this consent at any time without penalty, and the photograph will be confidentially shredded.

I was informed that if I have any comments or concerns resulting from my participation in this study, I may contact Dr. Susan Sykes (Director, Office of Research Ethics) at (519) 888-4567 ext. 36005.

____

Name of Participant

_______________________________________ _______________

Signature of Participant Date

Appendix D: Data Collection Form

Borg Rate of Perceived Exertion Scale

Exertion	RPE
Nothing at all	0
Very light	1
Fairly light	2
Moderate	3
Somewhat hard	4
Hard	5
	6
Very Hard	7
	8
	9
Very, very hard	10

Initial Measurements:

Age: ________ **Height: ____________** **Weight: ___________**

Initial RPE Rating: ______

Active Range of Motion: **Abduction _________°** **Flexion ____________°**

Impingement Tests (Negative/Positive):

1) Hawkins: ____________

2) Neer: _____________

Maximum Voluntary Force:

Shoulder Flexion #1: _____N

Shoulder Flexion #2: _____N **Average**: ___________N * 0.15 / 9.81m/s^2

Shoulder Abduction #1:_____N **Weight = __________kg**

Shoulder Abduction #2:_____N

Metronome Beat: _________

Collection Checklist:

- ☐ Measure initial parameters (RPE, Active Range of Motion, Negative Impingement Tests)
- ☐ Radiographs (0˚, 45˚, 90˚, 135˚)
- ☐ Maximal Voluntary Force Determination (+ Weight Calculation)
- ☐ EMG Preparation (shave, cleanse, place electrodes, test signal)
- ☐ Rest Trial
- ☐ MVCs

• Supraspinatus	☐	☐	☐
• Infraspinatus	☐	☐	☐
• Middle Deltoid	☐	☐	☐
• Pectoralis Major	☐	☐	☐

☐ Fatiguing Protocol	*RPE*	*EMG Trial*
• PRE	______	☐
• 1 minute	______	☐
• 2 minutes	______	☐
• 3 minutes	______	☐
• 4 minutes	______	☐
• 5 minutes	______	☐
• 6 minutes	______	☐
• 7 minutes	______	☐
• 8 minutes	______	☐
• 9 minutes	______	☐
• 10 minutes	______	☐
• 11 minutes	______	☐
• 12 minutes	______	☐
• 13 minutes	______	☐
• 14 minutes	______	☐
• 15 minutes	______	☐

- ☐ Radiographs (0˚, 45˚, 90˚, 135˚)