Development and Validation of a Cumulative Exposure Shoulder Risk Assessment Tool Based on the Fatigue-Failure Theory

by

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Abstract

Exposure to physical risk factors and the resultant cumulative loading has been identified as a major contributing factor for the development of workplace musculoskeletal disorders (MSDs). Nevertheless, the dose-response relationship of MSDs and their association with workplace risk factors is still not well understood. Previous studies have suggested various methods for addressing cumulative loading where the cumulative damage for the total job is estimated by considering each individual task. However, most of the methods use linear integration methods; which assume that low force, long duration and high force, short duration tasks have the same injury risk. More recent studies support the role of fatigue failure theory in the development of MSDs. Evidence supporting the fatigue failure process in the development of MSDs includes epidemiological studies, tissue loading in animal studies and in vitro testing for MSDs. Those studies explained the fatigue failure behavior of biological tissues including tendons, ligaments, cartilage, and spinal motion segments which also revealed a pattern of force repetition interaction consistent with the fatigue failure process. Thus, cumulative loading effects could be estimated using the fatigue failure process.

Upper extremity MSDs, including shoulder injuries, are second highest in terms of injuries causing occupational lost time claims after back injuries. Current observational tools available for upper extremity assessment generally do not consider the impact of cumulative exposure. Furthermore, combined effects of jobs comprising multiple tasks are not available. The aim of this dissertation was to develop and validate a cumulative exposure shoulder risk assessment tool based on the fatigue failure theory. Video recordings of jobs from an existing epidemiology study were analyzed to get the required inputs for the tool development. Postural estimates and repetitions per workday were obtained from this video analysis. Moments for both left and right shoulders were then estimated and shoulder strength capability was used to establish the ultimate strength of the shoulders. From this relationship, the number of cycles to failure was calculated for each level of stress so that the damage per cycle (DPC) could be obtained and repetitions used to estimate the cumulative damage (CD) per day. The CD can be easily summed for multiple tasks to get a daily dose of exposure, and the contribution of various tasks can be easily estimated. The tool was validated against the epidemiology database using numerous shoulder outcomes. Both crude and adjusted logistic regression results indicated strong dose-response associations between log CD and all shoulder outcomes ($p<0.0001$). Odds ratios (ORs) were higher for the self-reported symptoms such as current shoulder pain (1&2 vs 4&5) and current shoulder pain (1 vs 5). When the effect of the personal characteristics was introduced into the model and adjustments were made for the moments and capability strengths, significant results were also obtained. However, greater variability is observed in shoulder CD estimates which can be explained by the sex differences in terms of shoulder capability strength which in turn will affect the CD estimates. Subjective ratings for shoulder strength assessment were used to investigate the impact of subjective ratings on the model adequacy. Significant results were obtained for these subjective measures logistic regressions ($P<0.0001$). The ORs for the different shoulder outcomes were close to the ones obtained for the original model. All results indicated strong associations between shoulder cumulative damage estimate, and all investigated negative shoulder health outcomes. This provides further support for the impact of the fatigue failure and the estimated cumulative damage in the development of MSDs.

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List of Abbreviations

MSDs: Musculoskeletal Disorders

WMSDs: Work-related musculoskeletal disorders

NORA: The National Occupational Research Agenda

BLS: Bureau of Labor Statistics

OSHA: Occupational Safety and Health Administration

3DSSPP: 3D Static Strength Prediction Program

RULA: Rapid Upper Limb Assessment

REBA: Rapid Entire Body Assessment

UTS: Ultimate Tensile Strength

UE: Upper Extremity

LMM: Lumbar Motion Monitor

CTS: Carpal Tunnel Syndrome

EMG: Electromyography

DPC: Damage per Cycle

CD: Cumulative Damage

VAS: Visual Analog Scale

FTOV: First Time Office Visit

Chapter 1: Introduction

MSDs are one of the leading threats to occupational health. According to the Bureau of Labor Statistics (2015), MSDs accounted for approximately 31% of illnesses including days away from work and occupational injuries [1]. Indirect and direct costs resulting from MSDs in the US are extremely large, with $100 billion expended per year on indirect costs and $ 20 billion spent on direct costs including workers' compensation [2]. Upper extremity injuries, including shoulder injuries, are the second highest cause of occupational lost time claims after back injuries [3]. Shoulder pain is the third most common complaint leading to musculoskeletal related primary care consultation in the United States [4,5]. Recent studies of shoulder complaints in the working adult population have demonstrated shoulder symptoms in approximately 30% of the surveyed subjects [6]. In 2014, shoulder injuries and illnesses caused the longest absences from work compared to any other body part with a median of 26 days of lost work. In 2014, 88,980 non-fatal shoulder injuries and illnesses occurred that involved days away from work. [7]

Cumulative loading is widely believed to be a major contributing factor for the development of MSDs. Several studies have suggested methods for addressing cumulative loading where the cumulative damage for the total job is estimated by considering each individual task. Such studies, for instance, have considered measures such as peak spinal load, task duration, task frequency, loading during rest time, total rest time, and number of tasks performed. However, most of these studies have used linear integration methods, which assume that low force, long duration and high force, short duration tasks have the same injury risk [8,9]. However, other studies have shown that force increases are more detrimental for the development of MSDs when compared to increased exposure time. [10] Several studies have demonstrated that biological tissues exhibit an interaction between the risk factors of force and repetition, in a pattern anticipated by fatigue failure theory. For example, tendon, cartilage, and bone pathology as well as cytokine responses, all revealed a pattern of force-repetition interaction consistent with a fatigue failure process in a novel rat model examining upper extremity pulling tasks [11].

In a systematic review of epidemiological studies that examined force repetition interaction for the development of MSDs, correspondence with the fatigue failure process was clearly demonstrated. The pattern for MSDs and fatigue failure was found in many MSDs including tendinitis, epicondylitis, carpal tunnel syndrome (CTS), low back disorders and hand pain [12]. Evidence supporting the fatigue failure process in the development of MSDs included epidemiological studies, tissue loading in animal studies and in vitro fatigue testing of musculoskeletal tissues. This suggests that cumulative loading effects may be estimated using the fatigue failure process.

The exposure-response relationship for the shoulder pain and its association with the workplace risk factors is still unclear, and associations not well understood [13]. However, the public health burden of the shoulder pain highlights the need to develop models to predict shoulder pain and implement prevention strategies. In fact, the National Occupational Research Agenda (NORA) in October 2018, highlighted the need to understand the risk factors for work related MSDs and to improve methods for exposure assessment and develop new risk assessment models and methods [14].

Current observational tools available for upper extremity assessment (e.g. RULA, REBA), lack the ability to evaluate the impact of cumulative loading on MSD risk, nor is the ability to consider a variety of risk factors. In addition, assessment for effects of duration and frequency are not included and combined effects of jobs comprising multiple tasks are also not available. To this point, no model for shoulder risk assessment has used the concepts of fatigue failure theory. This highlights the need for a new tool that can be used to estimate the cumulative damage for the shoulder. To maximize utility and increase the likelihood of use by practitioners, such a tool should also be user friendly. This dissertation will be dedicated for the development and validation of a shoulder tool considering the risk factors that are known to be associated with shoulder pain, and it will consider the cumulative biomechanical loading based on the fatigue failure theory. Accordingly, the specific aims for the dissertation are:

Specific Aim 1: Development and validation of a shoulder risk assessment tool based on fatigue-failure theory. Associations between the cumulative damage per workday and shoulder symptoms outcome will be studied and investigated.

Specific Aim 2: Incorporating the effect of individual characteristics and their impact on the risk assessment for the shoulder model. The effects of individual characteristics will be used to make suitable model adjustments.

Specific Aim 3: Investigating the impact of ratings of perceived exertions of the shoulder strength assessment on the model adequacy. Associations and risk assessment will be further studied.

This dissertation is comprised of six chapters. The following structure has been employed: Chapter 1 provides an overall introduction to the topics included in the dissertation; Chapter 2 will be dedicated to general background, including: functional anatomy of the shoulder joint, shoulder kinematics in overhead reaching, shoulder pain and disorders, shoulder pain and the occupational risk factors. Moreover, this chapter will cover tools for shoulder pain assessment, methods for cumulative exposure integration, and the fatigue failure process in the development of musculoskeletal tissue damage. Chapter 3 will cover the development and validation of a shoulder risk assessment tool based on the fatigue-failure theory. Chapter 4 will investigate incorporating the effect of the individual characteristics and their impact of the risk assessment for the shoulder model. Chapter 5 will consider the impact of subjective ratings on the model accuracy and risk assessment. Conclusions and the need for future research will be discussed in chapter 6.

Chapter 2: Literature Review

2.1 Functional Anatomy of the Shoulder Joint

As a result of static and dynamic stabilizers complex, dynamic interplay of the bony articulations, ligament constraints, and dynamic muscle forces, the shoulder joint has the greatest range of motion of any joint in the human body [15]. The ligamentous and muscular stabilizers allow the motion arc of the glenohumeral joint, which is described by the small glenoid surface and large articulating humeral head. The shoulder girdle components function as a dynamic interrelated unit to give the shoulder joint its high rate of dislocations.

Four articulations account for the extraordinary flexibility of the shoulder joint. Those articulations include: glenohumeral, sternoclavicular, acromioclavicular, and scapulothoracic. Stability is therefore dependent upon a functional system of musculo-tendinous support. This support is both within (rotator cuff) and outside of joint capsule [12]. The combined movements of the glenohumeral and scapulothoracic are also responsible for the wide range of motion of the shoulder complex. Simultaneous movements of the bony anatomy (humerus, scapula, clavicle) are also vital for upper extremity normal function and for full elevation [15].

Thus, the interaction of multiple shoulder structures, which react to mechanical stimuli and adjust accordingly, gives the shoulder its ability for multiple degrees of motion. A mismatch exists between the glenoid and the articulating surfaces of the proximal humerus, this mismatch reduces the effectiveness of the inherent bony stability of the shoulder. The unequal proportions of surface area of the glenoid and the humeral head take part in this unstable articulation [16]. To add to the stability of the shoulder, the presence of a constrained capsule and glenohumeral ligaments, as well as the fibrocartilaginous labrum all has vital impacts as static stabilizing structures. The musculature surrounding the shoulder girdle, supports the static stabilizing structures, and provides dynamic stability. The rotator cuff muscles act as dynamic stabilizers, and their location and orientation around the glenohumeral joint add to the passive stability of the shoulder. During the motion arc, the static and dynamic stabilizers provide the required stability at different positions. Those stabilizers react to the forces applied through the glenohumeral joint. Additional degrees of motion are achieved by the scapulothoracic joint which also contributes to the stability of the shoulder joint. All these factors account for the biomechanically complex system of the shoulder, a system developed to respond for upper extremity needs [17]. However, the complex nature of demands on the shoulder joint increases its susceptibility to peri-articular and articular pathologies.

2.2 Anatomy of Shoulder Joint

The component structures of the shoulder girdle include: (bony anatomy): humerus, scapula, clavicle (figure 2.1), (bony/muscular articulations): glenohumeral, sternoclavicular, acromioclavicular, and scapulothoracic, (muscles or dynamic stabilizers): rotator cuff, deltoid, and scapular stabilizers and (static stabilizers): labrum, capsule, ligaments. [18]

2.2.1 Bony Anatomy

2.2.1.1 Humerus

The proximal portion of the humerus consists of the greater tuberosity, half spheroid articulating surface or head, lesser tuberosity, bicipital groove, and proximal humeral shaft. The humerus is the longest bone of the upper extremity. The humeral head shaft angle is 130^{o}-150^{o} with the head retroverted 26^o-31^o, figure 2.2. The humeral head is spherical where its size is determined by its thickness (neck length) and radius of curvature. The center of the humeral head does not coincide with the projected center of the humeral shaft. The humeral head offset can be defined as the distance between the center of the humeral head and the central axis of the intramedullary canal. This offset is correlated with humeral head radius and thickness. [19]

The three facets of the greater tuberosity provide the continual ring insertion of the rotator cuff. The surgical neck of the humerus is at the level of the metaphyseal flare of the distal tuberosity. The bony articulating surface for the humerus is represented by the glenoid fossa. [20,21] Glenohumeral dislocations can result from excessive forces applied to the shoulder.

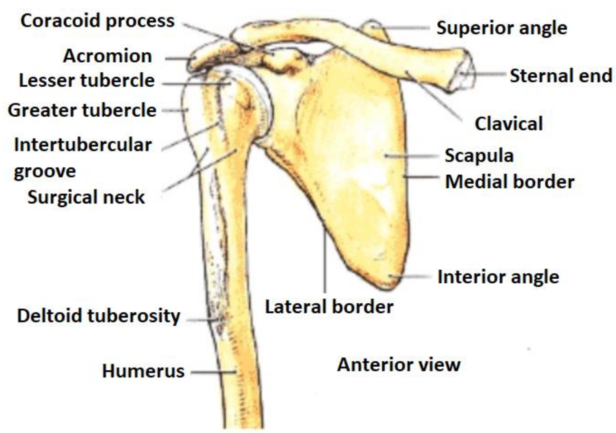

Figure 2.1: Bones of the shoulder joint [22].

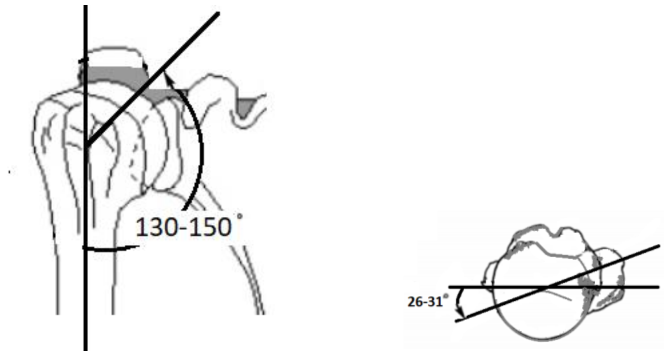

Figure 2.2: The humeral head retroverted 26°-31°, humeral head-shaft angle 130°-150° [22].

2.2.1.2 Scapula

The scapula is oriented 30°-45° anterior to the coronal plane and humeral head which provides the extensive range of motion for the shoulder. The scapula lies on the posterolateral aspect of the thorax and acts as a site for shoulder muscle attachments. The scapula rests on the posterolateral aspect of the thoracic cavity where it overlays ribs 2 through 7. The scapula is flat bone in shape and has a triangular shape having three distinct borders and three angles. The distinct borders include: Superior, axillary, and vertebral and the three angles are: superomedial, inferomedial, and lateral angle. [23]

The superior process or the spine forms the basis for the acromion and variations of its shape can affect the rotator cuff. The acromion and the distal end of the clavicle form the acromioclavicular joint. The acromion also serves as a lever arm for the deltoid. The acromion, coracoid process and the coracoacromial ligament form the coracoacromial arch. Movement of the rotator cuff against the arch and impingement of the humeral head can result in bursitis and Tendinitis. [15, 20]

2.2.1.3 Clavicle

The clavicle is responsible for the connection of the shoulder and trunk, which is achieved by the lateral and medial joints, the acromioclavicular joint and the sternoclavicular joint, respectively. [15,20] It articulates between the manubrium of the sternum at the sternoclavicular joint and the scapula at the acromioclavicular joint. The clavicle has an S shape which bends concavely posteriorly at the lateral one third of the bone and convexly anteriorly at the medial two thirds. [24] The middle third transitional zone of the clavicle is the thinnest and weakest mechanically. The clavicle acts as a strut, from which glenohumeral joint is suspended, it prevents the shoulder from medial displacement by counteracting the actions of the pectoralis major and trapezium. [25] Figure 2.3 show the osseous anatomy of the shoulder girdle, with the joint articulations.

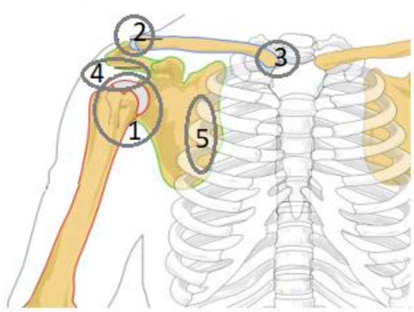

Figure 2.3: Bony anatomy of shoulder girdle (Anterior view):1) Glenohumeral joint. 2) Acromioclavicular joint. 3) Sternoclavicular joint. 4) Subacromial joint. 5) Scapulothoracic joint [26].

2.3 Joint Articulations

2.3.1 Glenohumeral Joint

The mismatched humeral head and the small glenoid articular surface make the glenohumeral joint suited for the extreme mobility. It is a synovial ball and socket joint between the scapula glenoid fossa and the humeral head, figure 2.4. [15] The glenohumeral joint permits significant rotation while maintaining the center of rotation for the humeral within 1-2 mm with respect to the glenoid [27]. The humeral head only has 20%-30% contact with the glenoid fossa. In the arc of motion, the normal shoulder restricts the humeral head within center of glenoid cavity. This restriction is a result of static and dynamic forces. This constraint may be lost in biomechanical dysfunction of injury. Direction of instability can be anterior, inferior, posterior or a combination depending on injured structures [15]. It has been found that stability of the mid-range the glenohumeral motion (where capsule and ligaments are lax) is affected by the concavity compression and that the intact glenoid labrum increase the effectiveness [28]. The glenohumeral center of rotation can be estimated as a center of sphere through the glenoid surface, with the humeral head radius [29]. Humeral head defects of the humeral head radius affect the stability of the glenohumeral joint. Studies have found that the glenohumeral joint stability is decreased by larger humeral defects where the stability is increasingly affected at neutral and external rotation, and at abduction [30, 31].

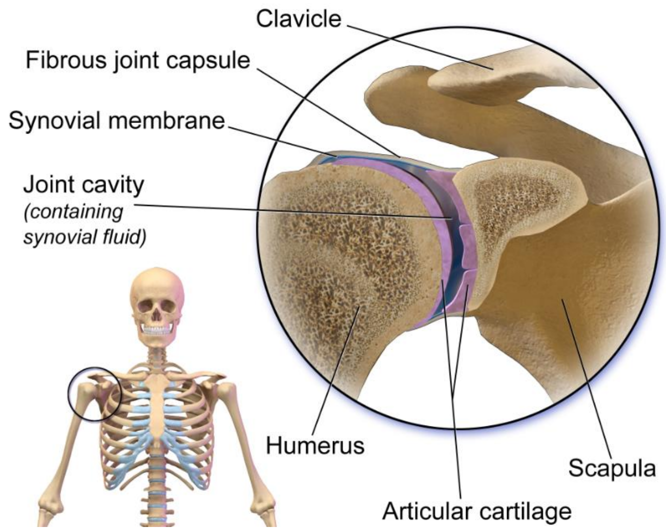

Figure 2.4: Anterior view of glenohumeral joint articulation [32].

Static and dynamic stabilizing structures govern the movement of the glenohumeral joint. The bony anatomy, the glenoid labrum, negative intra-articular pressure, the glenohumeral ligaments and the joint capsule (Figures 2.5, 2.6) represent the static stabilizers whereas the dynamic stabilizers include the rotator cuff muscles and the other muscles that surround the shoulder joint (figure 2.7). [35] The passive mechanisms include: Articular Surface, glenoid Labrum, joint capsule, and the ligaments. The multiple degrees of motion within the glenohumeral joint results from the combined effect of the stabilizers.

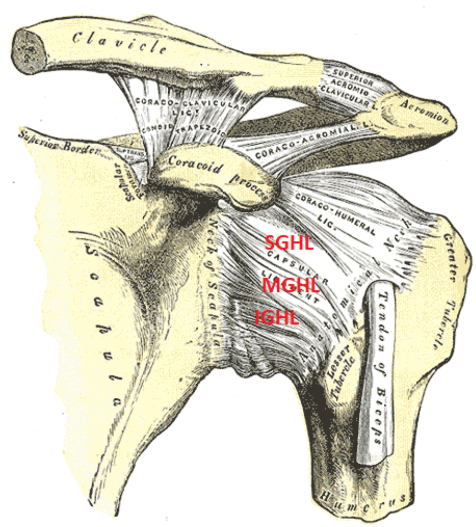

Figure 2.5: Glenohumeral joint capsule and ligaments. SGHL, superior glenohumeral ligament, MGHL, middle glenohumeral ligament, IGHL, inferior glenohumeral ligament [33].

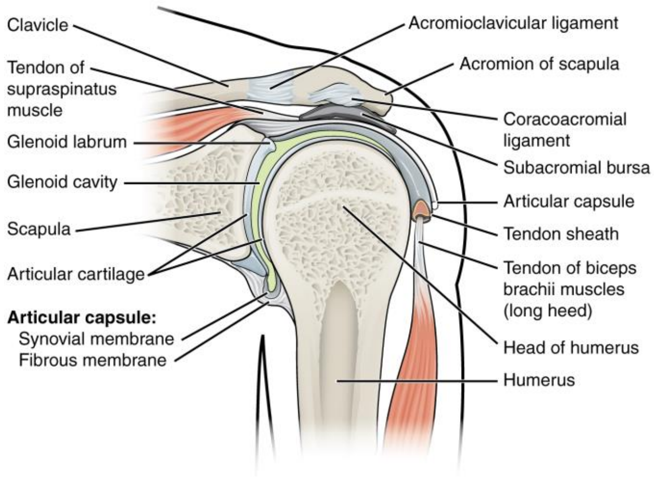

Figure 2.6: Glenohumeral joint capsule [34].

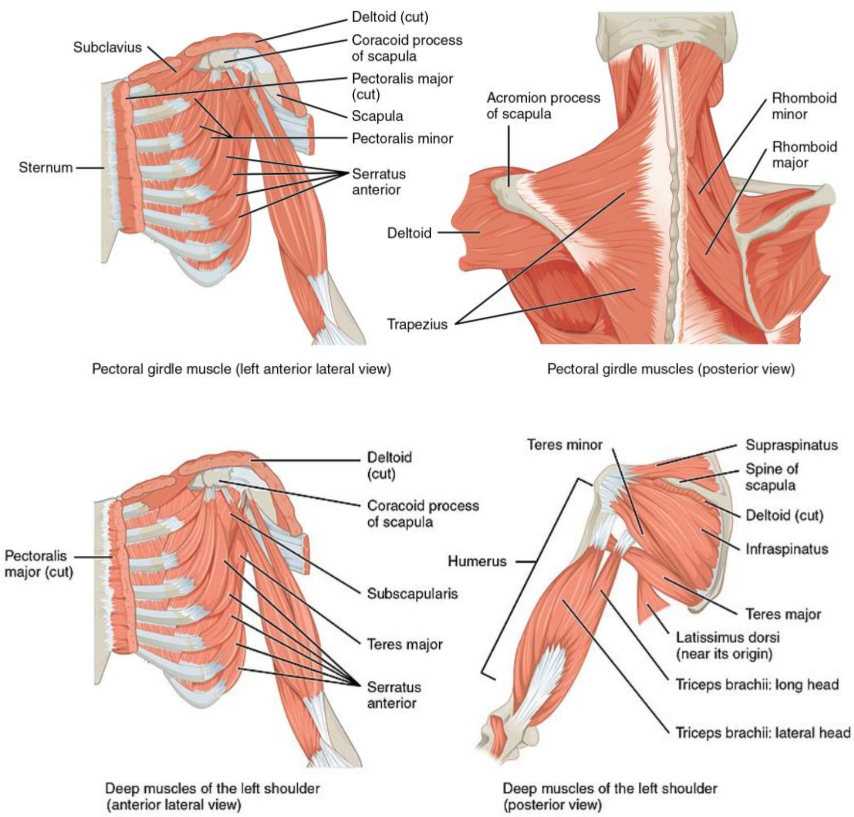

Figure 2.7: Muscles of the shoulder [36].

2.3.2. A Passive Mechanisms

Passive mechanisms, which act statically through phases of movement, in the shoulder joint include the articular surface, glenoid labrum, joint capsule and the ligaments. The glenoid articular cartilage provides the required conformity and stability for the glenohumeral joint. The negative intra-articular pressure prevents humeral head translation. The glenohumeral joint is sealed by the capsule and contains less than 1*ml* of joint fluid. Adhesion and cohesion forces also prevent the parts from being pulled apart. Those factors function at low loads.

The glenoid labrum is a fibrous structure to extend articular surface and provide larger contact area. For anterior-inferior glenoid rim the detachment of the labrum can be the reason for the high incidence of recurrent anterior dislocations [37].

The joint capsule tightens in various extreme positions to stabilize the joint. The glenohumeral ligaments and the capsule are adherent anatomically. When other stabilizing mechanisms are overwhelmed, ligaments function to provide the required stability at extreme ranges of motion.

The coracohumeral ligament extends from the base of the lateral coracoid into the lesser and greater tuberosities and provides the required stability in posterior and inferior translation in forward flexion and adduction (respectively), and for internal rotation and adduction.

The superior glenohumeral ligament extends from the glenoid's anterosuperior edge to the top of lesser tuberosity. The rotator interval region between anterior and superior borders of the supraspinatus and subscapularis, respectively is constituted by the superior glenohumeral ligament and the coracohumeral ligament which have a similar function.

The middle glenohumeral ligament starts from the supraglenoid tubercle, superior labrum, or scapular neck. In lower ranges of abduction (60°-90°) this ligament prevents the humeral head from anterior translation [20]. The ligament inserts on the medial aspect of the lesser tuberosity. It is considered as the most variable, thickest and most consistent of glenohumeral ligaments and it also functions to prevent the inferior translation at the side. Recurrent instability can result from the injury to the inferior glenohumeral ligament [15].

2.3.3 B Dynamic Stabilizers

The rotator cuff and the static stabilizers play a major role on the rotation and three-dimensional movements of the humeral head [35]. The subscapularis, infraspinatus, supraspinatus, and teres minor constitute the rotator cuff muscles. Figure 2.8 is an illustration of the orientation of the muscles. Rotator cuff muscles are positioned in a way that resists the glenohumeral shear stresses. The combination of the independent actions of the muscles contribute to the stability in mid and end range motions of the glenohumeral joint. Table 2.1 provides description of the muscles and their actions. [35] Thus, the rotator cuff can be considered as a musculotendinous unit consisting of four muscles. Those muscles can act concurrently to increase the shoulder joint stability. Their proximity to the shoulder joint and having their tendons blend and reinforce the glenohumeral joint increase their role for providing dynamic stability against unwanted translations [38].

Table 2.1: Rotator cuff muscles and their function [35].

Rotator Cuff Muscle	Description	Action
Teres Minor	Circumpennate Muscle	Provides external rotation force (generates about 45%) Helps to resist translations both posterior and superior
Subscapularis	Multicircumpennate muscle	Functions as an internal rotator Helps to resist translations both interior and inferior Contributes to the bicipital sheath
Infraspinatus	Circumpennate Muscle	Provides stability against posterior subluxation Provides external rotation forces (generates about 60%) all with the teres minor
Supraspinatus	Circumpennate Muscle	Acts with the deltoid to elevate the arm (humeral head abduction to 90^{o}) and provide stability for glenohumeral join

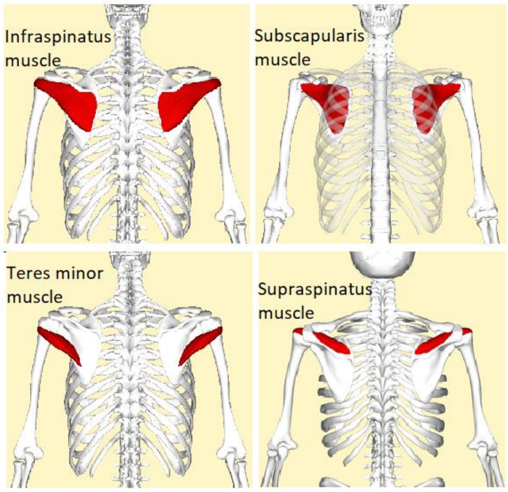

Figure 2.8: Rotator cuff muscles [39].

In glenohumeral abduction, the rotator cuff provides the required stability and they provide the required forces [20,40]. In shoulder motion, asymmetric contraction causes the humeral head rotation. Concavity compression can result from the rotator cuff contraction. The supraspinatus acts with the deltoid to elevate the arm and provide stability for the glenohumeral joint. The supraspinatus originates from the supraspinous fossa and inserts in the superior aspect of the greater tuberosity it inserts in the greater tuberosity forward and laterally.

The infraspinatus provides stability against posterior subluxation and it also provides external rotation forces all with the teres minor. It originates from the infraspinous fossa and it extends laterally to its tendinous insertion on the greater tuberosity middle facet. Several nerves act to innervate the infraspinatus, including the axillary and suprascapular nerve.

In maximum internal rotation, the subscapularis muscle can function properly, and its tendon is associated with the anterior capsule. The subscapularis muscle originates from the subscapular fossa and extends laterally to its insertion on the humerus lesser tuberosity. The subscapularis muscle functions as an internal rotator.

Depressing of the humeral head can be achieved by the rotator cuff and the long head of the biceps. The long head of the biceps stabilizes the joint anteriorly (when arm internally rotated) and posteriorly (when arm externally rotated). The rotator interval is defined as the space between the superior and anterior borders of the subscapularis tendon and supraspinatus tendon respectively. The capsular structures in this region have high variability and the capsule in the region of the rotator interval is noted by variably present openings, which are also known as synovial recesses. Specific capsular openings can be referred relative to the location of the middle glenohumeral ligament [41]. The capsule of the rotator interval is very thin measuring between 0.1 and 0.06 mm in cadaveric specimens. The negative intra-articular pressure of the shoulder is maintained by this capsular covering, which adds to the glenohumeral joint stability thus the rotator interval can prevent interior and posterior translations of the glenohumeral joint. The dimensions of the rotator interval vary with arm rotation being decreased by internal rotation [42]. Age, smoking and activity level have been associated with rotator cuff tears and the scapular anatomy has been correlated with degenerative tears. It was also found that the risk of re-tear after rotator cuff repair increases with the higher critical shoulder angle, where the critical shoulder angle is the angle between the most lateral border of the acromion and the superior and inferior bone margins of the glenoid [43].

2.3.4 Stability and Mobility of Glenohumeral Joint

2.3.4.1 Basis of Static Stability

Static stabilizers of the glenohumeral joint include: glenohumeral Ligaments, glenoid labrum, glenohumeral capsule, and bony stabilizers. In extreme motions, excessive translation of the humeral head is prevented by the glenohumeral ligaments. The circle concept of the capsuloligamentous stability can better explain how the static stabilizers work. Based on this concept, extreme translations in one direction may be required to prevent damage in same and opposite directions of the joint. Although the number of the restraints is limited, the glenohumeral joint can still maintain its stability. In dynamic shoulder motion, it is still necessary for the capsular ligaments to be balanced to maintain passive stability [35,44].

2.3.4.2 Basis of Dynamic Stability

Neuromuscular control is the primary facilitator of the active stability of the shoulder joint. The neuromuscular control between the scapulothoracic musculature and the rotator cuff muscles play a major role in active stability. To achieve further joint stability, the contribution of the dynamic stabilizers is required. This can be achieved by coordination of muscle forces to redirect forces to the center of glenoid surface, compression of articular surfaces caused by contraction, passive muscle tension caused by bulk muscle effect, barrier effect of contracted muscle, and joint motion which secondarily tightens the passive ligamentous constraints [43]. Both primary and secondary active stabilizers work together to achieve the stability of the glenohumeral joint, the primary active stabilizers include the rotator cuff muscles, the deltoid, and the long head of the biceps brachii. The secondary stabilizers include the teres major, latissimus dorsi, and pectoralis major muscles. The primary role of muscles in dynamic stability is to produce combined muscular contraction enhancing humeral head stability in arm movements. The muscles act in an agonist/antagonist relationship to provide movement and stabilize the glenohumeral joint. A balance of forces is also achieved by the muscles such as the rotator cuff and the deltoid muscles. Humeral head compression within the glenoid is achieved as the rotator cuff muscles counteract the shearing forces generated by deltoid muscles. The increased humeral head compression within the glenoid is a major contributor to joint stability. Contraction of the rotator cuff muscles is also important for joint stability. Tension within the capsular ligaments is produced because of the rotator cuff muscles contraction that tightens the glenohumeral ligamentous capsule and acts in centering the humeral head in the glenoid fossa. The humeral head translation is resisted as the rotator cuff muscles blend with the capsule creating active and passive barriers for the translation [31]. Centering the humeral head within the glenoid fossa plays a major role for glenohumeral joint stability. Studies suggested that when the hands are in overhead positions, compressive forces of about 90% of body weight are required to stabilize the glenohumeral joint and this is achieved at 90° of abduction [44].

Stability of the shoulder joint is increased by being ideally oriented by the functional scapulothoracic musculature. Risk of ligament failure in the shoulder joint is reduced by the rapid neural feedback as a response to forces. The glenohumeral ligaments and the rotator cuff muscles neural feedback are also important to prevent pathologic translation of the glenohumeral joint.

In glenohumeral joint abduction, stability as a dynamic fulcrum is achieved by the anatomic location of the rotator cuff. Interactions of the rotator cuff and other muscles are necessary in the shoulder girdle. The rotator cuff muscles dynamically stabilize the glenohumeral joint through the mechanical properties of the muscle stiffness and tendon compliance, rotator cuff muscles act as an extension of the osseous glenoid to control humeral head position [44]. For example, the humeral head is actively compressed in the glenoid cavity by the rotator cuff muscles and long head of biceps, which have a specialized anatomy and located in an ideal configuration. Torques and accelerations necessary for using the glenohumeral joint are produced by the rotator cuff which acts as a force couple around the joint. This is achieved by the coordinated activation of agonist and inhabitation of antagonist muscles and the coactivation of antagonist and agonist muscles. Force couples are achieved when the resultant force of two opposing muscle groups achieve a given net moment. The humeral head rotation in shoulder motion is caused by the asymmetric contraction of the rotator cuff muscles. Contraction of rotator cuff muscles also causes concavity compression. On the coronal plane at 60° the deltoid muscle decreases stability of the glenohumeral joint, whereas at 60° on the scapular plane the deltoid increases the glenohumeral joint stability. For abduction of glenohumeral joint between $60\text{-}150^{\circ}$, contraction of the infraspinatus and the subscapularis stabilize the glenohumeral joint. The infraspinatus and the teres minor act to reduce the anteroinferior capsuloligamentous strain and control the external rotation of the humerus. The biceps and the subscapularis provide the greatest stabilization in neutral and external rotation respectively [35].

Instability is affected by the disruption of the coupled activity of the rotator cuff muscles and the resulting force couples. The anterior dislocation of the humeral head on an intact anterior soft tissue surface is caused by the rotator cuff rupture. A rotator cuff tear leads to displacement of the humeral head and this displacement increases with increased tear size. Tear size has a vital effect on the stability in the inferior and anterior direction of tears, centered at critical area and at rotator interval, respectively. Stability is generally unaffected in partial tears, unless they represent more than fifty percent of the tendon width. Muscles affected by the rotator cuff tear are also a major factor for shoulder stability.

The integrity of the transverse force couple is a vital stabilizing mechanism for the rotator cuff. This force couple is dependent upon the subscapularis anteriorly and the infraspinatus/teres minor posteriorly and it can be disrupted by the tears involving the subscapularis and the infraspinatus/teres minor. Stability is unaffected by the isolated supraspinatus tears, which can be compensated by the remainder of the rotator cuff muscles. Anterosuperior escape (anterosuperior humeral head translation) can result from the disruption of the normal anatomic restraints. The disruption is caused when the cephalad forces of the deltoid are not counteracted by the rotator cuff. Massive rotator cuff tears, coincident with deficiency of the anterior acromion and disruption of the coracohumeral ligament, is an example of failure of the coordinated activity of the static and dynamic stabilizers [35].

2.3.4.3 Interaction of Static and Dynamic Stabilizers

When the humeral head is centered within the glenoid, in mid-ranges of motion, the capsuloligamentous structures are usually lax. Ligaments become progressively tighter (acting as check reins) in end ranges of motion. Midrange motion stabilization is achieved by the configuration of the articular surfaces, intra-articular pressure and labrum, and dynamic stabilizers.

The glenoid concavity and the compressive force generated by rotator cuff muscles are the main contributors to stability in midrange motion of the shoulder which is known as concavity-compression effect [45,46]. In concavity compression effect, the humeral head is compressed against the concave glenoid surface. This leads to concentric rotation of the humeral head on the glenoid. In end-range positions where forces acting on the glenohumeral joint increase the concavity-compression effect also becomes important. The capsuloligamentous structures can be protected at end-range positions by limiting the joint's range of motion and decreasing strain in those structures which is achieved by the shoulder muscle activity [47]. For end-range positions, the rotator cuff muscle and the scapulohumeral work in unity to provide stability and complement the glenohumeral ligament check reins. In end range positions, the deltoid or pectoralis major muscle forces are increased which decreases stability, but the rotator cuff muscle forces increase, which improve stability. Also, in end-range positions, rotator cuff muscles are more effective compared to the subscapularis and the long head of biceps may contribute to stability as well. The subscapularis is more effective in mid-ranges of abduction, where it works with the middle glenohumeral ligament [35]. The torsional rigidity of the glenohumeral joint is increased by 32% as a result of Biceps forces. The long head of the biceps can relieve the stress on the inferior glenohumeral ligament, and the biceps tendon plays an active role in anterior shoulder stability. [48]

Overpowering of the stabilizing interactions can result from excessive forces or repetitive stresses, which can lead to pathologic conditions. For example, Bankart lesion and other failures of the inferior glenohumeral ligament can result from forces that increase extension, abduction and range of external rotation. Avulsion of the glenoid labral attachments of the ligament complex happens as a result of a Bankart lesion. The check rein action of the glenohumeral ligaments can lead to gradual failure from the repetitive stresses. Lesions close to those caused by traumatic stresses can be produced, particularly if such forces are applied in end ranges of motion. Persons experiencing repetitive stress in the shoulder joint, and who cannot sustain shoulder dislocation can develop Bankart lesions and in such persons the ligament length and subsequently the capsular volume will increase. The repetitive interstitial ligament injury accompanied with remodeling and stretching is the primary reason for the increased volume. [35] Bankart lesions represent a wide spectrum of pathology related to the detachment of the capsulolabral complex and it is the essential lesion responsible for shoulder instability. Bankart described this avulsion as the essential lesion of recurrent anterior instability and being found in 90% first time traumatic anterior dislocations and it may have a fleck of bone attached on avulsion. It can be described as an avulsion of the anterior inferior glenohumeral ligament and labrum from the glenoid rim [49]. Thus, it is represented by the detached labrum and capsule from the glenoid. It has also been noted that the strongest areas of the glenoid labrum are those with common labral tears which are posterosuperior and anteroinferior, with the anteroinferior being Bankart tears. How the labrum and the capsule detach from the glenoid determines the type of the Bankart lesion. Three grades can be defined for the Bankart lesion, where all of them are characterized by capsular tears but Grade I has no labral lesions (stable), Grade II has partial labral detachment (mildly unstable), and Grade III has labral detachment as complete labral capsule detachment and are grossly unstable [49].

Instability signs can result in mid-range motions when the intracapsular volume increases. Symptoms can be in form of multidirectional instability under which stable shoulder positions can also have gross instability signs.

2.3.4.4 Mobility of the Glenohumeral Joint

The glenohumeral joint has three degrees of freedom: rotation, abduction/adduction, flexion/extension (Figure 2.9). If the humerus is maintained in internal rotation, the limited angle of the glenohumeral abduction in the coronal plane will be 60-90°. Tension in inferior glenohumeral ligament and impingement of the greater tubercle of the humerus are the main causes for this limitation. The abduction range can increase 90-120° when the humerus is allowed to rotate externally. Medial rotation of the humerus will result from the elevation of the humerus in the sagittal plane. Scapular plane abduction happens when the humerus is elevated in the scapular plane. Lateral rotation is not needed for the prevention of the impingement of the greater tubercle upon the acromion. For elevation in the scapular plane and when optimal alignment exists between the deltoid and supraspinatus to perform humeral abduction, in this case the glenohumeral joint capsule is not twisted. Throughout the elevation in the scapular plane, the humeral head will remain centered in the glenoid fossa. An exception to this happens in the upward glide that happens when the movement begins. In full elevation of the humerus in any plane, the end position will be the same. The humerus is in the scapula plane and medial epicondyle faces forward. The greatest congruency between the articular surfaces and the maximum osseoligamentous stability are achieved in this position. This can be considered as a close-packed position, where no active rotation or little active rotation for the humerus is permitted [15].

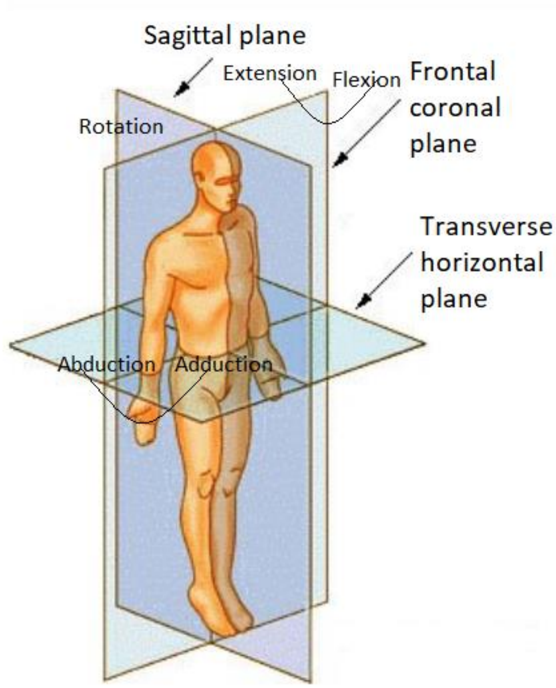

Figure 2.9: Motions of the shoulder joint. Frontal plane (flexion, extension), transverse (abduction, adduction), sagittal (rotation) [50].

2.4 Acromioclavicular Joint

In the acromioclavicular joint, the static stabilizers: capsule, ligaments, and intraarticular disc act for the stability of the joint [18]. It is a diarthrodial joint which links between the acromion's medial edge and small convex facet on the clavicle lateral end. High contact stresses can result in the articular surface due to small surface area of joint and high axial loads. Failures could happen such as: Osteolysis or osteoarthritis. The joint stability is dependent on the superior and inferior acromioclavicular ligaments which act for the reinforcement of the weak joint capsule [15]. The joint allows movement of scapula on clavicle in three planes where rotation occurs around sagittal, coronal and vertical axes.

The coracoclavicular ligaments provide additional stability for the acromioclavicular joint, the capsule of which surrounds the joint and is reinforced by the acromioclavicular ligaments. The trapezoid and conoid are also two ligaments they serve as suspensory ligaments of the shoulder girdle from the clavicle [20].

2.5 Sternoclavicular Joint

The sternoclavicular joint is a plane synovial joint; the medial end of clavicle articulates with cartilage of first rib and shallow sternal socket. The joint functions as a ball and socket joint with three degrees of freedom. The joint cavity is divided into two compartments. The articular disc, three ligaments and a strong capsule are responsible for stability. In the sternoclavicular joint, the surrounding ligament structures achieve the stability. This joint acts as the true point of articulation between the upper limb and axial skeleton (Figure 2.10) [51]. When forces are transmitted through the clavicle to the axial skeleton, the disc acts to prevent the medial displacement of the inner clavicle over the sternum. Excessive downward rotation of the clavicle can be checked using the costoclavicular ligament which also helps to limit clavicular protraction. The anterosuperior and posterior of the sternoclavicular joint are covered by the capsular ligament, which provide the required stability of the upward displacement of the inner clavicle [51]. Different types of movements can be done by the sternoclavicular joint, which includes rotation around its axis, forward and backward movements, and upward elevation motions with degrees of: 45-50°, 35°, and 30-35° respectively. Elevation and depression occur between medial end of clavicle and the disc, also clavicle can rotate around its longitudinal axis, protraction and retraction occur between the articular disc and the sternum [15].

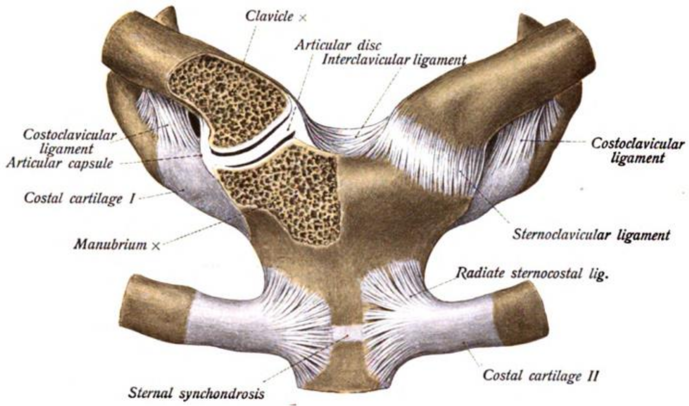

Figure 2.10: A: Anterior, B: Cross-sectional views for sternoclavicular joint [52].

2.6 Scapulothoracic Articulation

In scapulothoracic articulation, the scapula is allowed a smooth movement on the underlying thorax as the articulation is occupied by muscular, neurovascular, and bursal structures. The scapulothoracic articulation is a space between the anterior scapula concave surface and the posterior thoracic cage convex surface [20]. The articulation is located between the deep aspect of the scapula and thoracic rib cage at the levels of ribs 2 through 7 acting as a sliding junction. The scapulothoracic articulation allows increased shoulder movements beyond the 120° allowed by the glenohumeral joint. Intervening layers of multiple muscles and bursae facilitate the interactions at the scapulothoracic joint. Three levels/layers incorporating the muscle and bursal tissue are described in the literature which includes: superficial, intermediate, and deep. The superficial layer includes the trapezius and latissimus dorsi muscle. The rhomboid major and minor and levator scapulae muscles form the intermediate layer whereas the subscapularis and serratus anterior muscles form the deep layer. The intermediate layer does have important neurovascular structures as well which innervates the muscles [23].

The scapula is both stabilized and given its motion by being attached to several muscles, such as: serratus anterior, supraspinatus, subscapularis, trapezius, infraspinatus, deltoid, levator scapulae, infraspinatus, teres major and teres minor. The serratus anterior is the most important of these. The serratus anterior maintains the chest wall and trapezius medial angle. Bursae surround scapula at three different locations: the serratus anterior and the lateral chest wall, the serratus anterior and the subscapularis, and at the inferior angle [15].

Scapulothoracic muscles include the trapezius, which functions at scapula lateral angle for retraction and elevation; the rhomboids, for retraction and elevation of scapula and they insert in the scapula medial aspects; the levator scapulae, results in medial and upward rotation of the scapula, and the serratus anterior, their activation result in protraction and upward rotation [15]. The pectoralis minor, rotation and protraction of the scapula inferiorly are achieved by this muscle. The deltoid muscle has three portions and acts on force couples on glenohumeral joint and allow for forward elevation and in scapular plane elevation.

2.6.1 Scapulothoracic Mechanism

Atmospheric pressure and axioscapular muscles including the trapezius, keep the scapula in place, as it has no ligament or bony attachments to the skeleton other than through the acromioclavicular and sternoclavicular joints. The subscapularis and serratus anterior muscles separate external surface of thorax (convex) and anterior surface of scapula (concave) which glide over one other in movement.

2.6.2 Resting Position of Scapula

The scapula lies on the posterolateral aspect of the thorax over ribs 2-7 having a slight forward tilt in the sagittal plane. The plane of scapula is at right angles to the plane of glenoid. In the resting position, the scapula is 30-45°anterior to coronal plane lying between sagittal and front planes. Subjects with abnormal cervical and thoracic spine sagittal plane will have alterations to the resting posture of the scapula. This can lead to: Shoulder dysfunction, weakness or contracture of axioscapular musculature, and a reduction in the upper extremity range of motion [15].

2.6.3 Scapular Motion

Motions of the scapular can be translatory and rotatory and they are not independent of one another. Three rotatory motions and two translation movements (elevation and depression) comprise scapular motion. Upward or downward tilt of the glenoid fossa results from scapular rotation around sagittal plane. For the upward rotation, the trapezius and serratus anterior muscles are the vital movers. The scapular rotation around sagittal plane can be considered as abduction, adduction, and upward or downward rotations at acromioclavicular and sternoclavicular joints. The other two rotatory movements lead to the scapular winging and scapular tipping or tilting, and both occur at the acromioclavicular joint. Winging results from rotation of a vertical axis through acromioclavicular joint, whereas tipping or tilting results from rotation around a coronal axis. The translator movements can be toward or away from vertebral column or upward/downward on the rib cage. A combination of translation and rotation movement can happen such as the protraction movement where it includes the forward movement of scapula around thoracic wall and rotation of scapula around clavicle end this also include the lateral end of clavicle anterior movement [15]. For protraction and upward rotation, the serratus anterior (runs from scapula to rib cage) is the principal driver; it stabilizes the scapula against the thorax. Disruption of the lateral scapular tilting and scapulohumeral rhythm can be prevented by the strong scapular protraction. For subjects with winged scapula, they have less protraction strength and less serratus anterior activity [53]. The (serratus anterior and minor pectoralis), (middle trapezius and rhomboid) muscles are the primary movers for the protraction and retraction respectively [15]. In shoulder abduction, the muscles responsible for producing the abduction torque include the middle deltoid and accordingly the rotator cuff and axioscapular muscles (upper and lower trapezius, rhomboid major and serratus anterior). In scapular plane abduction the activation level for the aforementioned muscles increases and both the rotator cuff and axioscapular muscles act together to counterbalance the translational forces produced by other muscle groups and have a vital role for stabilization in shoulder abduction [54]. In maximal scapular protraction in horizontal abduction and adduction, the activated serratus anterior is stabilized by the pectoralis major and which consequently increase the protraction strength and the serratus anterior activity [55].

2.8. Other Shoulder Muscles

Other shoulder muscles include the latissimus dorsi, whose main function is to extend, adduct and internally rotate the humerus; the teres major, which helps in arm extension and for adduction and internal rotation of the shoulder; and the coracobrachialis, which starts from the coracoid process into the humerus anteromedial aspect [15,20]. Flexion and adduction of the glenohumeral joint is achieved by the latter muscle along with the short head of the biceps. The pectoralis major, functions in adduction and humerus internal rotation. The biceps two heads, the long head serves as a depressor in abduction.

2.9 Shoulder Kinematics During Overhead Reaching

Studies for the forces and moments at the shoulder while performing everyday tasks indicated that the greatest ranges of motion at the shoulder occurred during reaching and lifting tasks as did the greatest shoulder moment [56]. Thus, it is important to study the shoulder kinematics during reaching. For the shoulder kinematics during voluntary overhead reaching, studies defined that into four phases. Figure 2.11 demonstrates the four different phases.

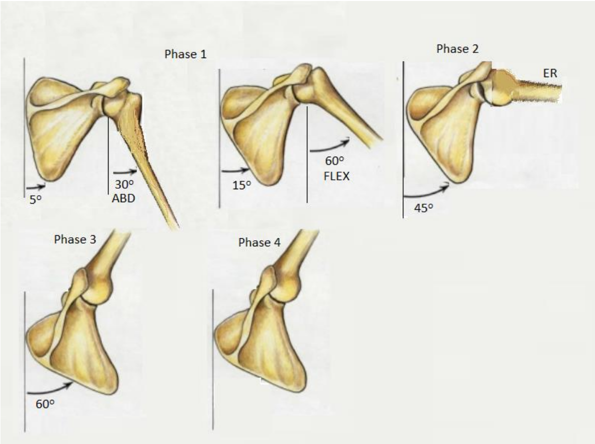

Figure 2.11: Kinematic model for overhead reaching of the shoulder (posterior view) [44, 57].

The first phase involved a 5-15° scapula movement in form of upward rotation that occurs in the scapulothoracic and acromioclavicular joints. The second phase involves elevation of the lateral aspect of the clavicle coupled with upward rotation of the scapula. This happens because of the motion of sternoclavicular joint about the anteroposterior axis. This motion is measured relative to the thorax and ranged from < 10-45° and associated with 100° of arm elevation. Motion of the sternoclavicular joint contributes to the scapulothoracic joint motion. The third phase involved posterior axial rotation of the clavicle around the sternoclavicular joint in the form of 30-50° of posterior axial rotation. Posterior tilt of the scapula is also observed in this phase where the clavicular axial rotation occurred between 70-90° arm elevation and end range overhead reaching. The final phase involved motion at the glenohumeral joint where during the overhead reaching, external rotation up to 70° happens at glenohumeral joint. The amplitudes of joint motions differ in overhead reaching and depend on different factors such as: age, gender, tasks performed and how the upper extremity is loaded and whether the load is held on hand. The scapula, humerus and clavicle move concurrently in overhead reaching and scapular translations with respect to the thorax vary in amplitude between subjects and the glenohumeral and scapulothoracic contributes to the motion in overhead reaching in a ratio of 2:1 [44].

Studies of shoulder kinematics in arm elevation have also shown that during arm elevation, migration of the humeral head increases with increased rotator cuff fatigue in individuals without shoulder dysfuncion [58]. Other studies of shoulder muscular fatigue in elevated arm positions used Electromyography EMG signs of shoulder muscular fatigue and involved other muscles. the EMG signal was recorded for the upper part of the trapezius muscle, the infraspinatus muscle, the middle and anterior part of the deltoid muscle and the biceps brachialis muscle. Abduction and forward flexion at a right angle in the shoulder joint were used. It was found that after five minutes in both positions, significant signs of fatigue were experienced by the supraspinatus and the upper part of the trapezius muscle. In the forward flexion (supraspinatus muscle) and in the abduction position (upper part of the trapezius muscle) EMG signs of fatigue were developed within a minute [59]. Some studies found that when the arm is abducted more than 30° from the side of the body rapid increase in fatigue rate is attained [60]. For the internal and external muscle rotators of the shoulder, eccentric and concentric muscle contractions showed indifferent fatigue patterns [61].

2.10 Shoulder Pain and Disorders

Shoulder pain can be elicited from various structures, including tendons, bursae, ligaments, and muscles. Shoulder function can be affected by structural abnormality, fear of pain, and may be altered by pain [62]. Shoulder pain can result from local pathologies or it can be referred from other pathologies such as neck symptoms which can be very difficult to be differentiated from those localized to the shoulder. There is a diverse range of causes for the shoulder pain. Those include: Referred pain, systematic disease, inflammatory rheumatic diseases, articular pathology, bone pathology, soft tissue local pathology, and pain syndromes.   Referred pain can be from the neck, intra-abdominal region, cardiovascular system, or diaphragmatic and pulmonary sources. Referred pain examples are illustrated in figure 2.12.

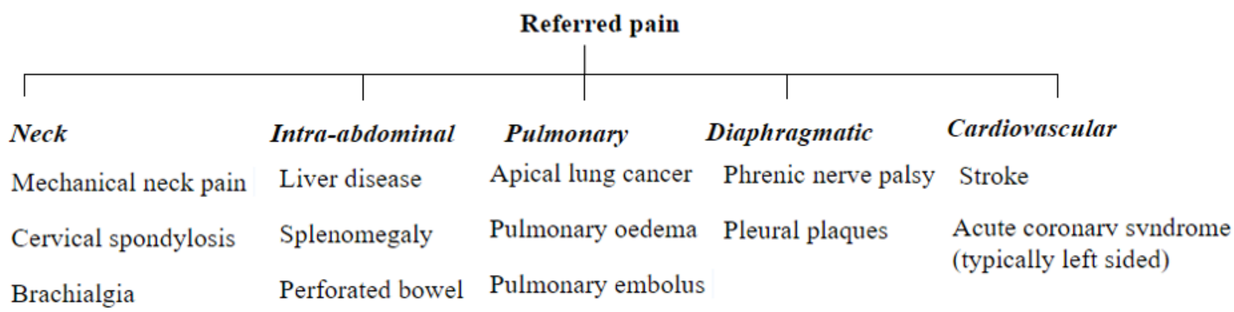

Figure 2.12: Shoulder Refereed pain causes [63].

Bone pathology resulting in referred shoulder pain may include tumor (primary or secondary), avascular necrosis, Paget’s disease, and fracture.

Examples of Systematic disease include malignancy (primary/secondary) and infection (septic arthritis, tuberculosis). Pain from inflammatory rheumatic disease may result from rheumatic polymyalgia, rheumatoid arthritis, psoriatic arthritis, and crystal arthritis. Examples of articular pathology as a cause of shoulder pain include osteoarthritis of glenohumeral joint, osteoarthritis of acromioclavicular joint, and Milwaukee shoulder (apatite-associated destructive arthritis). Soft tissue local pathology includes: Rotator cuff tendinopathy/impingement syndrome, biceps tendinopathy, adhesive capsulitis, calcific tendinitis, subacromial bursitis, shoulder instability, and labral tears. Pain syndromes include both fibromyalgia syndrome and shoulder-hand syndrome. Table 2.2 summarizes the articular pathology, bone pathology and soft tissue local pathology. [63]

Table 2.2: Examples of the articular pathology, bone pathology and soft tissue local pathology [63].

Articular pathology	Bone pathology	Soft tissue local pathology
Osteoarthritis of gleno-humeral joint Osteoarthritis of acromio-clavicular joint Milwaukee shoulder	Tumour (primary or secondary) Avascular necrosis Paget's disease Fracture	Rotator cuff tendinopathy /Impingement syndrome Biceps tendinopathy Adhesive capsulitis Calcific tendinitis Sub-acromial bursitis Shoulder instability

Many methodological problems are associated with shoulders which include: Diagnostic procedure, study design, methods of measuring risk, criteria, lack of homogeneity of shoulder disorder terminology and classification. For diagnostic purposes, upper limb conditions can be classified into three categories: specific conditions with evidence-based diagnostic criteria (rotator cuff syndrome), other specific conditions with no defined diagnosis (acromioclavicular syndrome), nonspecific conditions characterized by pain, discomfort, loss of muscle power and limited muscle movement, the nonspecific conditions do not allow for a specific diagnosis to be made [64]. Studies define pain in different aspects when dealing with the complex structure of the shoulder joint and its biomechanical association with adjacent areas such as the spine. Some studies ask simply for pain experienced, while others ask for pain, time, and use pain diagrams. A diagrammatic representation of the shoulder pain can be used that shows anterior, posterior, and lateral aspects of shoulder joint. Such a diagram may show the cervical spine and scapula to better define the pain of the joint [65-67]. Figure 2.13 shows an example of a shoulder pain diagram.

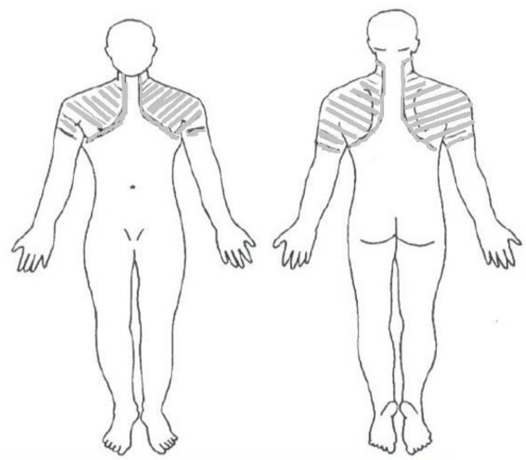

Figure 2.13: Diagrammatic representation of shoulder pain [68].

Shoulder pain can be a primary or secondary source of pain, which makes it difficult to identify the pain source. Figure 2.14 illustrates a diagnosis algorithm for shoulder problems. The high cost of imaging and orthopaedic diagnosis often makes the researchers use the generic term shoulder pain for all pain occurrences. Different measures are used in reporting rates in different studies, and undetected pain may result from self-perceived definition since pain may arise from surrounding structures to the shoulder joint. Many patients report issues of shoulder pain that can resolve, only to be experienced again in the near or distant future. Many risk factors predispose a person to shoulder pain including age, gender, occupational demands, and/or psychosocial factors. For the personal risk factors such as age and gender it was found that presence of pain increased with advancing age, and prevalence of shoulder pain more prevalent in females. The occupational factors include repetitive work, high force demands (physical demands), and vibration exposure, work-related postures, computer work, and/or psychosocial factors. The major predictor of outcome for patients of shoulder pain to primary care practitioners are pain intensity on first consultation and history of shoulder problems. It is hard to index patients with high/low risk categories for persistent shoulder pain where the indexing can be helpful to predict the likelihood of recovery [68,69].

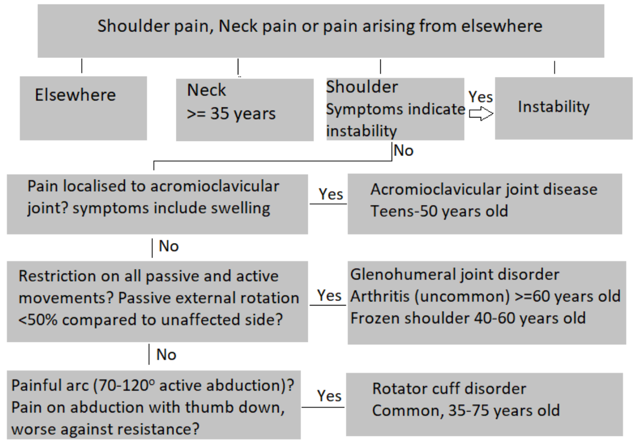

Figure 2.14: Diagnosis of shoulder problems [70].

2.10.1 Rotator Cuff Disorders (Age 35-75) Subacromial Pain, Impingement Syndrome

It is estimated that rotator cuff disease accounts for nearly 65–70% of all shoulder pain. This is associated with overloading, cuff degeneration with ageing, ischaemia, instability of the glenohumeral and acromioclavicular joint, muscle imbalance (adverse anatomical features), and musculoskeletal diseases [64].

Rotator cuff tendinopathy is the most common cause of shoulder pain and it is related to activity (occupational history of heavy lifting or repetitive tasks), but it can occur in non-manual lifting and in the non-dominant hand. Genetic susceptibility has been suggested in some studies [62]. The presence of a painful arc reinforces the diagnosis of a rotator cuff disorder. Rotator cuff tear is traumatic in young people and atraumatic in elderly people (related to attrition from bony spurs on the acromion undersurface or degeneration of the cuff) being indicated by history. Some studies found that the prevalence for rotator cuff tears is increasing with age. For the 50s and 60s age groups, the prevalence was significantly greater in males compared to females, but this was not noted in the 70s and 80s age groups. symptomatic tear was not as common as the asymptomatic one, where the latter was twice the former [71].

Rotator cuff tendinopathy is difficult to distinguish on examination from partial tears, as weakness in resisted movement happens in both conditions. In the presence of full thickness supraspinatus tears, studies suggested no correlation exists between symptoms and functional loss and that lower rotator cuff tears limits the ability to rotate beyond 20°. In asymptomatic people, partial and full thickness tears can be found in imaging, large or complete tears can be found using drop arm test [70].

2.10.2 Glenohumeral Disorders (Adhesive Capsulitis: Age 40-65, Median 50-55; Osteoarthritis: ≥60)

Adhesive capsulitis accounts for about 2% of cases of shoulder pain. It is associated with factors such as: female sex, shoulder trauma, older age, surgery, diabetes, stroke, thyroid disease and cardio-respiratory disorders [62]. A history of non-adhesive capsulitis symptoms often leads to adhesive capsulitis or frozen shoulder and true glenohumeral arthritis. Deep joint pain and restricted motion in the form of reduced external rotation can be a characterization of adhesive capsulitis. People with diabetes are more vulnerable to adhesive capsulitis and it can also happen after prolonged immobilization. Restriction of active and passive movements and global pain are the main symptoms apparent on examination. [70]

2.10.3 Osteoarthritis

Osteoarthritis is a rare glenohumeral joint disorder due to non-weight bearing capabilities of the joint. Full thickness rotator cuff tears and traumatic injuries of the joint are related with the secondary osteoarthritis. Traumatic injuries can include anterior shoulder dislocation. Restriction on range of motion, impaired function and pain on rest and activity are the regular symptoms. Restriction on range of motion is severe in patients with marked osteoarthritis [62].

2.10.4 Glenohumeral Arthritis

The Glenohumeral joint is involved in all types of arthritis. Pain on passive motion can be used to distinguish inflammatory and degenerative disorders thereby making the process of distinguishing the inflammatory diseases of the joint from other joint disorders easier [62].

2.10.5 Acute Tendonitis/ Bursitis

Intense pain in deltoid area radiating to thumbs in some cases is the primary method of recognizing acute tendonitis or bursitis, this pain is caused by secondary pain on nerve from swelling of tendons. Conditions leading to acute tendonitis/bursitis include: Unaccustomed activity or trauma. Severe reduction in range of motion and muscle strength can be affected by reflex pain inhibition of agonist muscle activity [62]. Patients with acute tendonitis/ bursitis are advised to relieve the load by shortening the lever arms of the load (Figure 2.15). For example, workers handling hand tools in awkward posture can do a whole-body movement while handling the tools to relieve the load.

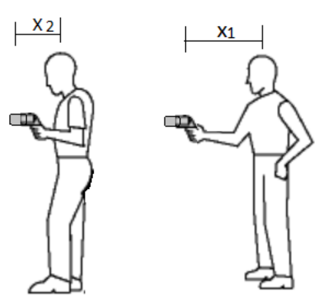

Figure 2.15: Shortening of the lever arm while using hand tools [72].

2.10.6 Tendinosis/Chronic Subacromial Pain

In shoulder abduction or flexion, the subacromial soft tissue can get impinged between the acromion and the humeral head, thereby causing what is referred to as impingement syndrome. Paresis of the serratus anterior muscle where paresis is defined as a muscle weakness caused by nerve damage or disease, glenohumeral instability, thoracic kyphosis, mechanical and dynamic factors all affects the tendinosis. Symptoms include pain when sleeping on affected shoulder or feeling of pain in deltoid area with arm elevation. Limited abduction motion with painful arc at 80-120° can be also a sign. However, some patients subluxate the humeral head in the painful arc to obtain full range of motion [62].

2.10.7 Rotator Cuff Tears

Rotator cuff tears accounts for a high percentage of the shoulder complaints with about an incidence of 4.5 million cases every year as of the United States being responsible for a high percentage of time lost at work. Rotator cuff tears are more common for the supraspinatus tendon compared to other tendons on the cuff. Tears of the pectoralis major and long head of biceps can be also observed. Weakness in the supra-spinatus impingement and weakness of external rotation can predict rotator cuff tears. Rotator cuff tears accounts for half shoulder injuries with increased prevalence after 50 years old (ruptures increase after 50 years old both partial and full thickness). Older and younger patients might not be the same regarding the tears, differences in the etiology of the tear, physical demand, levels of activity, and healing potential all affect the tears nature among older and younger patients. Traumatic origin full thickness tears are more common among young adults <40 years old where they respond well in terms of pain relief, but special considerations are needed to examine the treatment outcomes [73].

2.10.8 Instability

Shoulder instability focuses on the stabilizing structures and refers to dislocation of the shoulder. Traumatic shoulder dislocations are most common of all joint dislocations. Other concerns also include: Pain, fatigue and injury which may influence the glenohumeral joint. The functional instability becomes more dynamic moved from inflammation and subacromial impingement to a broader dynamic view. Examples include instability and position change of the glenoid resulting from winging scapula (scapula protrudes from the back in an abnormal position) from thoracic wall resulting from paresis of the serratus anterior muscle. Family history, apprehension, previous injuries and provoking activities are important factors when studying instability [62].

2.10.9 Biceps Tendinopathy

Biceps tendinopathy results in anterior shoulder pain. Bicipital tendinitis is associated with pain in resisted elbow flexion and resisted supination of the forearm. Few epidemiological studies have described attempts to discriminate bicipital tendinitis using an examination. Most of the studies used criteria based upon pain on resisted isometric elevation and flexion of the arm and of the elbow respectively. Tenderness over the tendon and shoulder pain are also other criteria. Biceps tendinopathy coexists with rotator cuff pathology and impingement. Isolated biceps tendinopathy is uncommon [74].

2.10.10 Acromioclavicular Joint Syndrome

Normal functioning of the joint is necessary for full shoulder elevation to take place. Dysfunction of the joint results in localized pain in positions of full shoulder abduction; it also results in tenderness, and swelling. Localized pain is also provoked by horizontal adduction of the joint and with the arm extended. Because of the complex anatomical and functional structures of the shoulder joint, diagnostic tests are rarely found for shoulder disorders. Their validity is questionable in population and workplace studies [74].

2.10.11 Nonspecific Shoulder Pain

Studies have shown that upper limb pain is associated with job demands, stressful work, and non-work-related stress. Other studies identified the risk factors associated with shoulder pain: repetitive movements, high psychological demands and poor control at work, poor job satisfaction, poor social support, repetition, and duration of task. Other physical risk factors also include: Physical work with a heavy load, awkward work postures, mental stress, and obesity. Preventive measures should focus on those areas of interest [62]. In Chronic pain, the behavior and psychosocial problems becomes important such as: anxiety, attention seeking, verbal pain complaint, medication use, general verbal complaints, distorted posture and mobility, fatigue, insomnia and depressive mood. Better diagnosis at source and better employee training will give guidance on how to perform tasks effectively avoiding both physical and psychosocial factors.

2.11 Shoulder Pain and the Occupational Risk Factors

Shoulder pain is the third most common cause of musculoskeletal consultation in primary care in the United States [4, 5]. Statistics based on self-report per population surveys, estimate that the shoulder pain prevalence is between 16% and 26% [5], and that 1% of adults have new shoulder pain annually for which they consult a medical practitioner [4]. Other statistics estimated the lifetime prevalence of shoulder pain roughly about 67%, with approximately 46% of the patients reporting a persistent pain 26 weeks after first consultation for a new episode of shoulder complaint

[44]. Recent studies of shoulder conditions of the working adult population have reported shoulder symptoms in about 30% of the surveyed subjects [6]. In 2014, shoulder injuries and illnesses caused the longest absences from work compared to any other body part with a median of 26 days of lost work. In 2014, 88,980 was the total number of non-fatal shoulder injuries and illnesses including days away from work [7]. Thus, the joint is one of the most common sites of regional pain [4]. The shoulder joint is a complex structure and is the most mobile joint in the human body [75] and it can have several pain mechanisms. Chronic shoulder pain has large health care costs and it has a major influence on the affected individuals which can impact their normal life, including absence from work, functional impairment, and disability. [6,13] Some estimates show that for patients with shoulder pain, about 47% of incurred costs are because of lost productivity from being away from work [44]. Statistics have also shown that only about 50% of new episodes of shoulder complaints presenting in medical practice show complete recovery within a 6-month period. [76] Work-related shoulder pain is a common reason to seek medical advice and shoulder pain is most common in middle-age and elderly people [70]. Multiple other recognized causes and medical conditions are found to be associated with shoulder pain and it may also arise from anatomical structures remote from the shoulder such as the neck [70]. Several work-related risk factors were confirmed to be related to shoulder conditions including, heavy loads, working in awkward posture, vibration and repetitive movements and combinations of these factors. [77]. About 62% of the working population is exposed to repetitive upper extremity movements based on a survey done in Europe, where those were exposed to repetitive movements for more than a quarter of their working day. Several studies highlighted the impact of static postures, muscle fatigue and repetition for the discomfort in neck and shoulder region [78]. Despite the abundancy of the epidemiological studies, there is little information to indicate that shoulder pain is

diminishing [77]. The exposure-response relationship for work relatedness of shoulder pain, associations with risk factors and its verification are still not well understood. Some multi-factorial models for shoulder pain also have some limitations [13]. These data highlight the public health burden of shoulder pain and the need to develop models to predict shoulder pain and implement prevention strategies.

The shoulder girdle components function as a dynamic interrelated unit which gives the shoulder joint its high rate of dislocations. The shoulder joint with its greatest range of motion of any joint in the human body may exhibit different pain in working environments. This also can be affected by the static and dynamic stabilizers and the complex dynamic interplay of the bony articulations, ligament constraints, and dynamic muscle forces [70,71,73-79]. Pain prediction for of this dynamic interrelated unit can be of significant impact. Several studies have considered the association between shoulder pain and work-related factors including, forceful exertions, repetitive movements, heavy physical load, awkward posture, exposure to vibrations from machine and tool, work with elevated arms and psychosocial factors related to work, Personal factors play a role as well [5,74,76,77,80,81-83]. In the available body of literature, some methodological limitations can hamper interpretation. For example, studies have adopted different methods and statistical approaches which can make the comparison and interpretation difficult [13]. Other concerns include heterogeneity because of the different exposure assessment methods, sample sizes, and study populations. As more risk factors are included larger populations are required, and the choice of statistical methods will be of significant impact. Restrictions, stratification, multi-variable analysis, randomization are all options for the statistical analysis. Multi-variable regression software has benefited epidemiological researchers, but it may introduce the risk of over-adjustment. An example of this can be the socioeconomic status (SES) and occupational exposure, stratified analysis is preferable as it illuminates the bivariate distribution and it avoids over-adjustments. Joint analysis of physical and psychosocial exposures is another concern; collinearity of effects cannot be undone by statistical adjustments. Overlapping measurements is an additional problem [84].

Discrepancies in research results, difficulty in replicating prior findings, represent a lack of certainty about the validity of those findings. Unmeasured differences between study populations may be represented by discrepant findings. Analysis of the problems may represent another possible cause of discrepant findings. The methodological features in the etiological studies of occupational risk factors for MSDs also contribute for the discrepancy. Different samples of the identical underlying dose-response relationship may lead also to variations of the reported risks. Thus, population features may lead to apparent discrepancies in results. Choices of metrics and cut-points between categories have a vital effect on exposure-response comparison estimations. Another source for discrepancy can be presence or absence of exposure and contextual factors other than those under study in the epidemiological exposure-response results [84].

For shoulder pain, several studies define shoulder pain based on self-report, even though reliance on exposure estimates from individuals can be less consistent as people overestimate the physical demands, even when estimate validation is done. Surrogate measures are often used in this case, which are based mainly on self-report questionnaires [5]. Another issue can be that many occupational studies of shoulder pain have been cross-sectional. Recall and selection bias can result from the cross-sectional prevalence studies which can lead to exposure underestimation. This happens when those affected tend to be selected out of employment. Those studies cannot identify the cause of the reported association between the occupational exposures and pain development (i.e., the cause-effect relationship). [5] The association of shoulder pain and the risk factors is still not well understood. Taken as a whole, this indicates the need to develop a shoulder pain model based on exposure- response relationship to overcome current limitations.

Data have suggested several work-related factors are associated with the shoulder pain. Herin, et al. [6] in their cohort study suggested that awkward posture, forceful effort, job demand, are predictors of chronic shoulder pain at work. Larsson et al. [77] in their review also confirmed the strong evidence for an association between shoulder pain and gender, repetitive movements, high force, work postures, and combinations of these factors. Windt et al. [13] showed that shoulder pain is the result of an action of many factors, including individual factors, physical workload factors, and the psychosocial work environment. Increased levels of muscle activity with few periods of low activity during awkward and static postures, and during repetitive movements also lead to shoulder pain. Several other studies have proposed multifactorial models to explain the etiology of musculoskeletal problems, and more specifically shoulder pain [13].

Van Rijn et al. [85] in their systematic review of the literature also highlighted the association between different work-related factors and shoulder disorders. Physical load factors, type of work, and psychosocial factors were included in the review of the literature. Rotator cuff tears, tendinitis of the biceps tendon, subacromial impingement syndrome, and suprascapular nerve compression were considered in the review. Several physical load risk factors were found to be associated with the subacromial impingement syndrome. The results showed that high levels of hand force >1 hr/day (OR 2.8–4.2), repetitive shoulder movements, hand arm vibration, and repetitive hand/wrist motion >2hrs/day were all associated with subacromial impingement syndrome. Other factors that were found associated are Forceful actions which require >10% maximum voluntary contraction (MVC), duty cycle for forceful actions ≥9% of time or forceful pinch 0% of time (OR 2.66). Other associations for lifting >20 kg >10 times/day, hands above shoulder level, and upper arm flexion

≥45° ≥15% of time with OR of 1.04–4.7, 2.43 respectively were also found on the results. The results also included association for High psychosocial job demand and subacromial impingement syndrome with OR 1.5–3.19. For the type of work, slaughterhouse OR 5.27 and working as a betel pepper leaf culler OR 4.68 were associated with subacromial impingement syndrome. Tendinitis of the biceps tendon OR 2.28 and subacromial impingement syndrome OR 3.38 were the highest in fish processing industry. For the rotator cuff tears and suprascapular nerve compression they were not associated with the type of work or physical load factors based on the reviewed articles. Based on the reviewed articles, subacromial impingement syndrome is highly associated with forceful actions in work, awkward postures, high repetitive work, and psychosocial job demand [85].

Hanvold et al. [62] in their longitudinal study examined the effect of working with prolonged arm elevation on the shoulder pain. The study followed 41 young adults (15 hairdressers, 15 electricians, 5 students, 6 with miscellaneous work) in their first years of working life for over a 2.5-year period; shoulder pain was evaluated by the participants using a pain drawing at baseline and twice in the follow up period. Arm elevation was measured at baseline during a full working day by an inclinometer. Data were analyzed using the GEE (generalized estimating equations) and stratification and adjustments for some of the factors were used (stratified by gender and adjusted for time, physical activity, prior shoulder pain, work demand, mechanical workload, and tobacco use). The study results indicated that work with prolonged arm elevation with angles of $>60^{\circ}$ and $>90^{\circ}$ is associated with shoulder pain among women. The shoulder pain reported was low but the study suggested that this might be an early work- related risk factor among women [62].

Bodin et al. [68] in their study assessed the association between sixteen organizational variables and symptomatic and clinically diagnosed shoulder disorders in workers in a French region, Loire

Valley region. The cross-sectional study involved 3,241 random workers. The organizational variables included in the study were: shift work, job/task rotation, repetitiveness of tasks, five binary variables measuring the work pace (paced work/automatic rate, colleagues' work, permanent controls or surveillance, customer demand and quantified targets), eight variables also measured decision latitude where it refers to the ability of the worker to affect decisions and develop/use their skills in their work. The variables were assessed using a self-administered questionnaire. Shoulder pain was assessed using a Nordic style questionnaire, the duration of pain in the preceding 12 months was noted, and rotator cuff syndrome was also diagnosed if certain conditions applied. Five forms of work organization were identified in the study using hierarchical cluster analysis HCA. The study results showed that (low decision latitude with pace constraints, a "Taylorism" form of work organization) was associated with higher risks of shoulder disorders and high levels were also found in women in high decision latitude with pace constraint form of work organization, thus pace constraints are harmful for the shoulder disorders.

Other studies analyzed the association between work related physical factors and psychosocial factors for the development of shoulder pain over time (multi-factorial nature of chronic shoulder pain) [6]. A prospective longitudinal study of a 5-year follow-up in a sample of 12,714 subjects in France was performed by Herin et al. [6] A self-administered questionnaire was used to assess the personal factors and work exposures; shoulder pain was assessed based on self-reported symptoms and clinical examination. Logistic regression modeling was used in the analysis to find the statistical association between chronic shoulder pain and personal and occupational factors. The study suggested that awkward posture is the most robust predictor of shoulder pain and that workers' perception of their task as monotonous is more predictive of shoulder pain compared to job demand. The study also showed that forceful effort, job demand and decision control in addition to awkward posture are predictors of shoulder pain in a 5-year follow up working population.

Pope et al. [86] also examined the multifactorial nature for the occurrence of shoulder pain and disability related to occupational factors. A case-control study was conducted, for which for those with shoulder pain and disability (the occupational exposures at the time of onset of symptoms) is compared with corresponding occupational exposures in those without shoulder pain and disability. The study comprised 500 random patients from the register of a general practice in UK. A posted questionnaire was used to specify symptoms or disability in the shoulder region. The occupational history for the patients was obtained including information for: physical exposure, working conditions, and workplace psychosocial risk factors. The study results supported the multifactorial nature for the occurrence of shoulder pain and disability. Using hands above shoulder level to perform tasks, the repetitive use of the arms and wrists and stretching to reach below knee level, those who reported those working conditions were at twice the risk of shoulder pain and disability. Carrying weights on one shoulder in men was associated with shoulder pain and disability. Very cold or damp conditions were also found associated in men. Work stress and monotonous tasks are associated with shoulder pain and disability in both men and women. Each of the studied factors has an independent effect of the occurrence of shoulder pain and disorder. Work-related physical activities, work-related physical conditions (at which the task is performed), psychosocial factors and work environment are all related to shoulder pain and disability.

Miranda et al. [87] investigated the effect of work-related factors and individual factors in addition to physical activity and sports on shoulder pain. A prospective longitudinal study was performed with a follow up period of four years among forestry workers in Finland with a total of 3,312 baseline study population. A modified version of the Nordic questionnaire was used to estimate the shoulder pain. The potential predictors were evaluated using the baseline questionnaire. A multivariate logistic regression model was used in the analysis. The study results indicated that awkward postures (hand above shoulder level, forward flexed trunk), heavy workload, mental stress and obesity are the predictive risk factors and that physical exercise (general sports activity) can be protective for the shoulder.

Another study done by Miranda et al. [88] investigated the role of occupational physical load for increasing the risk of subsequent chronic shoulder disorder. A prospective study was carried out among the general population of the finish adults. A representative sample of 7,217 of the population in 1977-1980 participated in the study. Twenty years later, 1,286 subjects were invited to be reexamined again. Nine hundred and nine subjects participated and after doing exclusion for subjects with shoulder disorders at baseline 883 subjects were included in the study for analysis. Questionnaires, interviews, standard laboratory and functional tests were included in the initial screening phase. Exposures were assessed based on a self-administered questionnaire on present or last occupations or previous occupation with longest duration. Physical factors included in the study were working forward flexed, twisted or awkward postures, shaking whole body or using vibrating equipment, repeated series of movement or work paced by machine, lifting/carrying heavy loads. Confounders such as: age, gender, BMI, prior shoulder injury, leisure time physical activity and others were used in the study. A standard clinical examination protocol and symptoms were involved in the study; diagnosis was done for rotator cuff tendinitis, biceps tendinitis, frozen shoulder, post-traumatic conditions, inflammatory arthritis, and non-specific shoulder disorder. Minimum of three-month symptoms before the examination was required. OR (95% CI) was used to represent the risk of having chronic shoulder disorder. Logistic regression was used in the analysis. The results showed that 63 subjects were diagnosed with chronic shoulder disorder.

Vibration (adjusted OR 2.5 CI (1.2-5.2)) and repetitive movements (adjusted OR 2.3 CI (1.3-4.1)) were found to increase risk of shoulder disorders. For at least three exposures the adjusted OR increased to 4. For men and women, the significant factors were different. Awkward postures and lifting heavy loads were significant for women, whereas vibration and repetitive movements were significant for men. When excluding subjects with baseline shoulder pain, the results remain the same. BMI and age modified the physical exposure effects [88].

Harkness et al. [89] performed a two-year prospective cohort study which involved newly employed workers from 12 diverse occupational settings. Mechanical and psychosocial risk factors were examined as predictors of new onset of shoulder pain for newly employed workers. A total of 1,081 workers were included in the study, a questionnaire was used at baseline to collect information about the demographic characteristics, manual handling activities, postures, repetitive movements, work related psychosocial factors, working conditions, and current pain status. Of the mechanical exposures, activities including heavy weights (lifting with one or two hands, carrying on one shoulder, pushing or pulling, lifting at or above shoulder level) were at high risk for the increased symptom onset. Of the psychosocial exposures, monotonous work was a strong predictor. Previous pain also was associated with the onset shoulder pain. Some of the previous variables were found independently associated with the onset of shoulder pain when a multivariate model is used, those include: Lifting with one or two hands, pushing or pulling, lifting above shoulder level and monotonous work.

The effect of occupational and personal risk factors for the onset of shoulder pain in occupations requiring repetitive work was examined by the study of Leclerc et al. [90]. This longitudinal study was performed including 589 workers in five activity sectors. Data were collected using a self-administered questionnaire at baseline and three years later. Shoulder pain was also assessed using the questionnaire. Bivariate association and Chi-square tests were used in the analysis in addition to logistic models. The study results indicated that several independent risk factors were associated with the incidence of shoulder pain which include biomechanical factors, Psychological symptoms and low level of job control. Repetitive use of tools was a predictor in men whereas working with arms above shoulder level and working with vibrating tools were the biomechanical predictors in women. Low level of job control was a predictor for both sexes. Presence of depressive symptoms also associated with the onset of shoulder pain.

Padma and Balasubramanie [91] performed another multifactorial study, where they assessed the occupational risk factors for the neck and shoulder pain using the analytical hierarchy process (AHP). AHP can be described as the presentation of a problem as a hierarchy, prioritization, and then calculation of the results. The three modular categories used in the study are the mechanical, personal, and psychosocial risk factors. Sub-categories were used for each one of the broad categories. Based on the AHP study results, mechanical risk factors (including: Carrying/ lifting heavy loads, repetitive movements, awkward posture, and performing monotonous work for a prolonged time) were the most important factors for as predictors of shoulder pain. Mechanical factors were followed by personal factors (age, sex, smoking, BMI, physical deconditioning because of lack of exercise) and finally the psychosocial risk factors (social factors, mental stress, job pressure, job satisfaction/ stimulus at work) as predictors of shoulder pain.

Andersen et al. [92] also conducted a study on the contribution of work-related physical factors, psychosocial workplace factors and individual factors to the onset of neck and/or shoulder pain. A total of 3,123 industrial and service companies' workers in Denmark participated in a four-year prospective cohort study. At baseline, a questionnaire was used to gather the required information and clinical examinations of all participants were performed. The physical workload was assessed at baseline by video recordings at the workplace. During the three follow up periods a screening questionnaire was used for symptoms and psychosocial risk factors and workers with new pain are clinically examined and physical workload was assessed for new or changed job tasks. The study suggested that work-related physical factors, job demand, precedent stress were independently related to neck/shoulder pain and pain in combination of clinical signs of pressure tenderness. Women were found to be at high risk to be a clinical case (as opposed to just symptomatic). Low pain pressure threshold predicted symptoms but not clinical future case [92].

Skov et al. analyzed the association between symptoms of pain and disorders of the neck, shoulders and low back in sales person and physical and psychosocial risk factors [93]. A self-administered questionnaire was used to collect information about demographic, physical and psychosocial risk factors. A Nordic questionnaire was used for the assessment of the symptoms of pain and disorders of the neck, shoulders and low back. A total of 1,306 salespersons were included in the study. The study results indicated that physical and psychosocial risk factors were associated with MSD symptoms and that tendency to feel overworked as a personality characteristic is associated with MSD symptoms. Results related of the shoulder symptoms showed that spending more than 10 hours in a car is associated with shoulder symptoms and that women had greater prevalence to shoulder symptoms compared to men (during the previous 12 months). High job demands had a significantly increased risk and as well as perception of uncertain employment prospects also associated with increased shoulder symptoms.

Bovenzi [94] in his prospective cohort study investigated the occurrence of neck and shoulder pain (NSP) in male professional drivers in various provinces in Italy. The drivers were from different industries: marble quarries, marble laboratories, dockyards, paper mills, garbage services, and public transport. A three-year follow-up period was used in the study. The population consisted of 537 male professional drivers. Frequency, duration and intensity were investigated. The cumulative incidences for neck and shoulder pain were 31.9% and 21.4%, respectively which occurred during the follow up period. The study accounted for several confounders such as: Age, BMI, physical activity, education, and others. The study results indicated that a measure of cumulative whole-body vibration was highly associated with NSP outcomes. For the shoulder outcomes, lifting loads and working with hands above shoulder level were the major contributors, whereas for the neck pain, driving with trunk bent or twisted was significantly associated with neck pain. Other predictors of neck outcomes included: limited job decision, low social support and job dissatisfaction. Psychological distress was associated with all NSP outcomes. The prospective cohort study highlighted the multifactorial nature of neck and shoulder pain (NSP) in professional drivers. Whole body vibration, physical load factors and psychological factors were all major contributors to NSP in a population of professional drivers [94].

Nordander et al. [95] studied the exposure-response relationship for the work-related neck and shoulder MSDs. The study contained 33 groups (24 females, 9 males) of similar tasks within each group (3,141 workers with 817 males). Diagnosis or physical examination was performed, and the prevalence of discomfort or complaints was recoded using a Nordic questionnaire. Postures, velocities, muscular activity, and psychosocial work environment were all assessed in the representatives' sub-groups. The head, right upper arm and right wrist postures and velocities were recorded using inclinometry and electrogoniometry. The muscular activity was recorded for the right trapezius muscle and the forearm extensors using the electromyography. A job content questionnaire was used for the psychosocial work environment assessment. The data was analyzed using linear regression analysis. Univariate and multivariate linear regression are used to reveal the significant associations. Many results were revealed from the associations. The wrist posture and angular velocity, head inclination, upper arm elevation and the muscle activity of the forearm extensors and trapezius were all associated with the neck disorders. For the shoulder disorders (right side), the head and upper arm velocity, wrist posture and angular velocity, the muscle activity of the forearm extensors and trapezius. When adjusting for muscular activity, postures, psychosocial exposure, and velocities, women experience higher prevalence of neck and shoulder complaints and tension neck disorders. Job strain and isostrain and low job control for the psychosocial environment were also associated with the neck and shoulder disorders [95].

Another study for predictors of neck and shoulder pain was performed by Evans and Patterson for non-secretarial computer users. The cross-sectional study involved 170 subjects from 7 workplaces in Hong Kong. Data about work posture and exposure was collected using a questionnaire. A questionnaire for work tension was also used. Some observations and measurements for postural and workstation factors were also included in the study (e.g. back rest inclination, seat height and depth, mouse and keyboard vertical position and distance), workstations were scored by one observer. A standard typing test was also used to record speed of subjects. The pain/discomfort was measured using a self-assed questionnaire. Multiple regression analysis was used to investigate predictors for neck or shoulder pain. The study results indicated that for the past month, 65% of the subjects suffered from neck/shoulder pain. Gender and work tension were significantly related to neck/shoulder pain. Typing skill, hours of computer use, and workstation factors were not associated with neck/shoulder pain. The study suggested that further investigation is required as neck flexion, prolonged unvaried computer use and fixed postures, static loads and repetitiveness were found to increase strain on MS system [96].

Frost et al. did a cross-sectional study [97] to evaluate the occurrence of shoulder tendinitis due to shoulder loads in repetitive work. Nine hundred sixty-one (961) workers in repetitive work and 782 referents were studied in Denmark. Quantification of Shoulder loads is done at task level and the task distribution determined the assignment of the measures of exposures. Shoulder tendinitis is defined based on symptoms in combination with clinical criteria. Exposed workers showed a higher prevalence of shoulder tendinitis (adjusted OR 3.1, 95% CI 1.3-3). Frequency of movements and lack of micro-pauses in shoulder flexion were not related to disease prevalence. The risk increased slightly with increasing force requirements (OR 1.6, 95% CI 1.0-2.6 per unit). The study showed that increased risk of shoulder tendinitis is found in workers with repetitive tasks which can be partially attributed to the force requirements.

Another cross-sectional study on shoulder tendinitis was done by Stenlund et al. [98]. The study investigated the relationship between shoulder tendinitis and heavy manual work and exposure to vibration. Construction industry workers were studied in the Stockholm region, Sweden (98 foremen, 55 rockblasters, 54 bricklayers). Information about the loads lifted, job title, vibration, and years of manual work were all obtained using a structured interview. Shoulder tendinitis or muscle attachment inflammation in the shoulder was examined using a clinical investigation. Shoulder examination and medical records were used in the clinical investigation. For rockblasters, the percentage of rockblasters with signs of tendinitis for the left and right shoulders was 33% and 44%, respectively. About 8-17% of foremen and bricklayers had shoulder tendinitis. Multiple logistic regression models were used in the analysis. Age, sport activities, smoking habits and dexterity were included as confounders. Working as rockblasters compared to foremen showed an OR of 3.33 and 1.71 for left sided and right sided shoulder tendinitis, respectively. The OR for vibration exposure was 1.84 for left side and 1.66 for right side. The Sum of load lifted through a workers' work life and years of manual working did not appear to be risk indicators for shoulder tendinitis. Bricklayer workers were also in low risk. Exposure to vibrating tools and working as rockblasters were risk indicators for shoulder tendinitis.

Chiang et al. [99] conducted a cross-sectional study for fish processing workers in Kaohsiung harbor in Taiwan. Prevalence of upper limb MSDs was investigated in the study. The study also evaluated the relationship between ergonomics risk factors and shoulder or upper limb disorders [99]. A cohort of 207 workers from eight factories was included in the study. A standardized questionnaire and a clinical examination were done in the study. An experienced occupational physician performed the clinical examination. Workers in the study were classified into three groups based on their ergonomic risks. Those groups are group I (61 workers) low repetition and low forceful movements of the upper limbs; group II (118 workers) high repetition or high forceful movements of the upper limbs; group III (28 workers) high repetition and high forceful movements of the upper limbs. Statistical analysis and the OR statistic were used in the study. Age, gender, repetition, forceful upper limb movements, and the interaction of forceful upper limb movements and repetition were all used as predictors in the study. The soft tissue disorders that were most common among workers were shoulder girdle pain (30.9%), epicondylitis (14.5%), and carpal tunnel syndrome (15.0%). Occurrences of those MSDs were indifferent for the 8 plants. For workers sustaining upper limb forceful movements, the OR of shoulder girdle pain was 1.8 (95% CI 1.2-2.5), whereas for workers with repetitive movement tasks for their upper limbs the OR was 1.6 (95% CI 1.1-2.5). Untrained or unskilled workers were more susceptible to upper limb MSDs. Employment duration was insignificantly associated with the aforementioned MSDs.

Another cross-sectional study performed on the fish processing industry is done by Ohlsson et al. [100]. The study was performed on 13 fish processing plants in Sweden on the southeast coast.

The study involved 206 women working in the fish processing industry and the number of control women used in the study is 208. Physical and psychosocial work factors in addition to personal factors were investigated. The association between the aforementioned factors and neck and upper limb disorders was the main interest in this study. Interviews based on a questionnaire were used in the study to obtain subjective complaints. Inability to work in the past 12 months, neck and upper limb complaints in the past 12 months and last 7 days were all used in the study. Physical examination is done for women in the control and exposed groups. A questionnaire was used to assess the physical and psychological work factors. The ergonomic work analysis method EWA was used in the study as a method of observation. The prevalence odds ratio (POR) was used to measure the effect. The prevalence of shoulder and neck diagnoses was about 35%. The fraction of time with repetitive work tasks, work strain, stress and muscular tension were associated with neck or shoulder disorders. The duration of employment for women less than 45 years old was also associated with neck or shoulder disorders.

Other studies highlighted the role of postural discomfort for the development of shoulder pain even for office workers. Chaiklieng and Krusun [101] conducted a prospective cohort study following a survey study at baseline to study incidence and health risk for shoulder pain. A risk matrix of covariation between ergonomic risk and discomfort level was used for the health risk assessment of shoulder pain among 231 office workers. The study results suggested that most of the population have moderate, high or very high health risk of shoulder pain. To identify new cases of the shoulder pain, cases with moderate to severe level of shoulder pain at baseline were excluded; the remaining workers were followed up periodically. The cumulative shoulder pain incidence increased with duration of working time for all levels of shoulder pain. The study also suggested that working on the desktop computers for more than 4 hours/day during working time for office workers will lead to higher risk of work-related shoulder pain and that a higher proportion of office workers are exposed to higher risks of shoulder pain [101].

Some studies also focused on the pace of repetitive work and its effect of arm movement variability (size and structure of motor variability in the shoulder and elbow). Srinivasa et al. studied the effect of work pace in a standardized repetitive pipetting task. The task was performed in fast and slow paces differing in 15%. 35 healthy university female students in Sweden were included in the study. Shoulder and elbow joint angles were obtained in 3D by tracking hand, arm and pipette movements. Two synchronized electromagnetic tracking systems were used. The kinematics of shoulder elevation and elbow flexion were computed using range of motion, peak velocity, average velocity, time to peak velocity and area under the movement curve. Standard deviations and indices of sample entropy and recurrence quantification analysis were used in the study. The study showed that size and structure of arm movement (in the shoulder and elbow) is decreased with the increased pace of repetitive work and it also showed that the size and structure of arm movement were associated with fatigue, pain and MSDs [102].

2.12 Tools for Shoulder Pain Assessment

A wide range of methods have been developed to assess exposure to occupational factors leading to MSDs. Those methods are categorized under three main headings which include: self-reports, observational methods, and direct measurement. Those are ordered based on increasing precision and invasiveness to the worker [103]. In self-reports, worker diaries, questionnaire/web-based questionnaire and interviews can be used to collect data. In observational methods, both simple and advanced techniques can be used. The simpler techniques involve an observer recording the exposure assessment using proforma sheets. Postural and physical factors can be assessed using those techniques. Table 2.3 summarizes some of the different tools used for observational assessment. Those methods have been found inexpensive and practical to be used in different occupational settings. But they might be subject to inter- or intra-observer variability when assessing different levels of exposure. Those tools better work for static or repetitive jobs. The scoring system in those tools is largely hypothetical and factors scoring, quantification and interaction need further investigation [103].

Table 2.3: Examples of simple observational methods [104].

Method	Function	Main feature
RULA	Body postures and force are assessed with action levels used for categorization	Assessment for upper body and limb
NIOSH Lifting Equation	Used for manual handling, Measurements are required for posture associated to biomechanical load	The risk factors are identified, and the required assessment can be done
The strain index	Six exposure factors are used to assess work tasks and are combined into one index	Used for risk assessment for distal upper extremity disorders
REBA	Body postures and force are assessed with action levels used for categorization	Assessment for upper body and limb
OCRA	Used for repetitive tasks, measures of posture and force are used for assessment	Assessment scores are integrated for different types of jobs
OWAS	Body postures and force are sampled over time	Recording and analysis of whole-body postures
FIOH Risk Factor Checklist	Used for repetitive tasks, questions for posture and physical load are used for assessment	Assessment of the upper extremities
ACGIH TLVs	Used to assess hand activity and lifting work based on threshold limit values	Exposure assessment for manual work

In the advanced observational techniques, video recording or other methods of data recording are used; data is analyzed using dedicated software. Biomechanical models can be also deployed for data analysis. The cost of those methods is substantial, and it is time consuming and requires technical support and they work better in simulated tasks compared to practical occupational tasks. Direct methods rely on sensors attached directly to the subject to obtain data for the exposure assessment. Accurate data result from direct measurement, but the measurement itself can affect the worker behavior. Skilled personnel and initial investments are also required. Precision and accuracy is increased in using the observational and direct methods compared to self-reports. However, measurement errors induced by each method are not well understood and this may lead to misclassification errors and hamper the association between physical workload and occupational morbidity [105]. Different risk factors are assessed using the different methods. Table 2.4 summarizes some of the tools and the factors they considered [104].

Table 2.4: Exposure factors assessed by different methods [104].

Method	Load/Force	Posture	Duration	Movement frequency	Recovery	Vibration	Others*
RULA	X	X		X			
NIOSH Lifting Equation	X	X	X	X	X		X
The strain index	X	X	X	X			X
REBA	X	X		X			X
OCRA	X	X	X	X	X	X	X
OWAS	X	X					
FIOH Risk Factor Checklist	X	X	X	X			X
ACGIH TLVs	X	X	X	X			

*These include psychosocial and individual factors, load coupling, mechanical compression, environmental conditions, visual demands, glove use, equipment, and teamwork.

Direct methods, observation and self-report have been used extensively to quantify the physical risk factors. Biomechanical models are also used to get the internal stresses for specific body regions by converting the external stresses to better quantify the exposure-response relationship. Most of the tools and methods use the presumed worst posture to quantify the exposure for example, hand activity level (HAL) uses peak forces for estimation and RULA uses the worst posture being the one with highest load or the sustained one for long duration.

Questionnaires, video recording and direct measurements can be all considered as cumulative measurement methods. Questionnaires can be used to capture information about the exposure and the health outcome. Ohlsson et al. [106] conducted a study where they evaluated the effectiveness of a screening questionnaire for the neck and upper extremity complaints including the shoulder. Varied or mobile work jobs and repetitive industrial jobs were included. A hundred sixty-five (156) women were included in the study and a clinical physical examination was also done. The sensitivity for Subjects with shoulder complaints on the questionnaire and having findings on the clinical physical examination was about 80%. Diagnosis for the shoulder was more often identified using the questionnaire (sensitivity 92%) compared to other body regions (sensitivity 66-79%). Thus, questionnaires can be used to estimate the status for the neck and upper extremities including the shoulder for working women. Though, clinical examination gives the detailed view about the size of the problem [106]. Another study done by Herberts et al. [107] used a questionnaire to report shoulder pain (supraspinatus tendinitis) among welders at shipyard and compared with occurrence for office clerks. Clinical examination was also used. The questionnaire covered items such as: repetitive periods of shoulder pain, pain extending to arms and weakness in shoulders. The questionnaire was effective for the estimation of the shoulder pain and the results revealed that the prevalence ratio was higher among welders compared to clerks (18%) and that age was not statistically significant. Another study was done by Wiktorin et al [108] to test the effectiveness of interviews versus questionnaire for the assessment of physical loads for low back and neck/shoulder disorders. Information about work posture, energy expenditure, manual material handling, leisure time activity, sports activity, was all included in the analysis. Questionnaires were found helpful for well-defined tasks even though interviews are preferable.

Video recording has been extensively used as a method for cumulative exposure assessment. The duration can be from few minutes up to 8 hrs. (based on the aims of the study), and the capture frequency can be from 3-60 Hz. Computer programs in addition to the manual analysis are also used to identify posture information. Some of the advantages of video recording is that body movements are recorded without an observer thus observer bias can be avoided, and data can be collected in real time. 2-D and 3-D motion recordings are available where 2 and 3 dimensional planes are used in recordings and movement for joint segments can be recorded simultaneously. A software application is used to simplify the data analysis. Andersen et al. conducted a study where they used the video to evaluate the physical risk factors for the neck shoulder pain among 3,123 workers with repetitive monotonous work. Psychosocial factors and other personal characteristics were also included in the study. The video observation method was used to obtain information about the exposure including time variation, intensity and magnitude. Questionnaires and clinical examination were also used. Study showed that quantification for the risk exposure is beneficial to understand the multifactorial nature for neck shoulder pain [109]. Another study done by Andersen et al. [92] included a total of 3,123 industrial and service companies' workers in Denmark participated in a four-year prospective cohort study. Questionnaire and clinical examinations of all participants were performed to gather the required information and the physical workload was assessed at baseline by video recordings at the workplace [92].

For direct methods, goniometric systems, sonic systems, electromagnetic systems, accelerometer and optical scanning systems can be considered as types of direct methods. There dimensional goniometers are used to record joint motions. Simultaneous measurements of the movements can be obtained using goniometers and data logger is used to record the data. Another type of goniometer is the triaxial electrogoniometer, an example of which is the lumbar motion monitor (LMM) which is used to record position, velocity and acceleration of the trunk. It is worn on the back and tracks the movement of the trunk for the subjects. Changes in postural behavior and discomfort in the use of goniometers might be an issue. Calibration and complex joints need better care. Inertial measurement unit sensor (IMU) is another example of direct measurement that uses a combination of gyroscopes, magnetometer, and accelerometers to measure body orientation, forces, acceleration, velocity and angular rates. IMUs are widely used for risk analysis for their low cost and power consumption as well as their light weight.

Light reflecting markers at specific anatomic points are used in the optical scanning system. Light scanning units are used to determine the displacement of the markers. Real time, three-dimensional outputs are obtained. In electromagnetic systems the magnetic waves are used to obtain data about the position and angular orientation. Transmitter and receiver units are used. In sonic systems, the same principle applies but with the use of ultrasonic waves. Displacement, velocity and acceleration information can be obtained. For accelerometers, piezoelectric and piezoresistive accelerometers are the most common types. The acceleration sensitive sensors can be used to differentiate between static and dynamic activities where posture variations are recorded continuously [110]. Several methods are available for the assessment of the workload on upper limbs. Takala et al. [111] have conducted a systematic review for the tools to determine which factors they consider and if they have a good scientific evidence for their MSDs association. Table 2.5 shows a comparison among the different observational tools [111].

Table 2.5: Description of observational methods. Exposure included in the method: posture (P), force (F), duration (D), frequency of actions (Fr), movements (M), and vibration (Vib). (RPE=rating of perceived exertion, NIOSH=national institute of occupational safety and health, VAS= visual analog scale, TLV= threshold limit value, MMH=manual material handling) [111].

Method and year of first publication	Exposures of interest	Metrics	Method of recording	Observation approach
Methods to assess workload on upper extremities				
Rapid Upper-Limb Assessment (RULA), 1993	F,P, static action	Scores of weighted items are summed	Video, pen & paper	No detailed rules
The Strain Index, 1995	F,P,Fr, D	Risk index; multiplied score	Pen & paper	No detailed rules
Occupational Repetitive Actions (OCRA), 1996	F,P,Fr,D,Vib	risk index, Scores of weighted items are summed	Pen & paper	Repetitive actions in a profile of work are assessed
American Conference of Governmental industrial Hygienists Hand Activity Level (ACGIH HAL), 1997	F,M	Force and hand activity on a VAS	Video, pen & paper	Typical activity
Methods to assess manual material handling				
NIOSH Lifting equation, 1981, revised 1991	F,P,Fr,D	Risk index; multiplied score	Computerized, pen & paper	No detailed rules
ACGIH Lifting TLV, 2004	F,P,Fr,D	Lifting TLVs that are hazardous	Pen & paper	No detailed rules
Washington State Ergonomics Checklists, 2000	F,P,Fr,D	A multiplied score is used to provide a lifting limit	Pen & paper	Most common and worst lifts
Arbouw,1997	F,P,Fr,D	Risk tables of three levels	Pen & paper	No detailed rules

The systematic review also provided evidence regarding validity and repeatability of the tools, intra- and inter-observer repeatability and association with MSDs. Table 2.6 [111] summarizes the results. Table 2.7 provides some of the strengths and limitations for the upper limb assessment tools [111].

Table 2.6: Validity and repeatability of observational methods. (- =insufficient information, NIOSH=national institute of occupational safety and health, MMH= manual material handling, MSD=Musculoskeletal disorders, SI= Strain index, X= association in cross sectional studies, L= prediction in longitudinal studies) [111].

Method	Association with MSD	Correspondence with valid reference (Good, Moderate, Low)	Intra-observer repeatability	Inter-observer repeatability
Methods to assess workload on upper extremities				
Rapid Upper-Limb Assessment (RULA)	X	Low-moderate (SI, OCRA, ACGIH HAL, Technical measures)	-	Moderate- good
The Strain Index	X, L	Moderate (ACGIH HAL, RULA)	Moderate- good	Moderate- good
Occupational Repetitive Actions (OCRA)	X	Moderate (ACGIH HAL, RULA, SI)	-	-
American Conference of Governmental industrial Hygienists Hand Activity Level (ACGIH HAL)	X, L	Moderate (Video, SI)	Good	Moderate
Washington State Ergonomics Checklists	X	-	-	Moderate
Methods to assess manual material handling				
NIOSH Lifting equation	X	-	-	-
ACGIH Lifting TLV	-	Moderate (NIOSH lifting equation)	-	-
Washington State Ergonomics Checklists	X	Moderate (NIOSH lifting equation)	-	Moderate
Arbouw	-	Moderate (NIOSH lifting equation)	-	-

Table 2.7: Practical issues relating to observational methods. (R=researchers, O= occupational safety/health practitioners/ergonomists; W=workers/supervisors; - = insufficient information, ?=not clear) [111].

Method	Strengths	Limitations	Decision rules	Potential users
Methods to assess workload on upper extremities				
Rapid Upper-Limb Assessment (RULA)	Computerized and easy to use	Exposure of duration is not considered, left and right hand scores are assessed separately no method to combine the scores	Level of risk is determined based on tentative limits	O, R
The Strain Index	The main risk factors and their interactions are used in the assessment. Easy to compare jobs	Vibration and contact stress are not included. Hypothetical multiplier values, subjective assessment; criteria not clear, limited for UE exposure assessment for monotask jobs	Specificity and sensitivity of index are described in the literature	O, R
Occupational Repetitive Actions (OCRA)	Easy, quick to use checklist, repetitive tasks in a complex job can be assessed, recovery periods are included in the analysis	Time consuming, needs a well-trained observer	Thresholds to indicate required actions	O, R
American Conference of Governmental industrial Hygienists Hand Activity Level (ACGIH HAL)	Quick, easy to use, individual capacity is included	Limited number of risk factors, subjective assessment	Thresholds to indicate required actions for monotask work (duration >4hrs)	O, R
Washington State Ergonomics Checklists	Quick, easy to use, considers most risk factors in addition to frequency and duration	used for risks screening	Decision rules are straight forward	O, W(?)

RULA and REBA are among the most common tools for the risk assessment of shoulder pain. REBA (Rapid Entire Body Assessment) is an observational postural tool for the whole-body activities. In REBA positions of the body segments are observed and postural scores are given based on deviations from neutral postures. The tool breaks the analysis into groups. The tool has 144 possible postural combinations. Group scores are combined into one combination of the 144 combinations to get a grand score. The load, coupling and physical activity are also observed and scored. Each observation will have a simple score that aggregates the risk using a series of tables. The risk is categorized into five levels ranging from unnecessary to immediate actions. Although REBA classified more postures at higher levels of risk, its observations have corresponded to those of OWAS tool. Duration and frequency are not included in REBA and left and right hand are assessed separately. The inter-observer repeatability is low for the upper limbs and moderate to good for trunk and legs, no association with MSDs is found for REBA. RULA (Rapid Upper Limb Assessment) works on the same concept compared to REBA. In RULA groups scores are also found and forces/loads and static and repetitive muscular activity are included where the final score is compared to a four levels risk table. Actions are then stated ranging from acceptable to immediate investigations and changes. The inter-observer repeatability for RULA has been good, although the quality of the methodological information in repeatability studies is so scant it cannot be properly evaluated. Correspondence with other methods such as OWAS and REBA has been moderate at best. Association for RULA high scores is found with increased discomfort in laboratory studies and with MSDs perception in cross sectional studies [104]. Both RULA and REBA do not provide sub-scores for different body regions and they adapt poorly to highly varied work situation and the big concern will be which task to assess in variable work [112].

Biomechanical models are also developed to provide insights into specific muscle load magnitudes to signal an increased shoulder risk. Dickerson et al. [113] developed a biomechanical shoulder model that incorporates geometric realism, systematic inclusion of kinematic and kinetic effects, population scalability, and empirical glenohumeral constraint. The model also integrates digital analysis software tools for ergonomics. Inputs for the modules include: Subject and task data, and motion data. The modules are shoulder geometry constructor, external dynamic moment calculator, and internal muscle force prediction. The model finally outputs an estimator for muscle forces. The combined output from both the geometric module and the external dynamic moment module although being independent but they serve as the main input for the internal muscle prediction module. Five parts are included within the geometric module: Segment parameter definition, shoulder rhythm implementation, muscle definition and line of action construction and other geometric definition. Inputs for the model are 3D postural motion files and outputs are positions, orientations, and lines of action and moment arms for defined muscle elements. Geometric data can be obtained from the 3DSSPS. Segment description, linear and angular kinematics and computation of the joint forces and moments are the main parts for the external dynamic moment calculator module. Inputs for the module are motion files and profiles of time series external force. Forces and dynamic joint moments caused by external forces are the outputs for this module. In the muscle prediction module, an optimization model is used for the load distribution among the muscles. The optimization module uses some constraints such as: muscle force, mechanical equilibrium, and glenohumeral joint force. The model results were comparable with a previous shoulder model (Van Der Helm model) and found to be similar, differences might come from different muscle element definitions [113]. The model overcomes several shortcomings on the previous models such as: lack of population scalability, being strictly static or not fully address the dynamic capability. The empirical shoulder stability constraint distinguishes this model from any other models. Other features of the model include integration with available ergonomic software, being applicable to a diverse population, inclusion of dynamic terms to calculate shoulder moments, quantitative representation of the glenohumeral interface for the directional non-dislocation requirements. Model limitations include the assumption that the instantaneous length and the muscle contraction velocity do not affect force production capability. The biological variability between individuals for their muscle use is another concern. Although ligaments provide stability to the glenohumeral joints at extreme postures, they were not included in the model. Thus, muscle physiology and model scalability should be considered as model limitations [113].

It is apparent that RULA and REBA are not adequate to be used for shoulder pain assessment due to their limitations. The biomechanical shoulder model also does not consider the muscle physiology and biological variability between individuals for their muscle use. This highlights the need for new tools for assessing shoulder pain and other outcomes. Table 2.8 summarizes some of the tools related criteria.

Several criteria can be used to assess tool adequacy and its applicability to the risk assessment those features include [114]:

- The tool is easy and quick to be used
- The tool is applicable to a variety of occupations and variable working conditions.
- The tool has a sound basis in the MSD literature.
- The scoring system provides a clear differentiation between low risk jobs and jobs with high suspected risk.
- The tool has some ability to predict injury risk.
- The tool can handle straightforward jobs and complex jobs without excessive required efforts and difficulty.
- The tool can represent a variety of risk factors leading to MSDs.
- The tool can predict injury risk

- The tool can evaluate the impact of cumulative loading

RULA, REBA and the biomechanical shoulder model fall short in terms of several of the previous criteria. Table 2.9 provides a summary for the tools and the criteria. The tools lack the ability to evaluate the impact of cumulative loading and they do not consider a variety of risk factors. The tools previously discussed limitations and those shortcomings highlight the need for a new tool that can satisfy the previous criteria and can be user friendly. Thus, as a result of the aforementioned shortcomings of the current available observational tools, this study will be mainly focusing on developing a shoulder tool considering the risk factors that are known to be associated with shoulder pain and it will consider the cumulative loading and can predict the risk.

Table 2.8: Summary on the tools and criteria.

Tool	Ease of use	Applicable to a variety of occupations	Basis In MSD literature	Score system	Predict risk	Cumulative loading	Handle complex and straightforward jobs	Variety of risk factors
RULA	Yes	Yes	Yes	Yes	No	No	No	No
REBA	Yes	Yes	Yes	Yes	No	No	No	No
Shoulder biomechanical model	No	Yes	-	-	No	No	No	-

Table 2.9: Practical issues related to the use of the tools.

Method	RULA	REBA	Dickerson shoulder biomechanical model
Association with MSDs	Association in cross-sectional studies	-	-
Inter-observer repeatability	Moderate-good	Low-moderate	-
Intra-observer repeatability	-	-	-
Target exposures	Posture, Force, Static action	Posture, Force	Force, Frequency of actions, Posture
Metrics	Sum-score of weighted items	Sum-score of weighted items	Muscle load magnitudes to signal an increased shoulder risk
Strength	- Quick to use, - computerization is available	- Quick to use, - computerization is available	- The model include integration with available ergonomic software, - Being applicable to a diverse population, - Inclusion of dynamic terms to calculate shoulder moments, - Quantitative representation of the glenohumeral interface for the directional non-dislocation requirements.
Limitations	- Duration of exposures not included. - Left and right-hand data cannot be combined	- Duration and frequency not included. - Left and right-hand data cannot be combined	- Muscle physiology and model scalability are not addressed adequately.

Chapter 3: Development and Validation of a Shoulder Risk Assessment Tool Based On Fatigue Failure Theory

3.1 Methods for Cumulative Exposure Integration

Excessive cumulative loading on human tissues has an adverse effect as evidence of in vitro biomechanical studies. Previous studies relating the reporting of MSDs and accumulated load have provided various methods to get estimates for cumulative loading. For example, to get estimates of load over time for low back pain (LBP), Kumar et al. [115] suggested using integration. Shear and compression accumulated over time were considered in the analysis. Equation 3.1 shows the cumulative load for one task for a specific worker.

$$OL = \sum_{i}^{n}(L_i \times t_i) \qquad (3.1)$$

Where *OL* is the overall load in N.s (shear or compression), L_i is the average force of the *ith* segment of the task, and t_i is the duration of the *ith* segment of the task. The daily cumulative load for multiple tasks can be found from equation 3.2

$$CDL = \sum_{j}^{n}(OL_j \times F_j) \qquad (3.2)$$

Where *CDL* is the cumulative daily load, OL_j is overall load for task *j*, F_j is the frequency per day for task *j*.

Different methods have been suggested to aggregate cumulative exposure such as integrating the peak load over time. Some of those methods used the loading during rest time, while others did not consider this factor in exposure estimation. Peak spinal load, duration of task, frequency of task, loading during rest time, total rest time, number of tasks performed have also been considered in cumulative load estimation. Other approaches have used duration and peak load where the cumulative damage is equal to the summation of the multiplication of tasks duration and peak loads. The duration that a load was held in the hand or load during upright standing or dividing the cycle into segments and using the loads within each segment have been other factors considered with peak loads to estimate cumulative spinal exposure. Such methods fall under the linear integration method using the assumption that low-force long-duration, and high-force, short-duration tasks have the same injury risk (assuming the area under the curve is the same). Rectangular integration is also considered as a linear integration method, for this method data sampled at 5 Hz can be integrated or the integration can be implemented for all frames sampled at 30 Hz. [8,9] Squared and tera power methods were also suggested, for example summation of the multiplication of the squares of loads lifted and their duration is one way where the squared method can be used. [10] Equations 3.3, 3.4, 3.5 summarize the linear, squared and tera power integration methods.

$$Linear \sum (F_i \times t_i)/T \qquad (3.3)$$

$$Squared \sqrt{\sum (F_i^2 \times t_i)/T} \qquad (3.4)$$

$$Tera\ power \sqrt[4]{\sum (F_i^4 \times t_i)/T} \qquad (3.5)$$

Where F_{i} is the disc load, t_i is duration of $_{\mathrm{i}}$, T is shift duration and i represents the time interval.

3.2 Fatigue Failure Process in the Development of Musculoskeletal Tissue Damage

3.2.1 Fatigue Failure of Physical Materials

Materials under load experience fatigue caused by both loads applied repetitively or by single cycles with high stress values. The relationship between cycles to failure and the applied stress is exponential in nature [116]. Figure 3.1 shows a typical S-N curve used to determine the cycles to failure under different loading conditions. The S-N curve can be approximated by a straight line when plotted on a log-log scale. Some materials exhibit fatigue threshold under which the material can be virtually cycled infinitely without failure. This happens under a certain stress level below which the material is assumed to receive no damage. Materials at high load conditions will experience fewer cycles to failure whereas those with low load conditions will require many more loading cycles to failure.

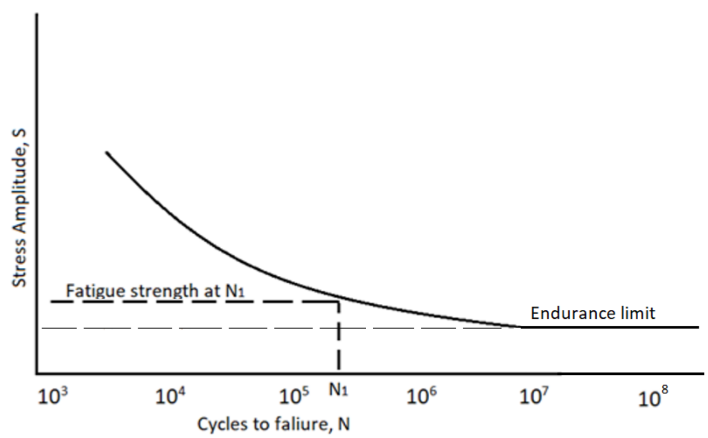

Figure 3.1: A typical S-N curve.

Fatigue failure analysis has been used to determine safe stress designs in many design applications and structures such as bridges, in the automotive industry, and for critical designs for nuclear applications, electronics manufacturing, and many other fields. Biological tissues are also materials and repetitive loading appears to cause damage in a similar fashion [117]. However, the physiological nature of biological tissues must also be considered. For instance, the self-healing capability of biological tissues allows for recovery from some of the damage; whereas, damage exceeding the healing capability may eventually be irreversible. Thus, biological tissues exposed to various loading conditions can fail under the same principles of the fatigue failure process; however, healing capabilities may help to extend the life of biological tissues.

3.2.2 Musculoskeletal Disorder as a Fatigue Failure Process

Evidence supporting a fatigue failure process in the development of MSDs includes epidemiological studies, tissue loading in animal studies and in-vitro testing of musculoskeletal tissues. As discussed below, several in-vitro studies have tested different tissues for the effect of loading. Those include tendons [117,120], ligaments [118,121], cartilage [119] and spinal motion segments [122].

Schechtman and Bader in their in-vitro study [117] tested the extensor digitorum longus (EDL) of the foot to explore the fatigue failure behavior in human tendons. Ninety specimens were used with 10 specimens per stress level. Physiological loading frequencies were used for the cyclic square tension-tension stress. An exponential relationship was found for the relationship between the applied stress and number of cycles to failure. Figure 3.2 shows the log cycles to failure and the normalized stress. The relationship between the normalized stress and log cycles to failure is summarized in equation 3.6,

$$S = 93.98 - 13.13\log(N) \qquad (3.6)$$

where S is the normalized stress as a percentage of the ultimate tensile strength (UTS), and N is number of cycles to failure. When a median fatigue life (50% probability of failure) is used, the relationship is described by equation (3.7):

$$S = 101.25 - 14.83 \log(N) \qquad (3.7)$$

Lipps, Wojtys, and Ashton-Miller studied the fatigue failure behavior of the anterior cruciate ligament (ACL) of the human knee when subjected to repeated loading to three- or four-times body weight. A fatigue failure response was observed in this study for the ACL [118].

Bellucci and Seedhom performed a study on the articular cartilage of the knee, where 72 tensile specimens were tested in directions parallel and perpendicular to collagen orientation in superficial layers. Sixteen sites (16) on the knee were studied at various depths. Better fatigue resistance was found in the direction parallel to collagen orientation but both orientations demonstrated fatigue failure behavior [119].

A study performed by Wang, Ker, and Alexander [120] tested wallaby tail tendons for different stress ranges; the frequencies used for testing were 1.1, 2.1, 5.3, 10 and 50 Hz. The results showed a similar exponential relationship between peak stress and cycles to rupture.

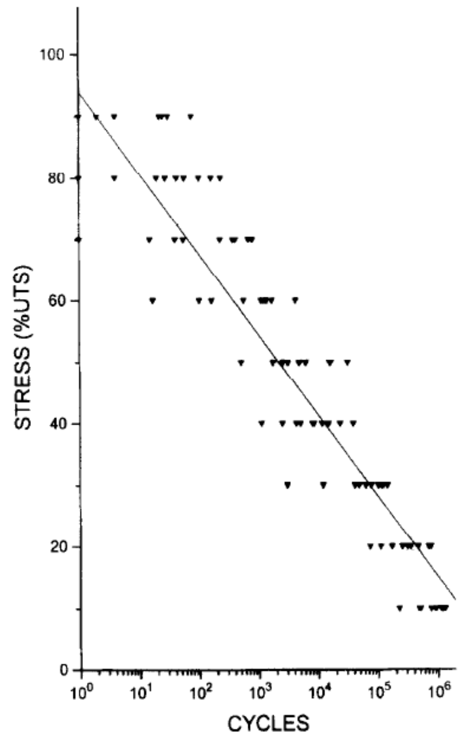

Figure 3.2: Cycles to failure for the extensor digitorum longus (EDL) of the foot [117].

Medial collateral ligaments for rabbits were tested by Thornton, Schwab, and Oxland, ligaments were subjected to static and cyclic loading at various stress values. Three loading conditions were used in the study. Cyclic loading was more detrimental compared to static (creep) loading. Exponential results were found for time to rupture and the percentage of the Ultimate tensile strength (UTS). [121].

Lumbosacral motion segments were loaded cyclically in a study done by Gallagher et al. [122], where loads were estimated at 3 angles for the torso flexion (0°, 22.5° and 45°). Twelve (12) spines were tested and were dissected to 3 motion segments. Segments were initially creep loaded, and then were cyclically loaded to failure. Results showed that torso flexion has a major impact on cycles to failure and that lumbosacral motion segments experienced a fatigue failure behavior.

Several studies have highlighted the fact that the response of biological tissues resembles the expected force repetition interaction anticipated by a fatigue failure mechanism [12]. Barbe et al. [11] in a rat model tested the following conditions: High force, high repetition, low force, low repetition, high force, low repetition, low force, high repetition with rats exposed to one of those conditions. Tendon, cartilage, cytokine and bone damages and responses all revealed a pattern of force repetition interaction consistent with the fatigue failure process with the highest risk for the high force, high repetition.

Gallagher and Heberger [12] conducted a systematic review on epidemiological studies that considered force repetition interaction for the development of MSDs and assessed correspondence with the fatigue failure process. The pattern for MSDs and fatigue failure is found in many MSDs including tendinitis, epicondylitis, carpal tunnel syndrome (CTS), low back disorders and hand pain. Figures 3.3 and 3.4 shows the results for the effect of force repetition and CTS and low back disorders respectively, which corresponds to the pattern anticipated if they result from a fatigue failure process. Figure 3.5 shows the fatigue failure curve and the force repetition represented in quadrants to illustrate the anticipated pattern if MSDs will be a result of a fatigue failure process.

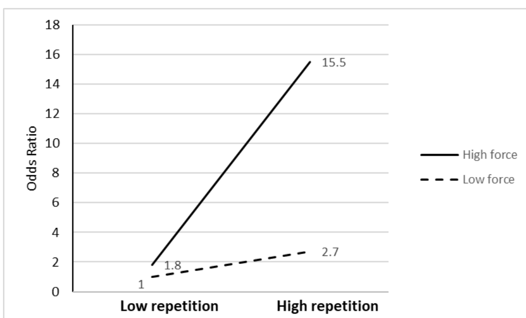

Figure 3.3: Effect of force and repetition on CTS [12].

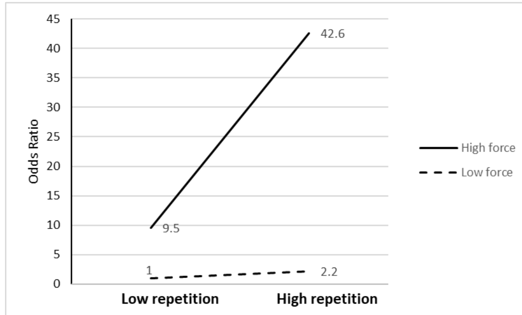

Figure 3.4: Effect of force repetition on low back disorders [12].

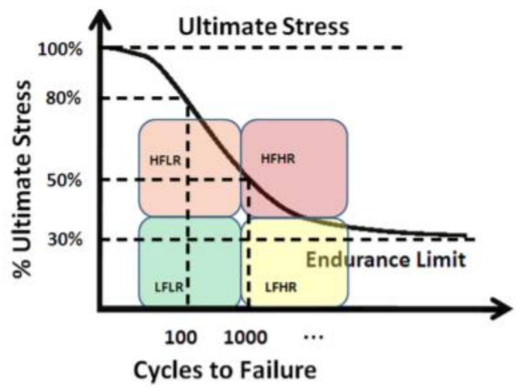

Figure 3.5: Fatigue failure curve and force repetition quadrants [12].

Effects of force and repetition have been also studied on muscles oxygenation. In a study done by Ferguson, Allread and Le [123], the effect of repetitive shoulder exertions on muscle oxygenation for the anterior deltoid and trapezius muscles was investigated. Reduced muscle oxygenation will lead to lack of nutrients causing muscle fatigue which in turn may result in shoulder injury. The study used near infrared spectroscopy (NIRS) device to measure muscle oxygenation. Ten (10) automotive assembly workers participated in the study. Shoulder flexion angles used were $<45^{\circ}$, $45\text{-}90^{\circ}$, and $>90^{\circ}$. Two (2) force levels were used (5 and 10lbs), along with three repetition levels 2, 6, and 10 exertions/minute. The results showed a decrease in muscle oxygenation for all main effects and that the interaction between shoulder angle and repetition was significant and also interaction between force and repetition was highly significant which supports the fatigue failure theory.

Harris-Adamson et al. conducted a large prospective epidemiological study where 2,474 participants were followed for 6.5 years. Association between Occupational risk factors and CTS was studied. The results indicated that forceful repetition was a major contributing factor for the development of CTS, which also corresponds with expectations based on fatigue failure theory [124].

The studies discussed above showed strong evidence supporting the notion that a fatigue failure process may play an important role in the development of MSDs. These have included several lines of evidence, including epidemiological studies, tissue loading in animal studies, and vitro testing for MSDs. The fatigue failure behavior of the biological tissues under cyclic loading demonstrated an exponential relationship between the applied stress and number of cycles to failure. In addition, most of the tested biological tissues demonstrating the expected force repetition interaction anticipated by a fatigue failure mechanism. The purpose of this study will be to determine whether this relationship also holds for the shoulder.

3.2.3 Cumulative Exposure Assessment in Fatigue Failure Theory

Musculoskeletal tissues usually experience variable loading in occupational settings. Estimates for cumulative damage as a result of variable loading are an essential part to estimate damage accumulation. A linear cumulative damage rule can be used to estimate the damage from variable loading. This methodology has been validated in the Fatigue failure theory, the method was suggested by Palmgren (1924) and Miner (1945), equation (3.8) [116,125].

$$c = \sum_{i}^{k} \frac{n_1}{N_1} + \frac{n_2}{N_2} + \cdots + \frac{n_k}{N_k} \qquad (3.8)$$

Where c is a constant often equal to one (but may vary somewhat), n_i is number of cycles at a certain force level at which N_i cycles would result in fatigue failure. In general, a value of 1 for the right side means the material is expected to initiate the fatigue failure process. The stress level at which the cycles are experienced and their corresponding cycles to failure is important to consider. Thus, for this method both force (stress) and its associated repetition need to be considered in the analysis. Table 3.1 shows an example for the linear method for cumulative damage estimation.

Table 3. 1: An example for the linear method for cumulative damage estimation.

%UTS	**Cycles to failure**	**Cycles experienced**
60%	1000	25
50%	10000	100
40%	100000	900

The cumulative damage can be calculated as:

$$D_t = \frac{25}{1{,}000} + \frac{100}{10{,}000} + \frac{900}{100{,}000} = 0.025 + 0.01 + 0.009 = 0.044$$

Where the 25, 100 and 900 represent the number of cycles that a tendon is stressed at 60%, 50%, 40% of UTS respectively, and the cycles to failure are assumed to be 1,000, 10,000, and 100,000 at 60%, 50%, 40% of UTS, respectively. This method of cumulative damage estimation has been well validated, but the linear relationship can be affected by other factors which can accordingly affect the fatigue failure process.

Various loading patterns can be experienced by the musculoskeletal tissues. Fully reversed loading where compressive and tensile stresses are applied repetitively, is a standard method to perform loading tests in fatigue failure. Fully reversed loading has a sinusoidal loading pattern and it is typically used to develop an S-N curve. Figure 3.6 shows some of the parameters for the cyclic loading. For fully reversed loading, the mean stress $\sigma_m$is zero, σ_a is the stress amplitude and is equal to the average for the minimum minus the maximum load for the cycle. The stress ratio *R* is equal to $\frac{\sigma_{min}}{\sigma_{max}}$. The amplitude ratio *A* is equal to $\frac{\sigma_a}{\sigma_m}$.

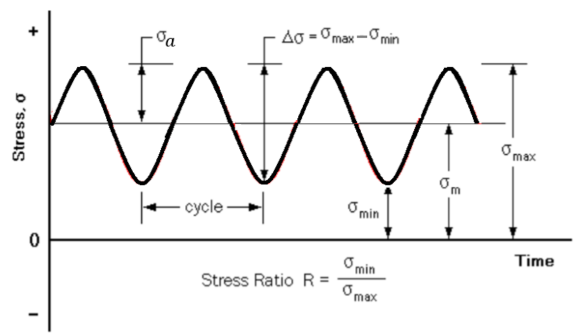

Figure 3.6: Typical cyclic loading parameters [126].

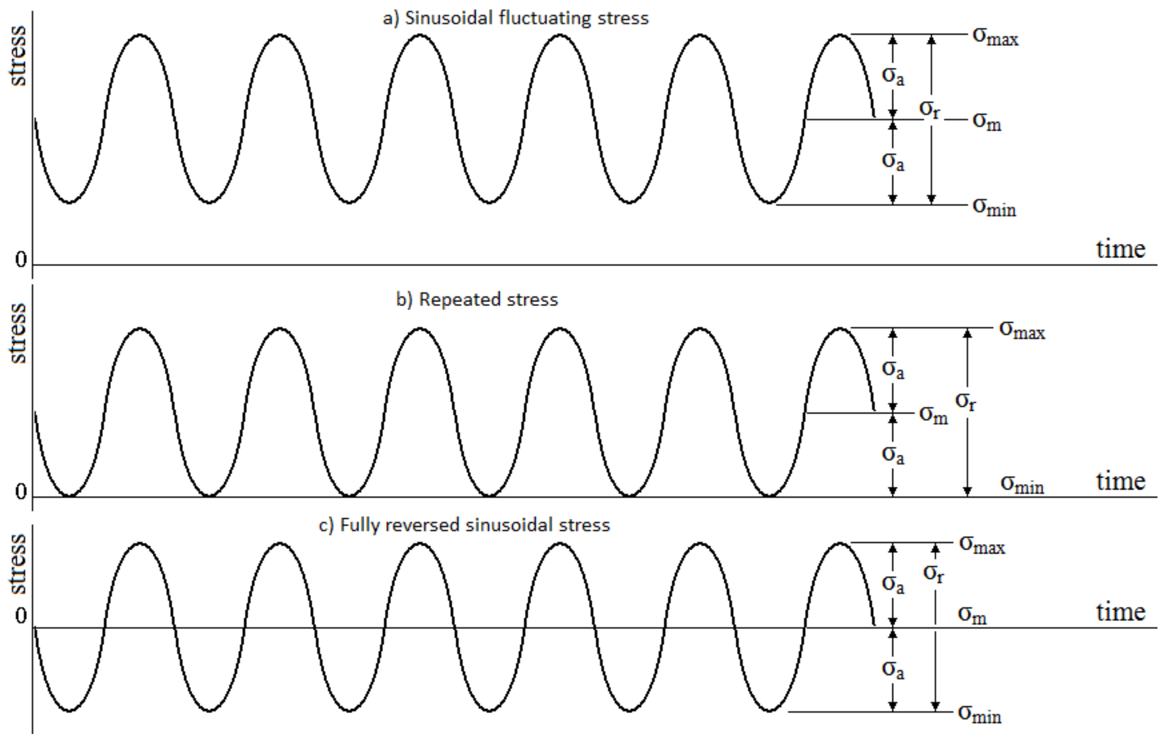

Figure 3.7: Types of sinusoidal loading [127].

Other loading conditions exist where $\sigma_m \neq 0$. Such loading conditions are shown in Figure 3.7, and include repeated stress and sinusoidal fluctuating stress. For repeated stress, the stress cycles can be positive or negative to represent tensile and compressive values respectively and the minimum stress is equal to zero. Tendons and ligaments may experience such a loading pattern. For the case of fluctuating stress, the minimum stress is not equal to zero. This cyclic loading modality is experienced by spine segments; this can be explained by the upper body weight which will imply a compressive load on the spine. When comparing the three cyclic loading, fully reversed loading will lead to more cycles to failure compared to the repeated and fluctuating loadings this can be also explained by the fact that the mean stress for the repeated and fluctuating loadings is non-zero which shifts the fatigue failure curve down. Figure 3.8 shows the effect of the mean stress on the S-N curve.

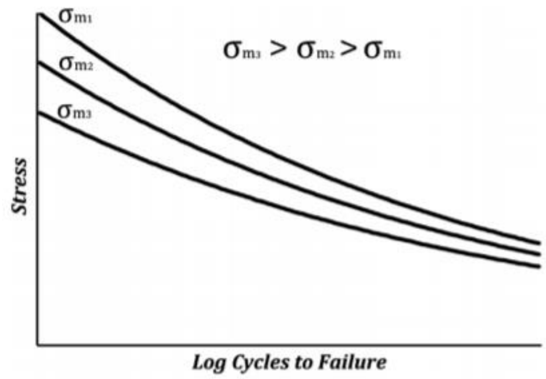

Figure 3.8: Effect of the mean stress on S-N curve [12].

When the mean stress is not zero, constant lifelines can be plotted on a Haigh diagram for different combinations between the mean stress and stress amplitude. Enormous amount of testing is required to construct such diagrams; thus, empirical relationships have been developed to address this issue. Curves from those relationships connect the endurance limit for the alternating stress with S_y yield the stress, S_u the ultimate stress, or σ_f the true fracture stress. A graphical comparison among the different methods used is shown in figure 3.9. Those empirical relationships can be helpful in the repeated and fluctuating loadings, where calculations can be completed to determine the cycles to failure and safety factors.

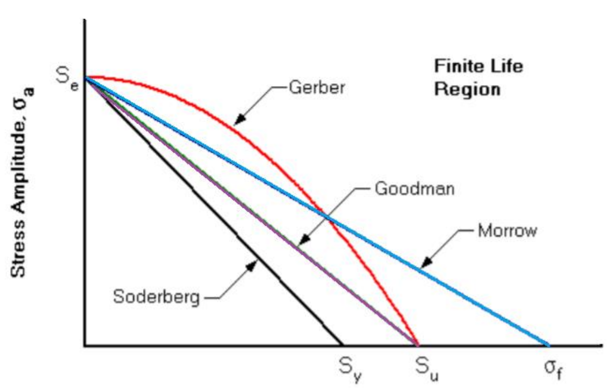

Figure 3.9: Infinite life curve, S_y is the yield the stress, S_u is the ultimate stress, S_e is effective alternating stress at failure for 10^6 cycles and σ_f is the true fracture stress [126].

Test data tend to fall between Goodman and Gerber curves and those two methods are widely accepted with the Goodman method being more conservative. Points above the curve are in the finite life region (each point on the curve corresponds to failure in 10^6 cycles) and points below the curve are in the infinite life region. When infinite life conditions, 10^6 cycles to failure, are exceeded (at certain σ_a and σ_m) cycles expected to failure often need to be estimated. Equations 3.9, 3.10 and 3.11 show calculations required to get cycles to failure for fully reversed loading.

$$N = \left(\frac{\sigma_a}{a}\right)^{\frac{1}{b}} \qquad (3.9)$$

$$a = \frac{(f.S_{ut})^2}{S_e} \qquad (3.10)$$

$$b = -\frac{1}{3} log\left(\frac{f.S_{ut}}{S_e}\right) \qquad (3.11)$$

Where N is cycles to failure, σ_a is stress amplitude, S_{ut} is the ultimate tensile strength, f approximates fatigue strength at 10^3 cycles and S_e is the endurance stress limit. In fluctuating and repeated stress σ_a can not be used thus another parameter need be used under which a value for fully reversed stress σ_{rev} can be used to replace σ_a . For the fluctuating stress under the Goodman relation equation 3.9 becomes:

$$N = \left(\frac{\sigma_{rev}}{a}\right)^{\frac{1}{b}} \qquad (3.12)$$

And

$$\sigma_{rev} = \frac{\sigma_a}{1 - \frac{\sigma_m}{S_{ut}}} \qquad (3.13)$$

For the Gerber relation, σ_{rev} will be equal to:

$$\sigma_{rev} = \frac{\sigma_a}{1 - \left(\frac{\sigma_m}{S_{ut}}\right)^2} \qquad (3.14)$$

The stress amplitude σ_a and σ_m can be estimated for discrete exposures, for example when duration of exertion, load and repetitions are known, σ_a can be estimated as the load value whereas σ_m is estimated as the load divided by duration of repetition.

Direct measurement devices such as EMG can be used to obtain analog stress waves in continuous variable exposure. Pairs of stress amplitude and stress mean can be used to categorize the variable exposure. Rainflow analysis is a technique used to assess highly variable loading in fatigue failure theory, which assumes no sequence effect and that loads are independent. Stress reversals resulting from the breakdown of the variable stress exposures are used in the analysis, Figure 3.10, where then Goodman or Gerber estimates can be used, and the cumulative damage can be estimated using the Palmgren-Miner technique.

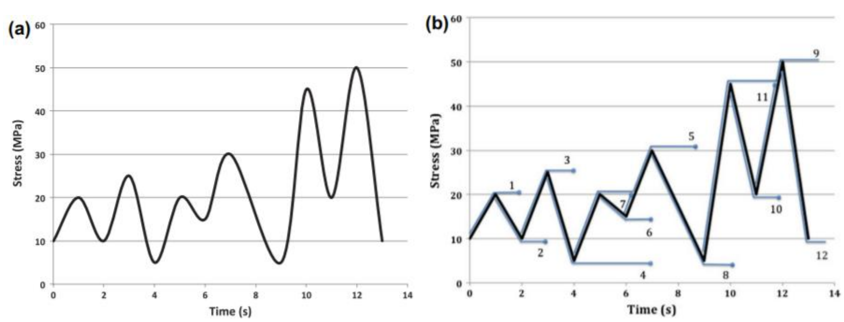

Figure 3.10: a) Variable loading experienced by biological tissues, b) Rainflow analysis and stress reversals for loading pattern in graph a [12].

3.3 Model Basis

Physical, psychosocial, and individual factors are considered to be the main factors contributing to the development of MSDs. Based on these known risk factors, a conceptual model for the effect of the risk factors for the development of shoulder MSDs is proposed below. In the model, physical, psychosocial, and individual factors were considered. Physical factors play a major role in the accumulation of tissue damage which is also affected by the psychosocial and individual factors, which eventually will lead to shoulder MSDs, figure 3.11. The individual risk factors such as the functional capacity, strength capability and injury history may increase the biomechanical loading in the tissues which will lead to damage accumulation. Damage accumulation is increased with the increase in the fatigue in the tissues and the reduced internal tolerances. When damage is exceeding the healing capability this will increase the damage accumulation in the tissues. On the other hand, the individual factors (e.g. pain perception); stress and the physiological responses can increase the symptoms and signs of shoulder MSDs. Besides, individual risk factors can affect both the stress and physiological responses.

The exposure-response relationship for work relatedness of shoulder pain, associations with risk factors and its verification are still not well understood [13]. Thus, data highlight the public health burden of shoulder pain and the need to develop models to predict shoulder pain and implement prevention strategies. The National Occupational Research Agenda (NORA) for Musculoskeletal Health in October 2018 highlighted the need to understand the risk factors for work-related MSDs and to improve methods for exposure assessment and develop new risk assessment models and methods [14]. Recent studies support the impact of fatigue failure process in the development of MSDs which includes epidemiological studies, tissue loading in animal studies and vitro testing for MSDs. Current tools available for upper extremity assessment, lack the ability to evaluate the impact of cumulative loading and they do not consider a variety of risk factors. Assessment for multiple task jobs is not provided. This highlights the need for a new tool that can be used to estimate the cumulative damage for the shoulder and can be user friendly. This study will mainly focus on the development and validation of a shoulder tool that considers the risk factors known to be associated with shoulder pain. It will consider the cumulative loading based on the fatigue failure theory.

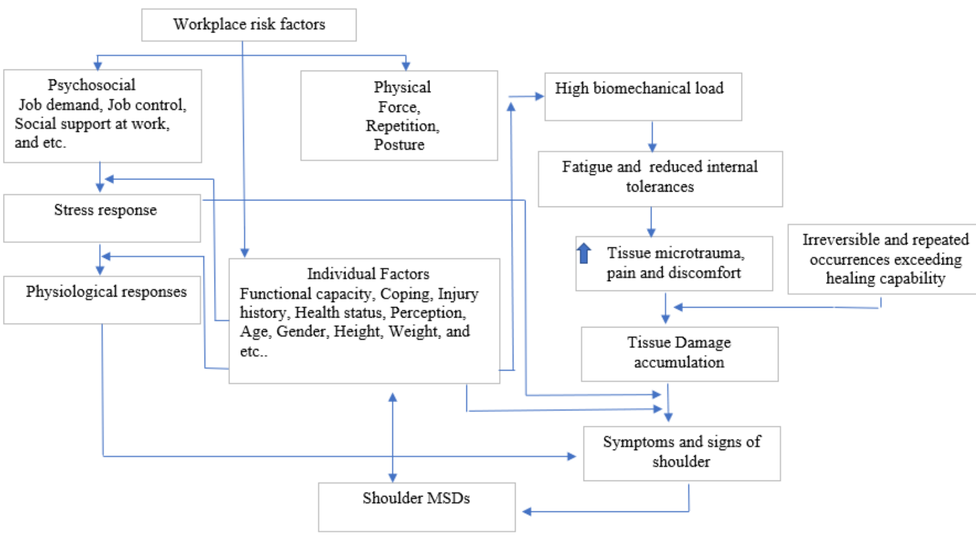

Figure 3.11: A proposed conceptual model for the associations between the risk factors and shoulder MSDs.

In this study, a new shoulder exposure assessment tool is presented that will estimate the "daily dose" of cumulative damage based on the fatigue failure theory. Inputs for the model include moments for both shoulder joints and the repetitions per minute for the job. The tool will be validated using an epidemiological database from a large automotive manufacturer in the US.

3.4 Methods

Tendons are the tissues of primary concern for the shoulder. Therefore, data on tendon fatigue failure (from in-vitro studies) was used to estimate damage per cycle (DPC) for different levels of stress and force [130]. Schechtman and Bader in their in vitro study [117] tested the extensor digitorum longus (EDL) of the foot to determine the fatigue failure behavior in human tendons. Ninety (90) specimens were used with 10 specimens per stress level. Physiological frequencies were used for the cyclic square tension-tension stress. An exponential relationship was found for the relationship between the applied stress and a median fatigue life (50% probability of failure), equation 3.7.

$$S = 101.25 - 14.83\log(N) \qquad (3.7)$$

Where S is the normalized stress as a percentage of the ultimate tensile strength (UTS) and N is number of cycles to failure. The DPC can be then estimated from which estimates can be obtained for damage incurred in one cycle at a specific stress level. When a worker is performing multiple tasks the DPC for each task is multiplied by its corresponding repetitions for the task. Summation of the cumulative damage (CD) for the tasks will give an estimate for the daily dose. Equation (3.15) shows the daily dose for cumulative damage.

$$Total\ CD = \sum_{i=1}^{j} DPC_i \times n_i \qquad (3.15)$$

Where *Total CD* is the daily dose for the cumulative damage for all tasks, DPC_i is the damage per cycle for task i, i is number of tasks in a job with a total of j tasks, n_i is the number of repetitions within task i [130].

3.4.1 Exposure Assessment

Video recordings from an epidemiological study conducted by Sesek in 1999 [128] were used to compute exposure estimates for the shoulder risk assessment model. The database in the epidemiology study involved symptom interviews and historical records for injury data. The study involved 1,022 participants. Data were collected from February 1998 to September 1999. Six different plants for a large automotive manufacturer were used in the study. Participants signed informed consent prior to data collection and the study was approved by the Institutional Review Boards at both the University of Utah and the University of South Florida. The age range was 20-70 years (m=41.0 years), heights were from 147-203 cm (m=174.8 cm), BMI ranged from 24.3 kg/m^2 to 30.3 kg/m^2 (m=27.5 kg/m^2), males represented 72.7% of the workforce. Since multiple workers can be doing a job, those experiencing an injury might not be the same as the ones used for exposure assessment. Jobs analyzed included up to six separate tasks. First time office visits (FTOV) were recorded and a visual analog scale (VAS) was used to rate subjects' pain for different body parts including the shoulder. Reports of discomfort and injury reports were included and self-reported symptoms on day of interview, and retrospectively for the previous year and subject attribution of job relationship participant too. Participants with cyclic jobs and who were on current job more than 30 days and agreed to be videotaped while doing their job were included in the study.

Two hundred and sixteen randomly selected jobs were used in the video analysis. For each job, the job description and its corresponding task descriptions were available from the automotive dataset. Most jobs were comprised of multiple tasks, and the total number of tasks analyzed was 446. Information about the repetitions per minute for the tasks was obtained by timing from start of one cycle to start for the subsequent cycle. Posture analyses were performed for the most awkward shoulder postures observed, where neutral posture is defined as arms by side of torso hanging straight down. Determination of the most awkward postures observed were based on the epidemiological evidence that repeated or sustained postures >60^{o} for flexion and abduction will lead to the development of shoulder MSDs [129]. Angles from 60^{o}-120^{o} of arm elevation are found to increase mechanical pressure from the acromion on tendon and 45^{o}-90^{o} of shoulder flexion and abduction was found to increase muscle activity of the deltoid [129]. Shoulder postural changes are considered when the angle between the upper arm and torso increases when arm is flexed, abducted, adducted, internally or externally rotated or extended. Sustained or repeated postures with load were also defined for cases where the upper arm was unsupported.

Manual observational analyses were performed, using frames at half the sampling rate. Analyses involved torso angles, lateral bending and axial rotation of the torso as well as head angle. To make sure that the estimates for the posture were as accurate as possible, the digital human in 3DSSPP was used to simulate the task being analyzed as a comparison. Figure 3.12 shows an example for a task done and its corresponding simulated task in 3DSSPP.

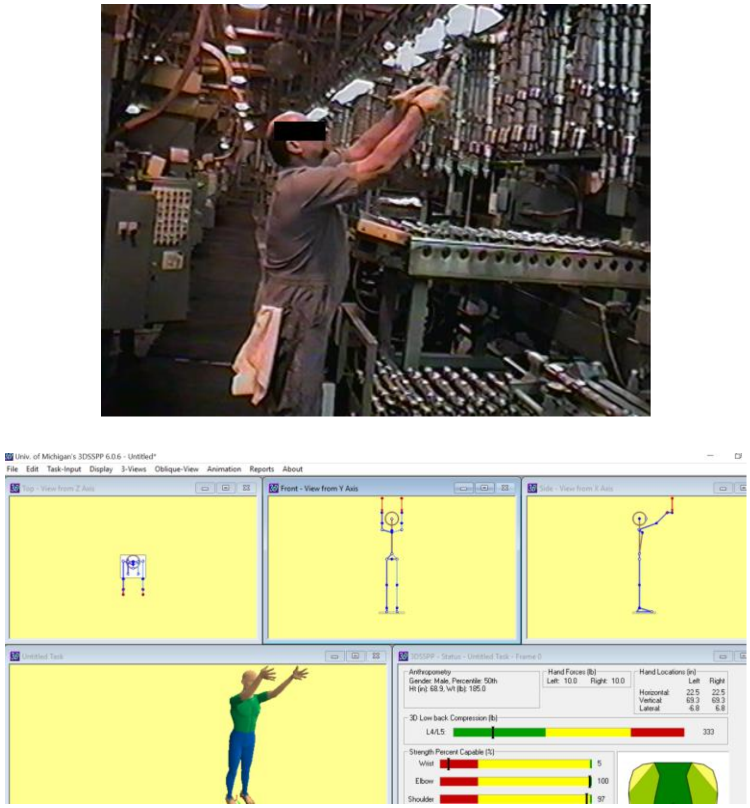

Figure 3.12: An example for a task analyzed and its corresponding digital human simulation.

To generate the required inputs for the shoulder model, postural data and the loads carried (magnitude and direction) were used to obtain the moment at each shoulder joint. The University of Michigan's model (3DSSPP version 6.0.6) was used to estimate the shoulder moments. Loads (e.g. part weights) used in the calculations for the moments were available and retrieved from the automotive dataset.

Moments for both right and left shoulders were used. The ultimate strength was estimated by considering the shoulder strength capability estimates from 3DSSPP (50% male population, lifting standing, average for left and right shoulders) and the calculated shoulder moments for each task. Numbers of cycles to failure for right and left shoulders were then obtained using equation 3.7.

$$S = 101.25 - 14.83\log(N) \qquad (3.7)$$

The DPC was then calculated using the reciprocal of the number of cycles to failure; the CD was then estimated by the multiplying DPC by the repetitions per minute. The job cumulative damage for the left and right shoulders were then calculated using equation (3.15).

$$Total\ CD = \sum_{i=1}^{j} DPC_i \times n_i \qquad (3.15)$$

An assumption was made that the highest value for the cumulative damage between left and right shoulders was responsible for a higher probability for the development of shoulder MSDs. Table 3.2 demonstrates an example for the daily dose cumulative damage calculations for a two task-job. Figure 3.13 illustrates the flowchart for the shoulder model.

Table 3.2: Example of daily dose cumulative damage calculations for a two tasks job. DPC RS: damage per cycle for right shoulder, DPC LS: damage per cycle for left shoulder, CD RS: cumulative damage for right shoulder, CD LS: cumulative damage for left shoulder.

Tasks for Job A	**DPC RS**	**DPC LS**	**Reps /min**	**CD RS**	**CD LS**	**JOB CD RS**	**JOB CD LS**	**CD MAX**	**CD/day**
1	1.496E-06	5.108E-07	2.50	3.740E-06	1.277E-06	5.403E-05	2.651E-06	5.403E-05	0.025933
2	2.011E-05	5.497E-07	2.50	5.029E-05	1.374E-06				

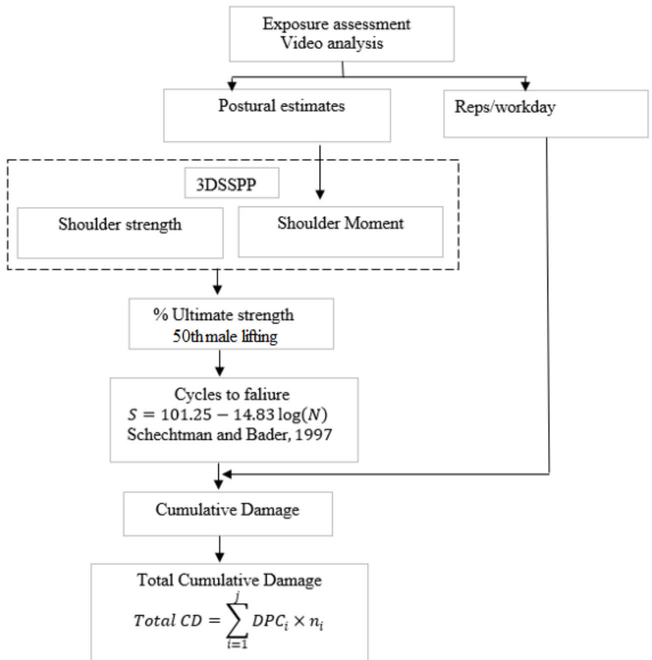

Figure 3.13: The development process flowchart for the shoulder tool.

3.4.2 Validation of the Tool

The epidemiology database included symptoms from a structured interview and historical records for injury data for all jobs analyzed. Jobs included up to six separate work tasks performed by the worker, and the cumulative damage for each task was summed to obtain the worker's daily dose. Health outcomes used in the validation included pain today, pain last year, records for injury data for neck and shoulder and subject attribution of their job's relationship to their symptoms. The FTOV were reported at the job level. A visual analog scale (VAS) was used by subjects to rate their pain for different body parts including the shoulder. Self-reports of discomfort and injury reports were included and self-reported symptoms on day of interview, and retrospectively for the previous year and subject attribution of job relationship to symptoms. Symptoms included in the study were self-reported and they fall into five groups: Category 1: Job-related where symptoms originated on the participant's job; Category 2: Job aggravated, symptoms not originating on job but aggravated by the participant's current job, Category 3: Symptoms not originating on job and no change or improvement in symptoms, Category 4: Symptoms improved on the job, symptoms improving but did not originate on job Category 5: No symptoms present.

For the validation, definitions of cases and controls involved shoulder pain (category 1 only) vs shoulder pain (category 5 only); as well as shoulder pain (categories 1&2) vs shoulder pain (categories 4&5). Outcomes were considered for shoulder pain today and shoulder pain last year and FTOV injury record. To be as a case a VAS>15mm was considered (VAS ranged from 0-100 mm with 0= no pain at all and 100= worst pain imaginable). Once the cumulative damage was obtained, binary logistic regression was used to test model significance and get estimates of the odds ratios associated with the log of the continuous CD.

Binary logistic regression was used to test the model significance and to find odds ratios associated with the log of the CD and the different outcomes. The analysis considered multiple workers performing the same job. Covariates included sex, age, and BMI. Age and BMI and sex were dichotomized, with 1M, 0F for sex, 40 years for age and >=30 for BMI. Regression equations were used to determine the relationship between the log of CD measure and the probability of an outcome (positive case) using the following equation:

$$\mathrm{P(event)} = \exp(\mathrm{Y'})/(1 + \exp(\mathrm{Y'})) \qquad (3.16)$$

where Y′ relationship will be derived from logistic regression

$$\mathrm{Y'} = \beta 0 + \beta 1 \times \mathrm{Log\,CD} \qquad (3.17)$$

Thus, this regression equation can be used to get the probability of a shoulder outcome for each value of CD.

3.5 Results

Five subsets of outcome definitions are used for the data analysis. The outcomes and the sample demographic characteristics are summarized in table 3.3.

Table 3.3: Demographic and outcome characteristics for the study participants.

Outcomes	All study participants	Cases	Non-cases
Injury (first time office visit for shoulder symptoms) FTOV			
Total N	293	76	217
Age group, n (%)			
<=40	155 (52.9)	46 (60.5)	109 (50.2)
>40	138 (47.1)	30 (39.5)	108 (49.8)
Sex, n (%)			
Female	81 (27.6)	23 (30.3)	58 (26.7)
Male	212 (72.4)	53 (69.7)	159 (73.3)
BMI, n (%)			
<30	231 (78.8)	63 (82.9)	168 (77.4)
>=30	62 (21.2)	13 (17.1)	49 (22.6)
Pain today			
Total N	293	47	246
Age group, n (%)			
<=40	155 (52.9)	30 (63.8)	125 (50.8)
>40	138 (47.1)	17 (36.2)	121 (49.2)
Sex, n (%)			
Female	81 (27.6)	22 (46.8)	59 (24)
Male	212 (72.4)	25 (53.2)	187 (76)
BMI, n (%)			
<30	231 (78.8)	39 (83)	192 (78)
>=30	62 (21.2)	8 (17)	54 (22)
Pain last year			
Total N	293	74	219
Age group, n (%)			
<=40	155 (52.9)	39 (52.7)	116 (53)
>40	138 (47.1)	35 (47.3)	103 (47)
Sex, n (%)			
Female	81 (27.6)	30 (40.5)	51 (23.3)

Table 3.3: (continued)

Male	212 (72.4)	44 (59.5)	168 (76.7)
BMI, n (%)			
<30	231 (78.8)	58 (78.4)	173 (79)
>=30	62 (21.2)	16 (21.6)	46 (21)
Self-reported symptoms (1&2 vs 4&5)			
Total N	282	51	231
Age group, n (%)			
<=40	149 (52.8)	27 (52.9)	122 (52.8)
>40	133 (47.2)	24 (47.1)	109 (47.2)
Sex, n (%)			
Female	74 (26.2)	19 (37.3)	55 (23.8)
Male	208 (73.8)	32 (62.7)	176 (76.2)
BMI, n (%)			
<30	222 (78.7)	40 (78.4)	182 (78.8)
>=30	60 (21.3)	11 (21.6)	49 (21.2)
Self-reported symptoms (1 vs 5)			
Total N	261	41	220
Age group, n (%)			
<=40	136 (52.1)	21 (51.2)	115 (52.3)
>40	125 (47.9)	20 (48.8)	105 (47.7)
Sex, n (%)			
Female	66 (25.3)	14 (34.1)	52 (23.6)
Male	195 (74.7)	27 (65.9)	168 (76.4)
BMI, n (%)			
<30	204 (78.2)	30 (73.2)	174 (79.1)
>=30	57 (21.8)	11 (26.8)	46 (20.9)

3.5.1 Current Shoulder Pain (1/2 vs 4/5) Outcome

A significant relationship was found between the CD measure and all shoulder outcomes tested. The logistic regression results for current shoulder pain with job attribution (1/2 vs 4/5) showed significant results with log CD and adjusting for covariates ($p<0.0001$). Log CD was significant ($p<0.0001$); however, none of the covariates demonstrated a significant relationship. Age and sex, however, did show a trend towards a significance level of 0.10. The model explained 23.96% of the deviance. The Odds ratio was 5.1989 with a 95% CI of (3.0192, 8.9522). Table 3.4 summarizes the logistic regression results.

Table 3.4: Deviance table for the logistic regression (1/2 vs 4/5).

Source	DF	Adj Dev	Adj Mean	Chi-Square	P-Value
Regression	9	63.887	7.0985	63.89	0.000
Log CD	1	49.513	49.5132	49.51	0.000
Age	1	3.446	3.4458	3.45	0.063
Sex	1	3.633	3.6329	3.63	0.057
BMI	1	0.013	0.0130	0.01	0.909
Site	5	5.148	1.0297	5.15	0.398
Error	272	202.706	0.7452		
Total	281	266.592			

Figure 3.14 shows the binary fitted line plot; we can notice that higher values of log CD are associated with an increase in probability of a shoulder outcome. The plot also has two extreme points (those refer to jobs with high force requirements for lifting and pushing tasks) with high value for the log CD, where one did report an outcome and one did not. This may be explained by differences among workers in reporting a shoulder outcome and their interpretation of a shoulder pain.

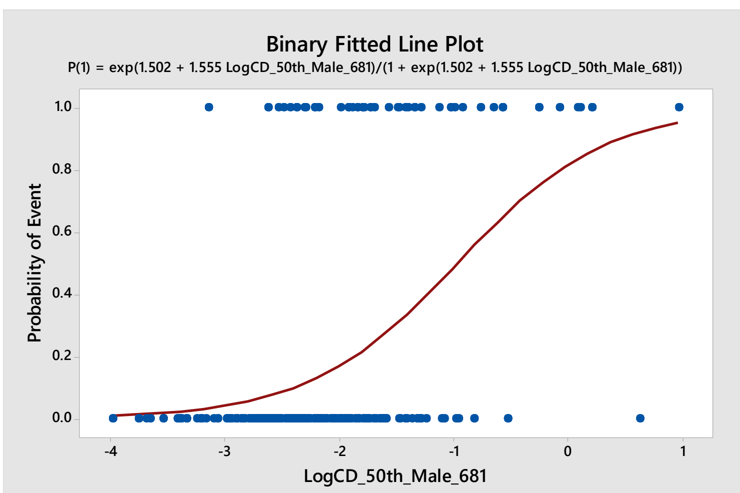

Figure 3.14: Binary fitted line plot (1/2 vs 4/5).

Table 3.5 summarizes the ORs between the quintiles of CD estimates and the current shoulder pain with job attribution 1&2 vs 4&5. For example, when the 20% category is compared to the high percentage (80%, 100%) categories, significant ORs can be observed indicating a distinguish power between those two categories. Figure 3.15 illustrates the binary logistic regression results between the Shoulder CD measure and shoulder outcome 1&2 vs 4&5. An increase in the probability of a shoulder outcome can be observed for the increase in the CD percentile.

Table 3.5: Odds ratios between quintiles of risk per CD estimates, starred values represent risk quintiles that different from each other.

	40%	60%	80%	100%
20%	5.38 (0.61, 47.63)	8.00 (0.95, 67.32)	16.93 (2.13, 134.49) *	45.16 (5.84, 349.54) *
40%		1.49 (0.44, 4.99)	3.14 (1.04, 9.52) *	8.39 (2.91, 24.16) *
60%			2.12 (0.77, 5.79)	5.65 (2.18, 14.61) *
80%				2.67 (1.18, 6.02) *

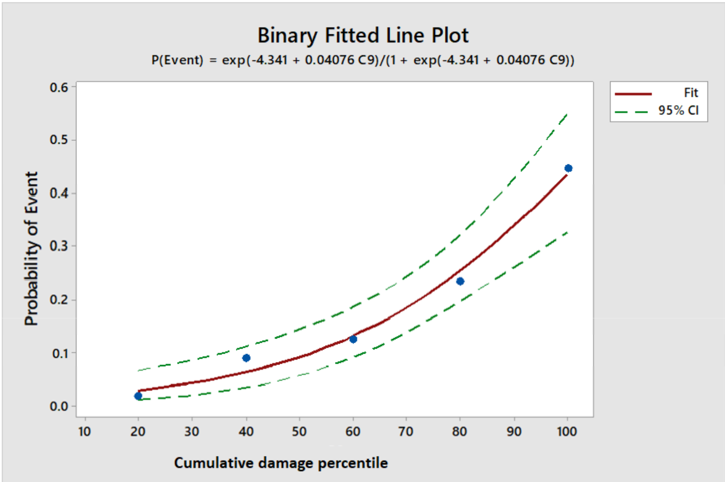

Figure 3.15: Logistic regression results between the shoulder CD measure and shoulder outcome (1&2 vs 4&5).

3.5.2 Current Shoulder Pain (1 vs 5) Outcome

The logistic regression results for current shoulder pain with job attribution (1 vs 5) showed significant results with log CD and adjusting for covariates ($p<0.0001$). Log CD was significant ($p<0.0001$), none of the covariates showed a significant relationship. However, age did show a trend towards a significance level of 0.10. The model explained 20.34% of the deviance. The Odds ratio was 3.9754 with a 95% CI of (2.2766, 6.9416). Table 3.6 summarizes the logistic regression results. The binary fitted line plot is shown in figure 3.16, a slight change in the trend can be observed when compared to figure 3.14.

Table 3.6: Deviance table for the logistic regression (1 vs 5).

Source	DF	Adj Dev	Adj Mean	Chi-Square	P-Value
Regression	9	46.175	5.1305	46.17	0.000
Log CD	1	29.155	29.1545	29.15	0.000
Age_	1	3.676	3.6757	3.68	0.055
Sex	1	1.587	1.5869	1.59	0.208
BMI_	1	0.920	0.9198	0.92	0.338
Site_	5	7.861	1.5721	7.86	0.164
Error	251	180.796	0.7203		
Total	260	226.971			

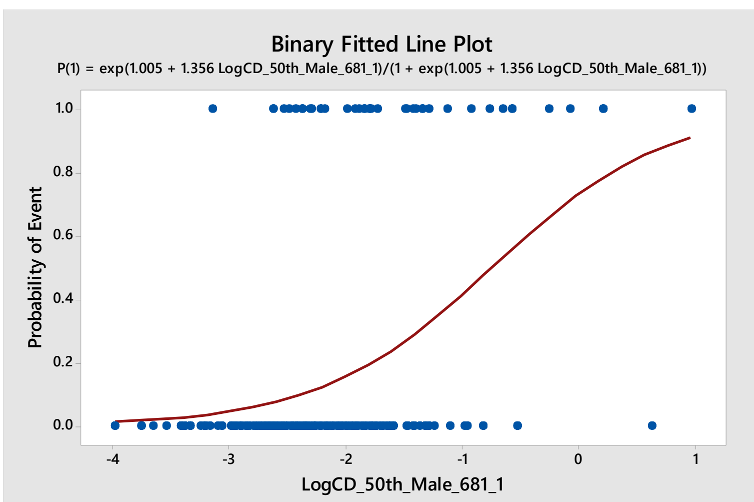

Figure 3.16: Binary fitted line plot for outcome 1 vs 5.

Table 3.7 shows the ORs categories for risk per CD estimates and the shoulder outcome 1 vs 5. Significant ORs are observed for some of the categories but less than the ones observed when current shoulder pain (1&2 vs 4&5) was analyzed. Figure 3.17 represents the logistic regression results between the shoulder CD measure and shoulder outcome 1 vs 5, the figure indicated that high cumulative damage percentiles are associated with high probability of a current shoulder pain (1 vs 5).

Table 3.7: Odds ratios between quintiles of risk per CD estimates, starred values represent risk quintiles that are different from each other.

	40%	60%	80%	100%
20%	5.53 (0.62, 49.08)	8.09 (0.96, 68.27)	12.38 (1.52, 100.65) *	27.53 (3.51, 215.89) *
40%		1.46 (0.43, 4.94)	2.24 (0.71, 7.08)	4.98 (1.68, 14.72) *
60%			1.53 (0.53, 4.39)	3.40 (1.28, 9.07) *
80%				2.22 (0.91, 5.44)

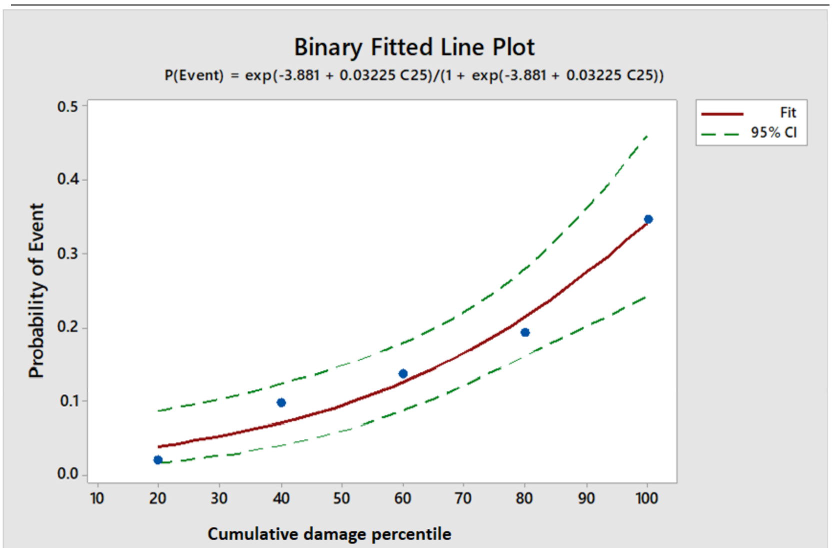

Figure 3.17: Logistic regression results between the shoulder CD measure and shoulder outcome (1 vs 5).

3.5.3 Shoulder Pain Last Year Outcome

When shoulder pain last year is used the model is significant (p<0.0001), the model explains 13.86% of the deviance and the odds ratio is 2.8470 with a 95% CI of (1.8780, 4.3161). Sex demonstrated a significant relationship (p=0.006). Table 3.8 summarizes the logistic regression results. Figure 3.18 shows the binary fitted line plot. The trend of the line is showing a good range for the probability that can be predicted. Table 3.9 summarizes the ORs for the different categories of risk per CD estimate, significant ORs can be observed among all categories when they are compared with the 100% except for the 80% category. The fewer number of cases in that category based on that outcome could be the reason behind that. Figure 3.19 illustrates the logistic regression results for CD risk and shoulder pain last year where higher values of CD percentiles are associated with a higher probability of shoulder pain last year.

Table 3.8: Deviance table for the logistic regression (pain last year).

Source	DF	Adj Dev	Adj Mean	Chi-Square	P-Value
Regression	9	45.897	5.0997	45.90	0.000
Log CD	1	28.782	28.7816	28.78	0.000
Age	1	0.994	0.9938	0.99	0.319
Sex	1	7.550	7.5498	7.55	0.006
BMI	1	0.011	0.0108	0.01	0.917
Site	5	3.786	0.7572	3.79	0.581
Error	283	285.269	1.0080		
Total	292	331.166			

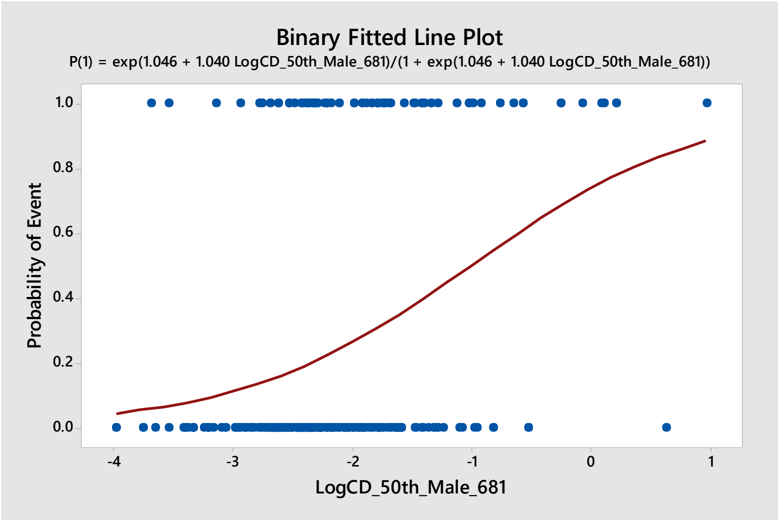

Figure 3.18: Binary fitted line plot (shoulder pain last year).

Table 3.9: Odds ratios between quintiles of risk per CD estimates, starred values represent risk quintiles that are different from each other.

	40%	60%	80%	100%
20%	1.34 (0.46, 3.86)	2.31 (0.86, 6.23)	3.08 (1.17, 8.13) *	6.47 (2.52, 16.61) *
40%		1.73 (0.68, 4.38)	2.30 (0.93, 5.71)	4.84 (2.01, 11.64) *
60%			1.33 (0.58, 3.04)	2.79 (1.27, 6.18) *
80%				2.10 (0.98, 4.52)

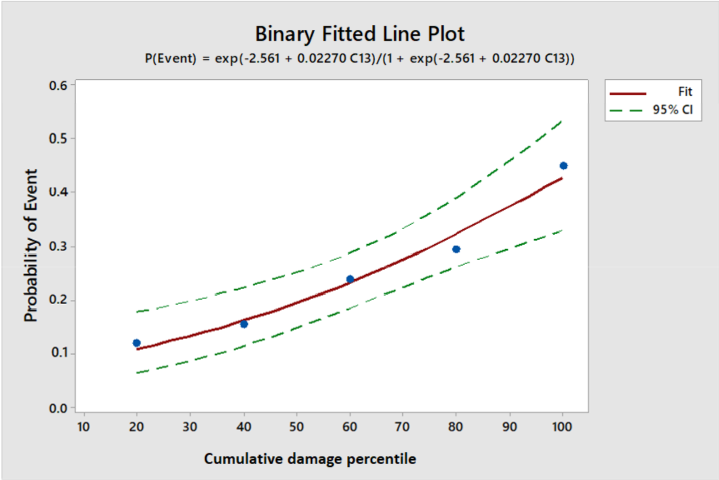

Figure 3.19: Logistic regression results between the shoulder CD measure and shoulder pain last year.

3.5.4 First Time Office Visit (FTOV) Outcome

Significant associations were also found when FTOV injury record is used in the analysis. For this outcome if any of the workers reported an injury it is considered as a case thus only site is included as a covariate. Site demonstrated a significant relationship in this analysis (p=0.023). Thus, differences in policies among the different sites in reporting an injury record could have an impact for the site effect in the logistic regression. The model explained 11.92% of the deviance. The odds ratio when the injury record data for shoulder FTOV were used was 2.5927 with a 95% CI of (1.7285, 3.8889). Table 3.10 summarizes logistic regression results. Figure 3.20 shows the binary fitted line plot; jobs with high CD can be observed on the plot where they are also associated with no probability of a shoulder outcome. Table 3.11 shows the ORs categories per risk of CD. Significant ORs can be observed between the 20% category and all other categories. Figure 3.21 shows the logistic regression of CD risk and shoulder FTOV, probabilities of an outcome are about equal for the 40, 60 and 80 percentiles which indicates that they have about the same number of cases.

Table 3.10: Deviance table for the logistic regression (FTOV injury).

Source	DF	Adj Dev	Adj Mean	Chi-Square	P-Value
Regression	6	39.99	6.666	39.99	0.000
Log CD	1	24.61	24.612	24.61	0.000
Site	5	13.04	2.609	13.04	0.023
Error	286	295.44	1.033		
Total	292	335.43			

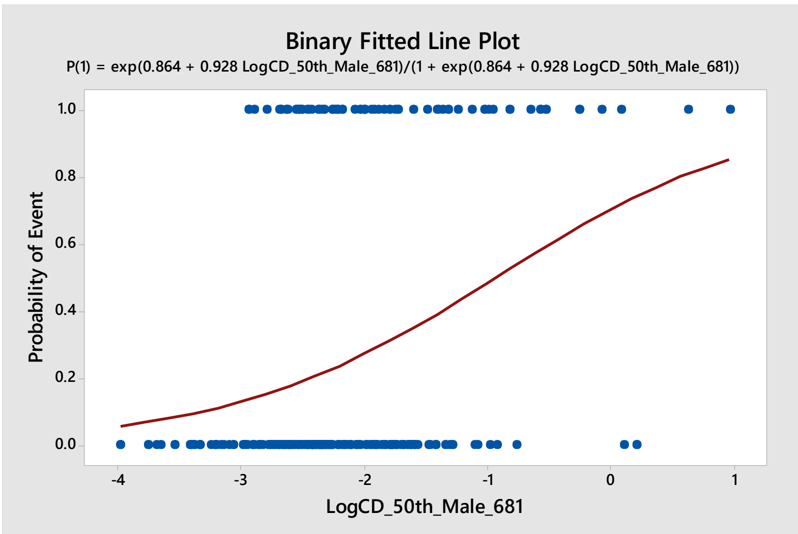

Figure 3.20: Binary fitted line plot (FTOV injury).

Table 3.11: Odds ratios between quintiles of risk per CD estimates, starred values represent risk quintiles that are different from each other.

	40%	60%	80%	100%
20%	5.12 (1.59, 16.42) *	4.69 (1.45, 15.13) *	4.79 (1.48, 15.49) *	11.17 (3.58, 34.91) *
40%		0.92 (0.40, 2.08)	0.94 (0.41, 2.13)	2.18 (1.00, 4.73) *
60%			1.02 (0.45, 2.35)	2.38 (1.09, 5.21) *
80%				2.33 (1.06, 5.09) *

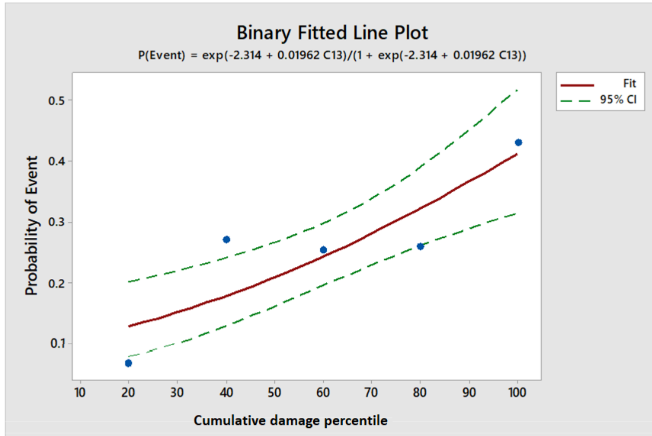

Figure 3.21: Logistic regression results between the shoulder CD measure and shoulder FTOV.

3.5.5 Shoulder Pain Today Outcome

When the shoulder pain today outcome is used the model remains significant ($p<0.0001$), the model explained 13.47% of the deviance and the odds ratio is 2.1219 with a 95% CI of (1.3736, 3.2778). Sex demonstrated a significant relationship ($p=0.003$) for the pain today outcome, where women reported more pain today outcome compared to men. Table 3.12 summarizes the logistic regression results. Figure 3.22 shows the binary fitted line plot. It can be noted that the predictive range for the probability of a shoulder outcome to happen is decreased when using the shoulder pain today in the analysis. The few points on the plot with a high CD value does not have a probability of a shoulder outcome, this in turn will affect the predictive range. Thus, regardless of the high CD estimates workers did not report any shoulder pain today. But those high CD values were associated with a probability of an outcome to happen for other definitions of shoulder outcomes such as FTOV and shoulder pain last year. Table 3.13 summarizes the ORs for the different categories of risk per CD estimate. Figure 3.23 illustrates the logistic regression results between CD percentiles and shoulder pain today, it can be noted that higher CD percentiles are associated with higher probability of a shoulder outcome. A summary of the ORs associated with the different shoulder outcomes is displayed in table 3.14. Higher ORs can be observed for the self-reported symptoms of current shoulder pain.

Table 3.12: Deviance table for the logistic regression (shoulder pain today).

Source	DF	Adj Dev	Adj Mean	Chi-Square	P-Value
Regression	9	34.308	3.8120	34.31	0.000
Log CD_	1	11.878	11.8779	11.88	0.001
Age	1	0.088	0.0879	0.09	0.767
Sex	1	8.642	8.6415	8.64	0.003
BMI	1	0.374	0.3744	0.37	0.541
Site	5	6.078	1.2156	6.08	0.299
Error	283	220.400	0.7788		
Total	292	254.708			

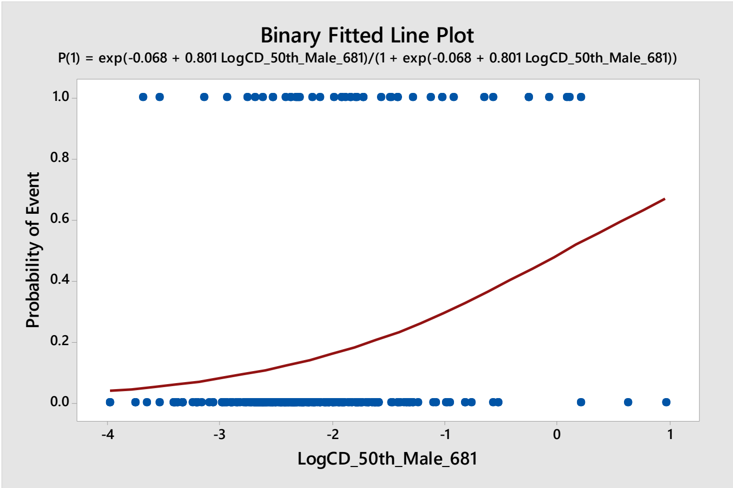

Figure 3.22: Binary fitted line plot (shoulder pain today).

Table 3.13: Odds ratios between quintiles of risk per CD estimates, starred values represent risk quintiles that are different from each other.

	40%	60%	80%	100%
20%	0.64 (0.17, 2.41)	1.39 (0.45, 4.27)	1.84 (0.62, 5.45)	3.98 (1.45, 10.93) *
40%		2.16 (0.61, 7.59)	2.86 (0.84, 9.73)	6.19 (1.94, 19.69) *
60%			1.33 (0.49, 3.65)	2.87 (1.13, 7.27) *
80%				2.16 (0.89, 5.21)

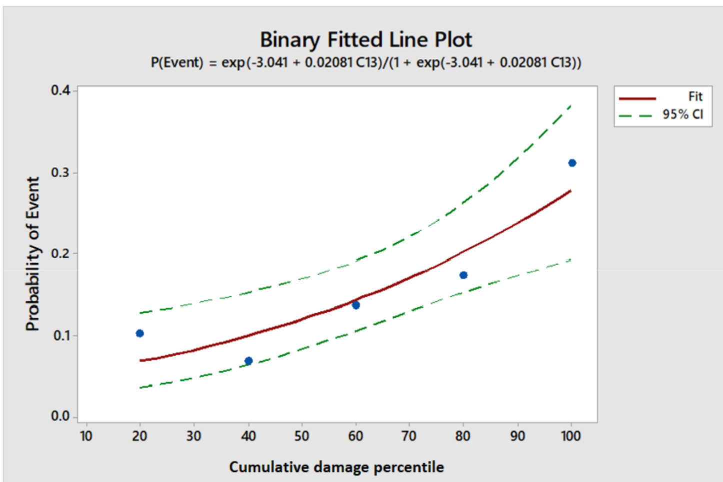

Figure 3.23: Logistic regression results between the shoulder CD measure and shoulder pain today.

Table 3.14: Summary of the crude and adjusted ORs for the different shoulder outcomes, N=total number, Var=various, df=degrees of freedom.

Outcome	**Analysis**	**Cases**	***N***	**Variable**	***df***	x^2	***p***	**OR**	**95% CI**
Pain today	Crude	46	293	Log CD	1	16.11	<0.001	2.2285	(1.495, 3.321)
	Adjusted			Log CD	1	11.88	0.001	2.1219	(1.374, 3.278)
				Age	1	0.09	0.767	0.8882	(0.405, 1.949)
				Sex	1	8.64	0.003	0.3443	(0.170, 0.699)
		`		BMI	1	0.37	0.541	0.7602	(0.312, 1.853)
				Site	5	6.08	0.299	Var	Var
Pain last year	Crude	74	293	Log CD	1	32.35	<0.001	2.8291	(1.910, 4.192)
	Adjusted			Log CD	1	28.78	<0.001	2.8470	(1.878, 4.316)
				Age	1	0.99	0.319	1.4029	(0.721, 2.730)
				Sex	1	7.55	0.006	0.4167	(0.224, 0.776)
				BMI	1	0.01	0.917	1.0390	(0.505, 2.136)
				Site	5	3.79	0.581	Var	Var
FTOV	Crude	76	293	Log CD	1	26.95	<0.001	2.5303	(1.735, 3.691)
	Adjusted			Log CD	1	24.61	<0.001	2.5927	(1.729, 3.889)
				Site	5	13.04	0.023	Var	Var
1&2 VS 4&5	Crude	51	282	Log CD	1	52.41	<0.001	4.7339	(2.875, 7.795)
	Adjusted			Log CD	1	49.51	<0.001	5.1989	(3.019, 8.952)
				Age	1	3.45	0.063	2.1384	(0.954, 4.794)
				Sex	1	3.63	0.057	0.4733	(0.221, 1.014)
				BMI	1	0.01	0.909	1.0522	(0.439, 2.520)
				Site	5	5.15	0.398	Var	Var
1VS 5	Crude	41	261	Log CD	1	34.24	<0.001	3.8804	(3.324, 6.479)
	Adjusted			Log CD	1	29.15	<0.001	3.9754	(2.277, 6.942)
				Age	1	3.68	0.055	2.2856	(0.975, 5.359)
				Sex	1	1.59	0.208	0.5886	(0.261, 1.330)
				BMI	1	0.92	0.338	1.5596	(0.636, 3.828)
				Site	5	7.86	0.164	Var	Var

3.6 Discussion

The analysis revealed that there is a strong association between the CD and the shoulder MSD outcomes, which may help explain the etiology of those MSDs. The dose-response associations were observed for the various shoulder outcomes. For the binary fitted line plots, we can notice that higher values of log CD are associated with an increase in probability of a shoulder outcome. Few extreme log CD points were observed in the binary fitted line plots, those points were reported as injuries for the FTOV outcome, which can be seen in figure 3.20. For this outcome if any of the workers doing the job reported an injury, it was considered a case. It is possible that those jobs were associated with a higher risk. For shoulder pain today those jobs were not considered as a case, whereas for the other outcome definitions those jobs alternate between being a case or non-case. For the shoulder pain today outcome, the predictive range for the probability is decreased compared to other outcomes. This can be explained by the fewer cases that are reported even for high CD estimates. Differences in individuals in reporting a shoulder outcome and the outcome definition could affect the worker responses. Also, workers on those jobs may have had, for example, shoulder pain last year but did not have a shoulder pain today at the time of the survey. Self-reported symptoms demonstrated higher ORs when compared to other shoulder outcomes. Most of the workers reported 1 or 5 for that outcome and those values were used to define a case or non-case in the analysis and demonstrated good results of association with the log CD estimate.

The strong associations between the CD and all shoulder outcomes supports fatigue failure theory and its potentially important role in the etiology of MSDs. Recently, material fatigue theory to assess MSD risk have been used by Gallagher et al. to develop two new risk assessment tools, one for the distal upper extremity (the Distal Upper Extremity Tool, or DUET) and one for the low back, the lifting fatigue failure tool (LiFFT). In DUET, the authors estimated the force exertion by using OMNI-RES scale along with respective repetitions per workday to get estimates of the cumulative damage in a similar way to the suggested methodology in the current study [130]. In LiFFT, estimates of DPC were obtained by estimating compressive load based on peak load moment for a lift. The latter tool used data from fatigue failure studies for the spinal motion segments [131]. Both LiFFT and DUET were validated using epidemiological studies including the database used here and they demonstrated significant results and significant odds ratios. The current results indicate that application of the fatigue failure method also works extremely well in assessing the probability of association with shoulder outcomes.

This study aim was to develop and validate a shoulder risk assessment tool based on the fatigue failure theory. This tool overcomes the limitations of the other current observational exposure assessment tools. Current tools such as RULA and REBA fall short in terms of the impact of cumulative loading. Duration and frequency of tasks were also not included which have been shown to influence MSDs. Inability to deal with multitask jobs is another shortcoming of previous tools, as many jobs are multitasked in nature.

In the current tool, dose-response relationships were observed between the CD and pain prevalence. The tool will provide a CD measure and an estimated outcome probability can be obtained for any given value. The CD can be easily summed for multiple tasks to get a daily dose of exposure, and the contribution of the various tasks will be easily estimated. The proposed tool will be designed to be easy to use requiring inputs for moments and repetitions per workday for each task performed. Since the study showed promising results for the fatigue failure application in the shoulder tool, estimates for the shoulder moments requiring easy inputs from the user will be further investigated. Study limitations include the fact that only difficult postures were included in the analysis and other risk factors such as the personal characteristics, speed of work and duty/rest cycles were not considered in the analysis. Moreover, all self-reported symptoms were subject attributed. Recall bias and non-differential errors (exposure misclassification occurs equally between subjects with symptoms and subjects without symptoms) could impact the responses. Temporal sequence of exposure and effect is hard to be determined and is another limitation of the cross-sectional study. Study Two will consider the effect of personal characteristics on the shoulder tool.

Chapter 4: Development and Validation of the Shoulder Risk Assessment Tool Using The Personal Characteristics

4.1 Personal Characteristics and Shoulder Disorders

MSDs account for a large percentage of the occupational injuries and illnesses in the US, as per the Bureau of Labor Statistics (2015). In 2015, MSDs accounted for approximately 31% of illnesses including days away from work and occupational injuries [1]. Upper extremity injuries, including shoulder injuries, are the second most frequnet injuries causing occupational lost time claims after back injuries. In 2014, 88,980 non-fatal shoulder injuries and illnesses occurred that involved days away from work and shoulder injuries and illnesses caused the longest absences from work compared to any other body part with a median of 26 days' work [7].

Individual, physical and psychosocial factors are the leading factors leading to the development of MSDs, and each of these categories can be used to get exposure estimates for different risk factors leading to MSDs. Physical risk factors include force, repetition, posture, and vibration exposure. Psychosocial risk factors include (but are not limited to), social support at work, job demands and job control. Individual risk categories including personal characteristics also have been shown to play a role in MSD development [132-137].

It is known that there are differences in structural and functional body characteristics between men and women, including size and strength. Differences in the anthropometric measurements for men and women are particularly noteworthy. At the musculoskeletal tissue level, it has also been found that women's tendons are more sensitive to overstretch [132]. This may provide an explanation for why women having more flexible joints, which is highly notable in the pelvic, lumbar, and shoulder joints [132,138]. Information for other joints is still unclear. Muscle strength, power and endurance are other functional aspects where large differences are found between sexes. In general, men can generate more strength compared to women especially for the upper limbs [132]. However, greater fatigue resistance is found in women compared to men [132]. The muscular fatigue difference may be attributable to the greater proportion of type I muscle fibers in women compared to men, which increases their endurance but may increase risk of overload [132]. Some studies have highlighted the contribution for the muscle fiber type composition for the effect of age on endurance and fatigue in the shoulder muscle (specifically the middle deltoid). Differences in isometric work capacity have also been found to be different between older and younger individuals [139].

Women have been found to report higher pain perception compared to men, and studies suggested that women have fewer and narrower pain adaptation strategies. [132] For example, in the presence of pain, women were less able to redistribute muscle activity across the upper trapezius muscle compared to men [138]. In non-painful contractions, changes in relative muscle activity are considered an efficient strategy to reduce the overloading of specific muscle regions, where force is maintained by distribution of the activity among different regions of the muscle [138,140]. Since changes in muscle activity in non-painful conditions are observed, an assumption can be made that they are similar in fatiguing conditions, thus women response in painful conditions can be considered sub-optimal [138,140]. Endurance characteristics of women and men are also dependent on muscular recruitment patterns. For example, the longer time to fatigue is associated with high variability in the signals (e.g. amplitude, frequency) of individual muscles in women; whereas it is associated with inter-muscle characteristics in males. Based on this information, fatigue can be predicted using differing mechanisms, which may help explain the higher prevalence of neck/shoulder disorders in women [78].

Thus, functional capacity differences are highly attributable to anthropometry and muscle fiber characteristics that, in turn, could be a vital factor in the gender differences in reports of neck/shoulder WMSDs. Côté et al. suggested a conceptual model (Figure 4) that can be used to explain the gender differences for the prevalence of neck/shoulder WMSDs. It can be noted that smaller and less numerous muscle fibers in women may lead to higher muscular stresses which, in turn, increases the prevalence of neck and shoulder WMSD symptoms and diagnoses in women [132].

Treaster and Burr, conducted a literature review on sex differences for prevalence of MSDs specific for the upper extremities (UE), including shoulder disorders [133]. The main objective of the study was to examine the strength of evidence for the sex differences for the prevalence of MSD for the upper extremities. The hypothesis that women have a higher prevalence of MSDs for the upper extremities compared to men was examined to determine the strength of support. Studies including both general and working populations were included in the literature review. Studies including self-reports and self-report plus physical examination were considered and the frequency, prevalence and incidence rates were analyzed. The study accounted for issues such as the effect of data type and adjusted for confounders, especially for the effect of age on the results. Women were found to have a greater propensity for MSDs of the upper extremities compared to men, and it was found that adjustments for confounders (e.g. age and physical work factors) and data type (e.g self-report/self-report and physical examination) did not change that trend. Thus, this study suggested that if women have the same job responsibilities as men, they will have higher occupational-related injuries putting women at a higher risk compared to men. The OR and prevalence ratios (PRs), with men as the referent, ranged from (0.85-10.05) and (0.66-11.4) for self-report and self-report plus physical examination, respectively. Thus, women are found to be at a higher prevalence of MSDs for the upper extremities including the shoulder [133].

Another study of gender differences for UE musculoskeletal complaints was done by Zwart et al. [134]. A cross-sectional questionnaire (periodic occupational health survey) was used in this study, which included 16,874 employees in the general working population in Netherlands. Subjects were grouped into 21 occupational classes. Complaints for UE MSDs were analyzed, and gender differences were studied for associations within each occupational class. Adjustments for the occupational class were also done. Higher risk of complaints was found in women in the study sample including the shoulder. This higher risk of complaints was also significant when considering analysis within occupational classes. For shoulder complaints, female status was found to be a significant factor, having a prevalence ranging from 8.8%-34.1%, with food and beverage industry workers demonstrating higher prevalence. Thus, women reported more UE musculoskeletal complaints; however, this does not necessarily mean that they had a different occupational exposure. Factors both related and not related to work need to be considered to describe this phenomenon. Studies suggest that physical and psychosocial risk factors related to work and those not related to work need to be considered when studying the sex differences and interactive effects for neck and shoulder disorders [135].

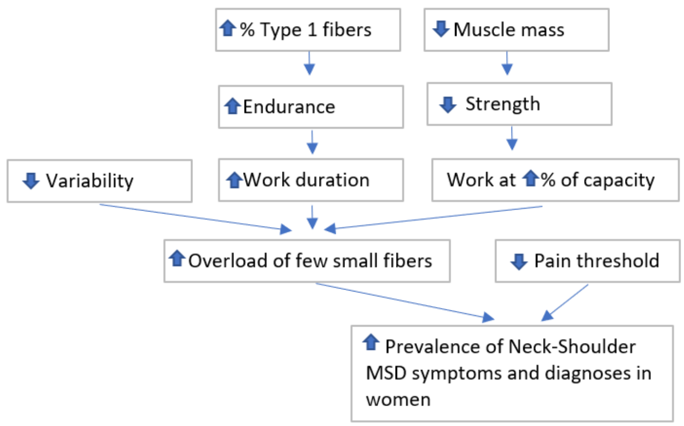

Figure 4.1: Mechanisms behind the physical basis for sex differences in the prevalence of neck/shoulder WMSD symptoms and diagnoses in women. *Increases and reductions are represented by arrows [132].

Shoulder functional capacity is also significantly affected by age. Specifically, decreased acceleration and mobility in certain axes and planes of the shoulder are observed with increasing age. Isometric strength and activity are also decreased with age. These results may be attributable to the degenerative physiological changes that occur with age. Several studies focused on rotator cuff degenerative changes with age [141]. Rotator cuff tears are commonly associated with age, where ruptures can be caused by poor vascularization. Twenty-five percent of individuals suffer from full thickness rotator cuff tears in their 60s, and this percentage is increased to 50% in their 80s. The prevalence of rotator cuff tear was found to increase with age in asymptomatic shoulders [142, 143]. Other studies found that partial or full thickness tears were more prevalent after the 50s, and that the increased prevalence was statistically significant [144, 145]. Subjects in their 80s (80%) also have a higher percentage compared to subjects in their 70s (50%), in the dominant shoulder [146]. Some studies have assessed rotator cuff abnormalities using four groups: general population, symptomatic patients, asymptomatic patients, and patients after having a shoulder dislocation. Overall prevalence increased from 9.7% to 62% for patients younger than or equal to

20 years and 80 or more respectively. When age intervals of ten years were used, all groups had high prevalence. Thus, rotator cuff degeneration can be considered as a common sign of human aging. [146] Heavy workload, less muscle strength in external rotation and abduction, and a less active forward elevation at the scapula plane were all found to be associated with the rotator cuff tears among the general population. Aging, dominant arm, and trauma history have also been found to be risk factors for rotator cuff tears [147].

Glenohumeral ligaments are also affected by age-related changes. Signs of osteoarthritis and histopathologic changes in the glenoid labrum are developed in the articular shoulder joints as the body ages [141]. Degenerative changes (degenerative disease, narrow joint space) of the acromioclavicular joint were also found to be associated with age for symptomatic shoulders [148].

Many studies have found that prevalence of shoulder pain increases with age, where age seemed to be a contributing factor [149]. Other studies examining the flexibility of the shoulder joint (measured as range of shoulder abduction) also showed a significant difference between young and elderly people [150]. For men and women aged over 65 years, a 10° decline per decade for functional joint range was noted for both sexes within the groups. Loss of functional joint range in old age is greater in women compared to men where other studies showed that, in younger age, women have greater flexibility compared to men of similar age. The rate of collagen changes with age (loss of elasticity), lower muscle strength, greater body fat and symptoms of arthritis or shoulder disabilities could all be causes for the reduced shoulder range in women compared to men [150].

Cassou et al. [136] conducted a study on the effect of age and occupational factors on chronic neck and shoulder pain. The study was conducted in seven regions of France using a large longitudinal epidemiological survey. The study sample included 21,378 subjects selected randomly from the occupational physicians' files and a checklist was used to report the working conditions by the workers. Physical and psychosocial work factors were assessed. Self-reported pain and clinical examination were used to evaluate chronic neck and shoulder pain. Data was collected in 1990 and again in 1995. The statistical analysis results revealed that both women and men experienced an increase in the prevalence rate with age. Women were found to have higher prevalence rates compared to men. Controlling for working conditions of age and high job demand, repetitive work and awkward postures were found to be predictors for neck and shoulder pain.

Other studies examined how shoulder injuries differed between sexes and age groups. In a general population prospective cohort study done in Oslo, Norway, shoulder injuries were registered prospectively for subjects with suspected shoulder injuries at a primary health care facility. In this study 3,031 shoulder injuries were registered in one year. The study results suggested that age and gender were significant in explaining the shoulder structures affected by trauma. Incidence rates for shoulder injury were higher in young men and the elderly [151].

As explained earlier, shoulder strength differences can affect the prevalence of shoulder WMSDs. Many studies examined in detail the differences in shoulder strength based on gender and age group. Hughes et al. [152] in their cross-sectional study evaluated isometric shoulder strength for a set of exertions and postures. A modified Cybex II dynamometer was used in the analysis where dominant and nondominant hands were tested. Shoulder motions studied included: internal rotation (IR), external rotation (ER), abduction, adduction, flexion and extension. Twenty combinations for posture and exertion were studied. Subjects on the normal laboratory value list at Mayo clinic in Rochester, Minnesota were recruited in the study. A total of 120 subjects (60 women, 60 men) participated with an age range of 20-78 years. The mean height was (172 cm, ± 10 SD), and the mean weight was (76 kg ± 14 SD). Pre-screenings for neck, upper extremity, neurological or cardiovascular injuries or disorders were also used as exclusion criteria. The study hypothesized that all the aforementioned isometric shoulder strengths are age dependent. Multivariate analyses were performed, where age, sex and weight were considered in the analysis. Controlling for age and weight, the study results showed that sex influenced shoulder strength, with males higher in their isometric shoulder strength compared to females. Dominant and non-dominant shoulders were statistically significant for some strength measures (1-flexion in all test postures, 2-ER at 15° of abduction and 30° of IR, 3-IR at 15° of abduction and 0° of IR, 4-IR at 15° of abduction and 30° of ER, 5-ER at 90° of abduction and 0° of IR, and 6-ER at 90° of abduction and 30° of ER). Weight was positively associated with all shoulder strength measures, whereas age was negatively associated with them.

Another study for sex and age differences was done by Balcells-Diaz et al. [153] This study involved a random sample of the general population in a small to medium-size city in Spain. The constant score as a shoulder function measurement tool was used in the study to measure the shoulder strength. Significant differences between genders were found for shoulder strength and a significant decline with age was also noted.

Barnes et al. [137] conducted a study where the effects of age, sex and arm dominance were considered for the shoulder range of motion. 280 Subjects with variable ages from 4-70 years old were included. Ten (10) year intervals for the age groups were used with 40 subjects within each group. A goniometer was used to take the measurements for the range of motion. Results for internal rotation, external rotation, abduction, and adduction were analyzed. Based on the results age was statistically significant for abduction, forward elevation, and external rotation with arm adducted and abducted. All decreased with age except for internal rotation. Dominant arms were better in the range of motion in external rotation whereas non-dominant arms were better in extension and internal rotation. No differences were found for other types of motion. In all motions studied, females demonstrated greater range of motion compared to males.

All the studies described how the functional capacity differences, which are also highly attributable to anthropometry and muscle fiber characteristics could be a vital factor in the sex differences in the reports of shoulder disorders. Thus, sex appears to be significant for describing the etiology for the shoulder disorders. Age is also another important factor, as studies found that age is significant in explaining the shoulder structures affected by trauma and that the prevalence of shoulder pain is increased by age for both women and men. As a result of all previously discussed personal characteristics and their effect on the etiology of shoulder pain and disorders. The current study will focus on evaluating a shoulder tool that includes personal characteristics of the workers involved in the study. Thus, the study aim is to develop and validate a shoulder risk assessment tool based on the fatigue failure theory including personal characteristics. This tool will overcome the limitations of the current tools. Current tools such as RULA and REBA fall short in terms of the impact of cumulative loading and they do not consider a variety of risk factors. Personal characteristics and their impact of the development of MSDs have not been discussed in the current tools. Other limitations include: Duration and frequency of tasks were also not included which have been shown to influence MSDs. Inability to deal with multitask jobs is another problem too as many jobs are multitasks in nature.

In this study, a new shoulder exposure tool that considers the personal characteristics will be discussed which will estimate the daily dose cumulative damage based on the fatigue failure theory. Inputs for the model will include personal characteristics, moments for both shoulder joints and the repetitions per workday for the job. The tool will be validated using an epidemiological database from a large automotive manufacturer in the US.

4.2 Model Logic

Many epidemiological studies, studies of tissue loading in animal studies, and in vitro testing for MSDs support the idea that MSDs may result from a fatigue failure process. Evidence also suggests that this process happens in vivo [130]. Damage can develop as a result of repeated loading and unloading at stress less than the ultimate stress for a material. Fatigue failure behavior of biological tissues including tendons, ligaments, cartilage, and spinal motion segments has been studied. Relationships between cycles to failure and the applied stress will be exponential in nature.

Data for tendons fatigue failure in vitro is used to get the Damage per Cycle (DPC) for different levels of stress and force. Schechtman and Bader in their vitro study [117] tested the extensor digitorum longus (EDL) of the foot to determine the fatigue failure behavior in human tendons under cyclic square tension-tension stress. An exponential relationship was found for the relationship between the applied stress and a median fatigue life (50% probability of failure) as seen in equation 3.7.

The DPC can be then estimated for damage incurred in one cycle at a specific stress level. When a worker is performing multiple tasks the DPC for each task is multiplied its corresponding repetitions for the task. Summation of the cumulative damage for the tasks will give an estimate for the daily dose using equation (3.15) shows the daily dose for cumulative damage.

4.2.1 Exposure Assessment

Video recordings from an epidemiological study implemented by Sesek in 1999 [128] were used to compute exposure estimates for the shoulder model. The database in the epidemiology study involved symptom interviews and historical records for injury data. The study involved 1,022 participants. Data were collected from February 1998 to September 1999. Six different plants were used in the study. Participants signed informed consent prior to data collection and the study was approved by the Institutional Review Boards at both the University of Utah and the University of South Florida. The age range was 20-70 years (m=41.0 years), heights were from 147-203 cm (m=174.8 cm), BMI ranged from 24.3 kg/m^2 to 30.3 kg/m^2 (m=27.5 kg/m^2), males represented 72.7% of the workforce. Since multiple workers may be performing the same job, those experiencing the injury might not be the same as the ones used for exposure assessment. Jobs analyzed included up to six separate tasks. First time office visits (FTOV) were recorded and a visual analog scale (VAS) was used to rate subjects' pain for different body parts including the shoulder. Reports of discomfort and injury reports were included and self-reported symptoms on day of interview, and retrospectively for the previous year and subject attribution of job relationship participant too. Participants with cyclic jobs and who were on current job more than 30 days and agreed to be videotaped while doing their job were included in the study.

Two hundred and sixteen randomly selected jobs were used in the video analysis. For each job, the job description and its corresponding task descriptions were available from the automotive dataset. Most jobs were comprised of multiple tasks, and the total number of tasks analyzed was 446. Information about the repetitions per minute for the tasks was obtained by timing from start of one cycle to start for the subsequent cycle. Personal characteristics were available from the dataset. Posture analysis was performed for the most awkward posture, where the same definition of deviation from the neutral posture (as described in chapter 3) were used. Analysis involved torso angle, lateral bending and axial rotation of the torso and head angle. To ensure that the estimates for the posture are accurate, the digital human in 3DSSPP was used to simulate the task being analyzed.

In this model the personal characteristics will be used to get shoulder moments for each shoulder joint. The personal characteristics combined with the postural data and the loads carried (magnitude and direction) will be inputs to get the shoulder moments. The University of Michigan's model (3DSSPP version 6.0.6) is used to get the shoulder moments.

Moments at right and left shoulders will be used. The ultimate strength will be calculated by considering the strength capability estimates from 3DSSPP and the calculated shoulder moments for each task.

In this model, the moment for each subject is calculated using his height, weight and sex. Those inputs for the personal characteristics will be used in 3DSSPP to get the modified moment values at each shoulder joint. The shoulder strength capability is calculated based on the sex and height. The strength capability for each subject is estimated based on the distribution of the heights from which an estimate for the strength capability will be used to represent the strength capability for the subject. For example, the distribution of the heights for the data in 3DSSPP can be illustrated as shown in figure 4.2. Based on that distribution, the z-scores for the heights of the subjects included in the epidemiology database can be found using equation 4.1.

$$x = \mu + z\sigma \qquad (4.1)$$

Where x is the data value, μ is the mean, z is the z score, and σ is the standard deviation.

The height z-scores will be then used to match the z-scores for the distribution of the strength capabilities (figure 4.3) to find the strength capability for each subject. The distributions have been established for the male and female groups to account for the differences based on sex.

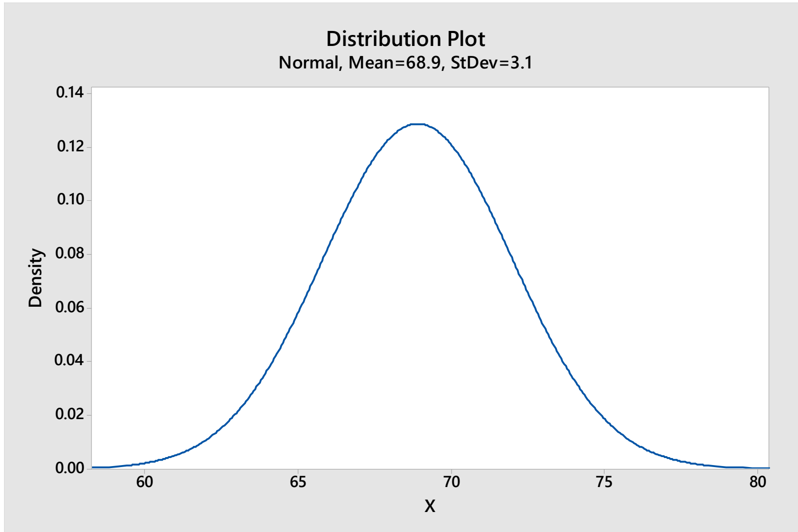

Figure 4.2: Distribution of the heights.

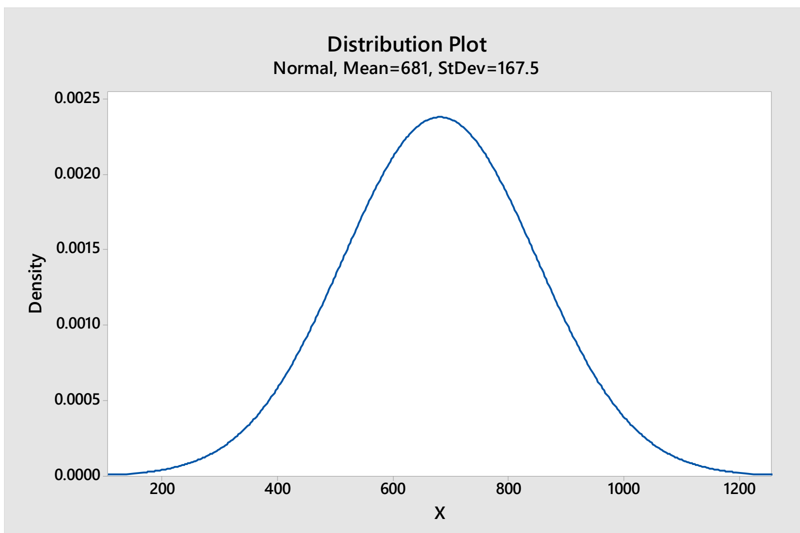

Figure 4.3: Distribution of the strength capabilities.

Data can be also analyzed where a constant ultimate strength is used based on the sex of subjects in the database. The effects of using both analyses will be discussed in more detail in the results section. Assumptions that have been made for this analysis include: Strength capabilities are assumed to be associated with the height of subjects. It has been found that for 3DSSPP at a given posture the subjects weight did show proportional effect on load moments for the body joints and stature was the personal characteristic used to scale the kinematic lengths for the body segments [154]. Another assumption is that the population in 3DSSPP is used to represent the distribution of the height and strength capability and it may be different from the population used in the epidemiology dataset. The joint angles are assumed to be the same for subjects doing the same job.

The number of cycles to failure for right and left shoulders is then obtained using equation 3.7. The reciprocal of the number of cycles to failure will give the DPC; the CD is then equal to the multiplication of the DPC by the repetitions per workday. Both left and right shoulder cumulative damage scores are then calculated, as in equation 3.15. An assumption has been made that the highest value for the cumulative damage between left and right shoulders will be responsible for a higher probability for the development of shoulder MSDs. The daily dose cumulative damage for a job will be the summation of the CD measures for the different tasks comprising a job.

4.2.2 Validation of the Tool

The epidemiology database involved symptoms from a structured interview and historical records for injury data, for all jobs analyzed. Jobs analyzed included up to six separate tasks. Health outcomes used in the validation included pain today, pain last year, records for injury data for neck and shoulder, and subject attribution of job relationship. The FTOV outcome was reported on the job level. A visual analog scale (VAS) was used by subjects to rate their pain for different body parts including the shoulder. Self-reports of discomfort and injury reports were included and self-reported symptoms on day of interview, and retrospectively for the previous year and subject attribution of the job's relationship to pain. Symptoms included in the study were self-reported and they fall into five groups: Category 1: Job-related where symptoms originated on the participant's job; Category 2: Job aggravated, symptoms not originating on job but aggravated by the participant's current job, Category 3: Symptoms not originating on job and no change or improvement in symptoms, Category 4: Symptoms improved on the job, symptoms improving but did not originate on job Category 5: No symptoms present.

Since multiple tasks were performed within the same job, the cumulative damage summation across all tasks was used to produce an overall estimate for the damage for a job a daily dose. For the validation, definitions of cases and controls involved shoulder pain (category 1 only) vs shoulder pain (category 5 only); as well as shoulder pain (categories 1&2) vs shoulder pain (categories 4&5). Outcomes were considered for shoulder pain today and shoulder pain last year and FTOV injury record. To be as a case a VAS>15mm was considered (VAS ranged from 0-100 mm with 0= no pain at all and 100= worst pain imaginable). Once the cumulative damage was obtained, binary logistic regression was used to test model significance and get estimates of the odds ratios associated with the log of the continuous CD.

Binary logistic regression was used to test the model significance and to find odds ratios associated with the log of the CD and the different outcomes. The analysis considered multiple workers performing the same job. Covariates included sex, age, and BMI. Age and BMI and sex were dichotomized, with 1M, 0F for sex, 40 years for age and >=30 for BMI. Regression equations were used to determine the relationship between the log of CD measure and the probability of an outcome (positive case) using the following equation:

$$P(\text{event}) = \exp(Y')/(1 + \exp(Y')) \qquad (4.2)$$

where Y' relationship will be derived from logistic regression

$$Y' = \beta 0 + \beta 1 \times \text{Log CD} \qquad (4.3)$$

Thus, this regression equation can be used to get the probability of a shoulder outcome for each value of CD.

4.3 Results

The personal characteristics effect has been analyzed using two different methods. The first method includes adjustments made on the moment calculations based on the height, weight and sex of subjects. The strength capability for the subjects has been adjusted based on sex. Two strength capability values (averages for left and right shoulders) were used to account for male and female subjects. Strength capability values are employed accordingly for the calculations of the ultimate strength. After the proper calculations are done for DPC, the Shoulder CD measure is then quantified based on the calculations used in chapter 3.

For the second method, the personal characteristics will be used to adjust for the moment calculations based on the height, weight and sex of the subjects. The strength capability will be also adjusted for each subject based on the height and sex. The height and strength capability distributions will be used for that purpose. Similar calculations will be then implemented to quantify the shoulder CD measure. Results for the first method will be displayed first.

4.3.1 Capability Strength Adjusted Based on Sex

4.3.1.1 Current Shoulder Pain (1/2 vs 4/5) Outcome

A significant relationship was found between the CD measure and all shoulder outcomes. When current shoulder pain (1/2 vs 4/5) is used and adjusting for covariates, the logistic regression results showed a significant association with log CD ($p<0.0001$) and sex ($p = 0.001$). Age, however, also showed a trend towards significance at a level of 0.10. The model explained 22.44% of the deviance. The Odds ratio was 4.3978 with a 95% CI of (2.6631, 7.2624). Table 4.1 summarizes the logistic regression results. The binary fitted line plot is shown in Figure 4.4. This figure illustrates how higher values of log CD are highly associated which higher probabilities of a shoulder outcome. The Odds ratios between Quintiles of risk per CD estimates (table 4.2) did show a distinguish power between the quintiles of risk per CD estimates when high and low percentile categories are compared together. Figure 4.5 shows the relationship between percentiles of CD measure and the shoulder outcome, increasing the CD percentile is associated with high probability values.

Table 4.1: Deviance table for the logistic regression (current shoulder pain (1/2 vs 4/5)).

Source	DF	Adj Dev	Adj Mean	Chi-Square	P-Value
Regression	9	59.820	6.6467	59.82	0.000
Log CD	1	45.447	45.4467	45.45	0.000
Site	5	5.150	1.0299	5.15	0.398
Age	1	3.110	3.1098	3.11	0.078
Sex	1	11.099	11.0990	11.10	0.001
BMI	1	0.743	0.7435	0.74	0.389
Error	272	206.772	0.7602		
Total	281	266.592			

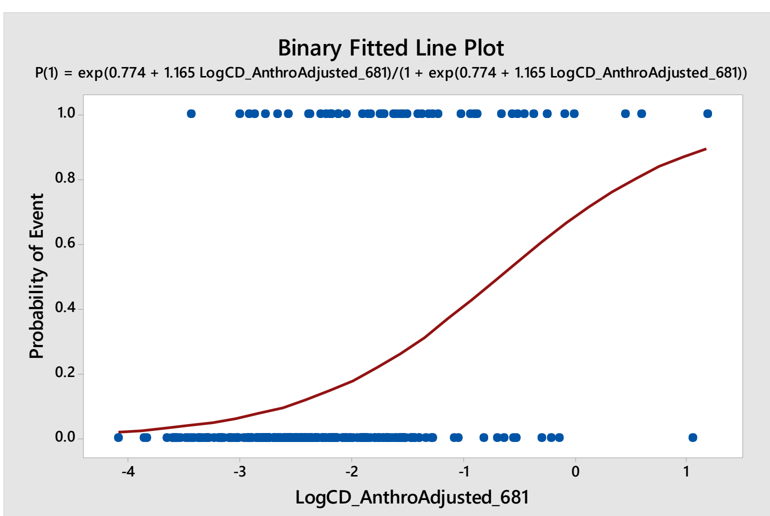

Figure 4.4: Binary fitted line plot (current shoulder pain (1/2 vs 4/5).

Table 4.2: Odds ratios between quintiles of risk per CD estimates, starred values represent risk quintiles that are different from each other.

	40%	60%	80%	100%
20%	0.75 (0.16, 3.51)	1.89 (0.52, 6.87)	4.01 (1.22, 13.18) *	9.64 (3.07, 30.26) *
40%		2.52 (0.62, 10.31)	5.34 (1.43, 19.96) *	12.85 (3.59, 46.05) *
60%			2.12 (0.77, 5.79)	5.09 (1.97, 13.17) *
80%				2.41 (1.07, 5.42) *

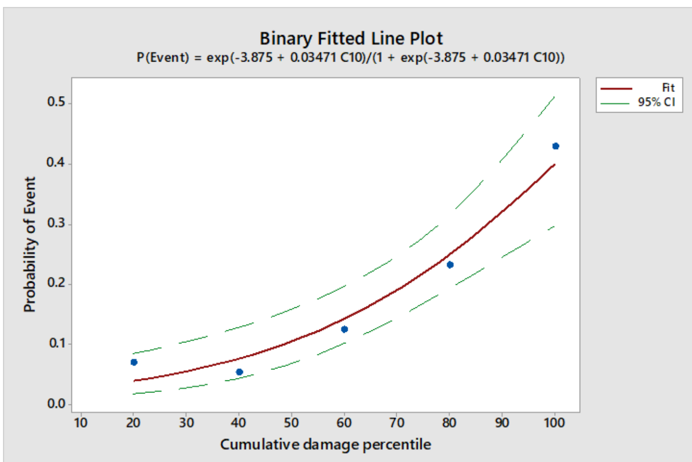

Figure 4.5: Logistic regression results between the shoulder CD measure and current shoulder pain (1/2 vs 4/5).

4.3.1.2 Current Shoulder Pain (1 vs 5) Outcome

For current shoulder pain (1 vs. 5), significant relationships were also found. The logistic regression results are summarized in table 4.3. Significant relationships were found for the Log CD (p<0.0001). Sex also demonstrated a significant relationship (p = 0.019). However, age did show a trend at a significance level of 0.10. The model explained 19.93% of the deviance. The

Odds ratio was 3.5458 with a 95% CI of (2.1095, 5.9602). Figure 4.6 illustrates the binary fitted line plot; higher CD values are associated with a higher probability of a shoulder outcome. A similar pattern for the extreme points can be noted here as well. Table 4.4 shows the ORs for the quintiles of risk per CD measure, significant ORs can be noticed between low and mid quintile categories and the high percentile category. Figure 4.7 represents the logistic regression plot between percentile of CD measure and the probability of a shoulder outcome; higher CD values are associated with higher probability of a shoulder outcome.

Table 4.3: Deviance table for the logistic regression (current shoulder pain (1 vs 5)).

Source	DF	Adj Dev	Adj Mean	Chi-Square	P-Value
Regression	9	45.235	5.0261	45.24	0.000
Log CD	1	28.215	28.2150	28.21	0.000
Site	5	8.598	1.7195	8.60	0.126
Age	1	3.402	3.4020	3.40	0.065
Sex	1	5.519	5.5187	5.52	0.019
BMI	1	0.098	0.0976	0.10	0.755
Error	251	181.735	0.7240		
Total	260	226.971			

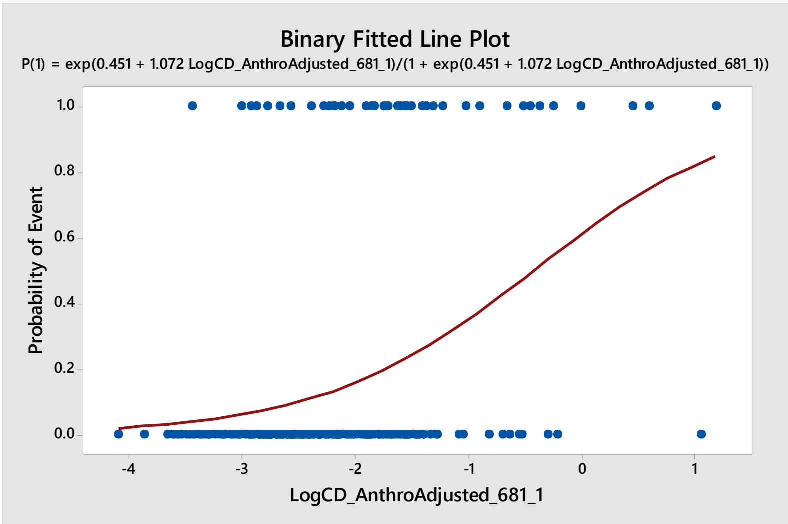

Figure 4.6: Binary fitted line plot (current shoulder pain (1 vs 5)).

Table 4.4: Odds ratios between quintiles of risk per CD estimates, starred values represent risk quintiles that are different from each other.

	40%	60%	80%	100%
20%	0.75 (0.16, 3.53)	1.60 (0.42, 6.03)	2.92 (0.85, 9.98)	6.49 (2.02, 20.86) *
40%		2.13 (0.50, 9.02)	3.89 (1.00, 15.07) *	8.65 (2.36, 31.67) *
60%			1.83 (0.61, 5.46)	4.06 (1.46, 11.31) *
80%				2.22 (0.91, 5.44)

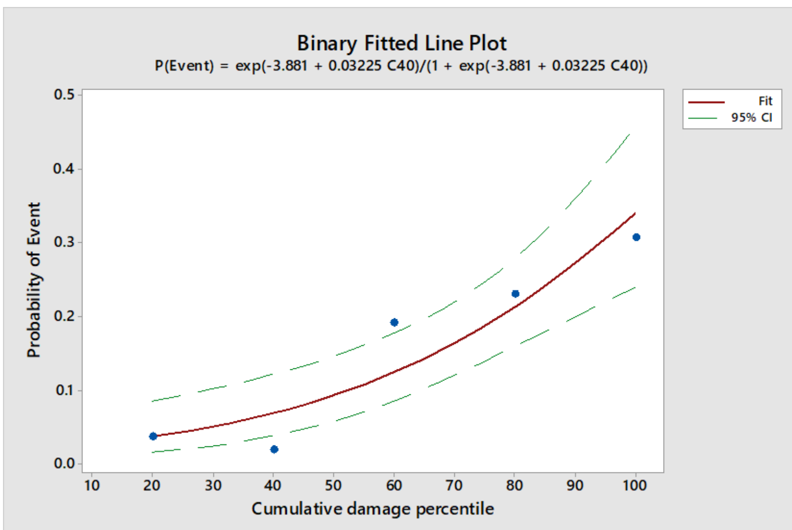

Figure 4.7: Logistic regression results between the shoulder CD measure and current shoulder pain (1 vs 5).

4.3.1.3 Shoulder Pain Last Year Outcome

For the shoulder pain last year, a significant relationship is found between log CD and shoulder pain last year ($p<0.0001$). Table 4.5 summarizes the logistic regression results. Sex demonstrated a significant relationship ($p<0.0001$). However, none of the covariates did show a trend. The model explained 12.59% of the deviance. The odds ratio was 2.4772 with a 95% CI of (1.6864, 3.6387).

The binary fitted line plot is demonstrated in figure 4.8. A change in the curve and a reduction in the maximum predictive value compared to the other shoulder outcomes can be noticed. Table 4.6 summarizes the Odds ratios between Quintiles of risk per CD estimates starred values represent risk quintiles that are different from each other. The logistic regression relationship between percentiles of CD and probability of a shoulder outcome is illustrated in figure 4.9.

Table 4.5: Deviance table for the logistic regression (shoulder pain last year).

Source	DF	Adj Dev	Adj Mean	Chi-Square	P-Value
Regression	9	41.695	4.6328	41.69	0.000
Log CD	1	24.580	24.5796	24.58	0.000
Site	5	4.307	0.8615	4.31	0.506
Age	1	0.854	0.8541	0.85	0.355
Sex	1	13.933	13.9334	13.93	0.000
BMI	1	0.306	0.3064	0.31	0.580
Error	283	289.471	1.0229		
Total	292	331.166			

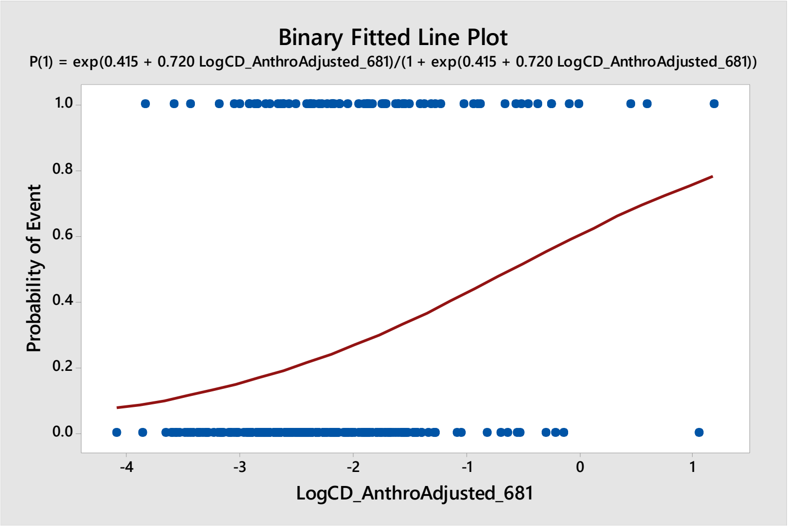

Figure 4.8: Binary fitted line plot (shoulder pain last year).

Table 4.6: Odds ratios between quintiles of risk per CD estimates, starred values represent risk quintiles that are different from each other.

	40%	60%	80%	100%
20%	0.68 (0.25, 1.85)	1.14 (0.46, 2.84)	1.81 (0.76, 4.29)	3.44 (1.49, 7.91) *
40%		1.66 (0.62, 4.43)	2.64 (1.04, 6.74) *	5.02 (2.03, 12.42) *
60%			1.59 (0.68, 3.72)	3.02 (1.33, 6.84) *
80%				1.90 (0.89, 4.08)

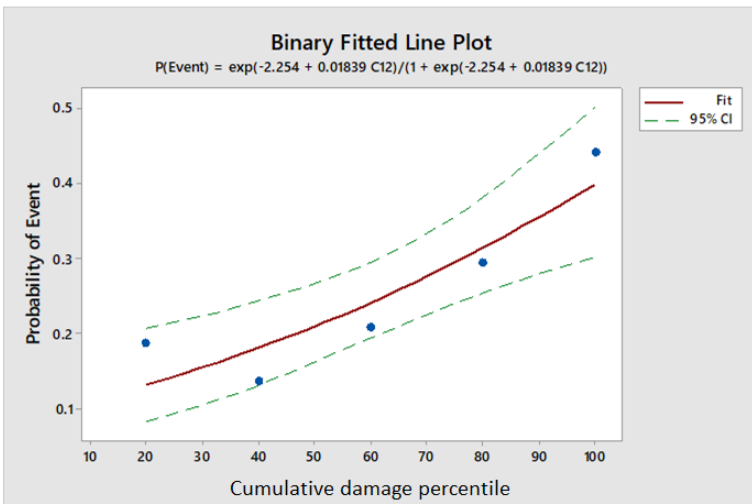

Figure 4.9: Logistic regression results between the shoulder CD measure and shoulder pain last year.

4.3.1.4 First Time Office Visits (FTOV) Outcome

For the FTOV injury record, a significant relationship is found between log CD and shoulder pain last year ($p<0.0001$). Table 4.7 summarizes the logistic regression results. Site demonstrated a significant relationship ($p=0.013$). The model explained 11.38% of the deviance. The odds ratio was 2.2988 with a 95% CI of (1.5936, 3.3161). The binary fitted line plot is demonstrated in figure 4.10. A change in the curve compared to the other shoulder outcomes can be noticed here as well.

Table 4.8 summarizes the Odds ratios between Quintiles of risk per CD estimates; all percentile categories demonstrated significant ORs when they are compared with the 100% percentile category. The logistic regression relationship between percentiles of CD and probability of a shoulder outcome is illustrated in figure 4.11. An increase in a probability of a shoulder outcome can be observed with the increase in the CD value.

Table 4.7: Deviance table for the logistic regression (FTOV injury record).

Source	DF	Adj Dev	Adj Mean	Chi-Square	P-Value
Regression	6	38.17	6.362	38.17	0.000
Log CD	1	22.79	22.789	22.79	0.000
Site	5	14.43	2.886	14.43	0.013
Error	286	297.26	1.039		
Total	292	335.43			

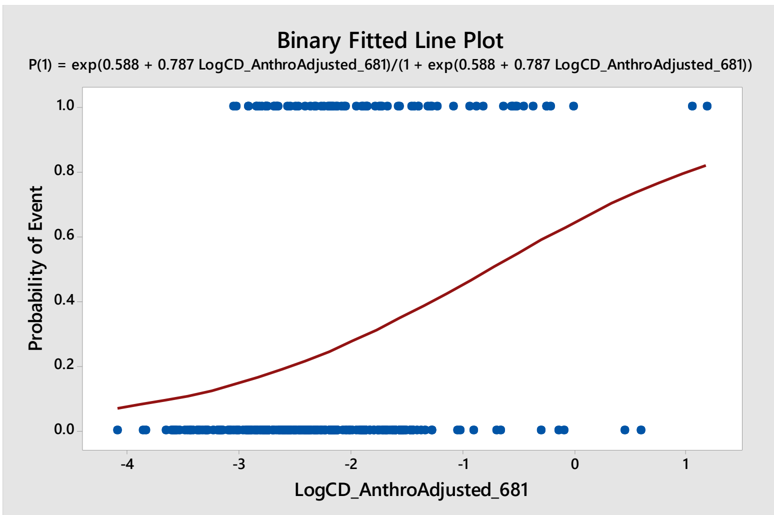

Figure 4.10: Binary fitted line plot (FTOV injury record).

Table 4.8: Odds ratios between quintiles of risk per CD estimates, starred values represent risk quintiles that are different from each other.

	40%	60%	80%	100%
20%	2.10 (0.77, 5.71)	2.36 (0.88, 6.37)	2.59 (0.97, 6.93)	6.27 (2.45, 16.06) *
40%		1.13 (0.48, 2.66)	1.23 (0.53, 2.89)	2.99 (1.34, 6.65) *
60%			1.10 (0.47, 2.54)	2.65 (1.20, 5.84) *
80%				2.42 (1.11, 5.27) *

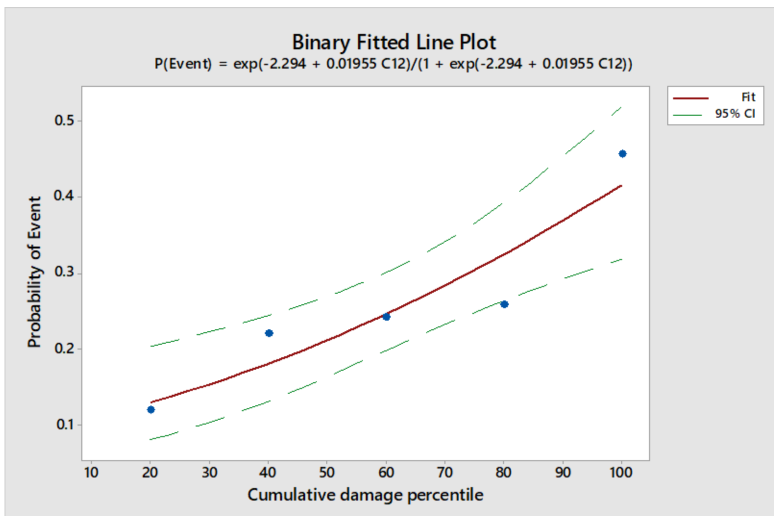

Figure 4.11: Logistic regression results between the shoulder CD measure and FTOV injury record.

4.3.1.5 Shoulder Pain Today Outcome

For the shoulder pain today, significant relationship was also found for log CD (p=0.001), and sex also demonstrated a significant relationship (p<0.0001). However, none of the covariates demonstrated a significant relationship (table 4.9). The model explained 13.20% of the deviance. The odds ratio was 2.0074 with a 95% CI of (1.3265, 3.0377). The binary fitted line plot in figure 4.12, illustrated a reduction in the prediction power, a probability of about 0.5 is the maximum that can be observed from the graph. The fewer number of cases that are reported for this outcome could explain that reduction in the prediction of a probability of an outcome. Significant odds ratios are observed between quintiles of risk per CD estimates between 40% and 100%; 60% and 100% categories. Less significant ORs can be observed when compared to other outcomes (table 4.10). A wider confidence interval also can be observed for the logistic regression plot CD percentile and the probability of a shoulder outcome (figure 4.13). Table 4.11 summarizes the ORs for the different shoulder outcomes. Higher ORs are observed for self-reported symptoms for current shoulder pain.

Table 4.9: Deviance table for the logistic regression (shoulder pain today).

Source	DF	Adj Dev	Adj Mean	Chi-Square	P-Value
Regression	9	33.619	3.7355	33.62	0.000
Log CD	1	11.189	11.1890	11.19	0.001
Site	5	6.237	1.2475	6.24	0.284
Age	1	0.112	0.1120	0.11	0.738
Sex	1	12.697	12.6971	12.70	0.000
BMI	1	1.031	1.0307	1.03	0.310
Error	283	221.089	0.7812		
Total	292	254.708			

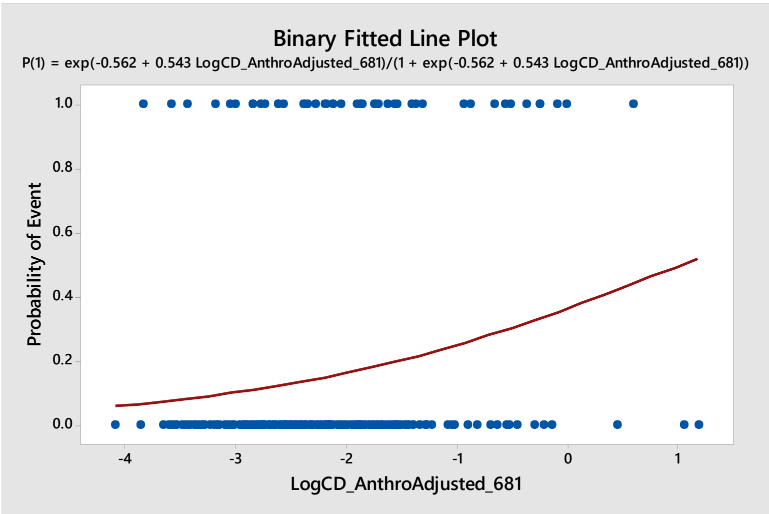

Figure 4.12: Binary fitted line plot (shoulder pain today).

Table 4.10: Odds ratios between quintiles of risk per CD estimates, starred values represent risk quintiles that are different from each other.

	40%	60%	80%	100%
20%	0.59 (0.18, 1.92)	0.74 (0.24, 2.27)	1.49 (0.55, 4.03)	2.37 (0.93, 6.08)
40%		1.25 (0.36, 4.33)	2.53 (0.82, 7.80)	4.02 (1.36, 11.85) *
60%			2.03 (0.70, 5.91)	3.22 (1.16, 8.96) *
80%				1.59 (0.66, 3.80)

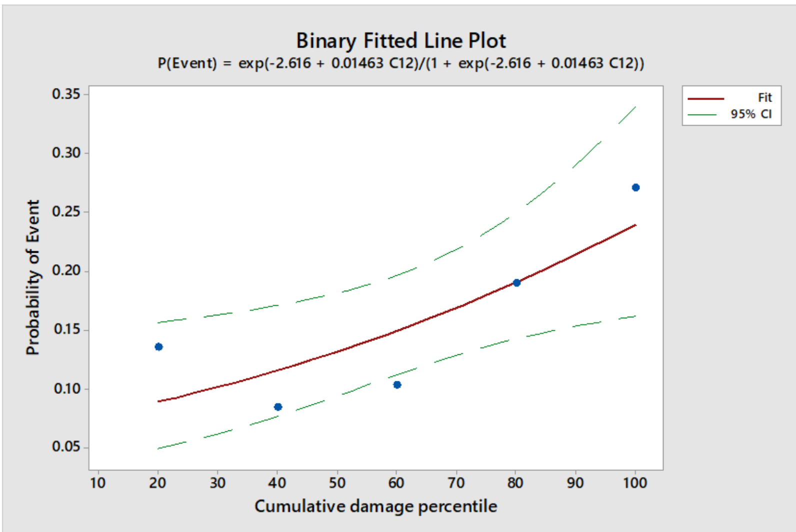

Figure 4. 13: Logistic regression results between the shoulder CD measure and shoulder pain today.

Table 4. 11: Summary of the crude and adjusted ORs for the different shoulder outcomes, N=total number, Var=various, df=degrees of freedom.

Outcome	**Analysis**	**Cases**	***N***	**Variable**	***df***	x^2	***p***	**OR**	**95% CI**
Pain today	Crude	46	293	Log CD	1	8.94	0.003	1.7208	(1.208, 2.451)
	Adjusted			Log CD	1	11.19	0.001	2.0074	(1.327, 3.038)
				Age	1	0.11	0.738	0.8745	(0.398, 1.923
				Sex	1	12.70	0.000	0.2598	(0.123, 0.549)
				BMI	1	1.03	0.310	0.6354	(0.259, 1.558)
				Site	5	6.24	0.284	Var	Var
Pain last year	Crude	74	293	Log CD	1	20.03	<0.001	2.0545	(1.478, 2.856)
	Adjusted			Log CD	1	24.58	<0.001	2.477	(1.686, 3.639)
				Age	1	0.85	0.355	1.3669	(0.705, 2.652)
				Sex	1	13.93	<0.001	0.2938	(0.154, 0.562)
				BMI	1	0.31	0.580	0.8165	(0.396, 1.682)
				Site	5	4.31	0.506	Var	Var
FTOV	Crude	76	293	Log CD	1	23.74	<0.001	2.1957	(1.571, 3.069)
	Adjusted			Log CD	1	22.79	<0.001	2.2988	(1.594, 3.316)
				Site	5	14.43	0.013	Var	Var
1&2 VS 4&5	Crude	51	282	Log CD	1	39.17	<0.001	3.2053	(2.135, 4.813)
	Adjusted			Log CD	1	45.45	<0.001	4.3978	(2.663, 7.262)
				Age	1	3.11	0.078	2.0506	(0.920, 4.570)
				Sex	1	11.10	0.001	0.2554	(0.114, 0.573)
				BMI	1	0.74	0.389	0.6836	(0.284, 1.645)
				Site	5	5.15	0.398	Var	Var
1VS 5	Crude	41	261	Log CD	1	27.99	<0.001	2.9201	(1.896, 4.498)
	Adjusted			Log CD	1	28.21	<0.001	3.5458	(2.110, 5.960)
				Age	1	3.40	0.065	2.2139	(0.942, 5.180)
				Sex	1	5.52	0.019	0.3544	(0.150, 0.837)
				BMI	1	0.10	0.755	1.1554	(0.469, 2.847)
				Site	5	8.60	0.126	Var	Var

4.3.2 Strength Capability Adjusted Based on Sex and Height

4.3.2.1 Current Shoulder Pain (1/2 vs 4/5) Outcome

For the second method of incorporating the effect of personal characteristics for both the moments (Sex, weight, height) and strength capability (Sex, height), significant relationships have been also found. For current shoulder pain (1&2 vs 4&5), a significant relationship was found for log CD ($p<0.0001$). None of the covariates demonstrated a significant relationship (table 4.12). The model explained 18.62% of the deviance. The odds ratio was 3.3576 with a 95% CI of (2.1455, 5.2546). Figure 4.14 illustrates the binary fitted line plot. Data points on the plot seems to be scattered compared to the first method of analysis, this can be explained by the differences in the strength capabilities between male and female subjects which can lead to higher CD estimates for female subjects. Many significant ORs can be observed between quintiles of risk per CD estimates (table 4.13). Figure 4.15 demonstrates the logistic regression relationship between CD percentile and the probability of a shoulder outcome; higher CD percentiles are associated with a higher probability of a shoulder outcome.

Table 4.12: Deviance table for the logistic regression (current shoulder pain 1&2 vs 4&5).

Source	DF	Adj Dev	Adj Mean	Chi-Square	P-Value
Regression	9	49.627	5.5142	49.63	0.000
Log CD	1	35.254	35.2538	35.25	0.000
Site	5	6.867	1.3733	6.87	0.231
Age	1	1.954	1.9537	1.95	0.162
Sex	1	0.658	0.6585	0.66	0.417
BMI	1	1.102	1.1022	1.10	0.294
Error	272	216.965	0.7977		
Total	281	266.592			

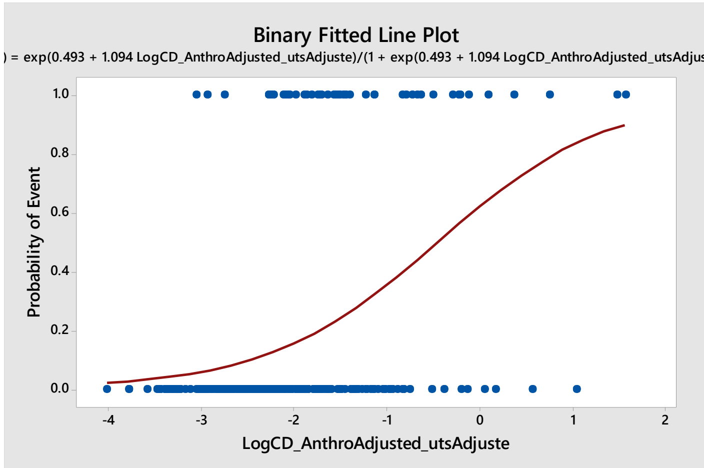

Figure 4.14: Binary fitted line plot (current shoulder pain 1&2 vs 4&5).

Table 4.13: Odds ratios between quintiles of risk per CD estimates, starred values represent risk quintiles that are different from each other.

	40%	60%	80%	100%
20%	0.50 (0.04, 5.68)	6.72 (1.42, 31.90) *	9.17 (1.97, 42.55) *	18.60 (4.12, 83.95) *
40%		13.44 (1.67, 108.12) *	18.33 (2.32, 145.02) *	37.21 (4.80, 288.22) *
60%			1.36 (0.56, 3.34)	2.77 (1.19, 6.44) *
80%				2.03 (0.91, 4.53)

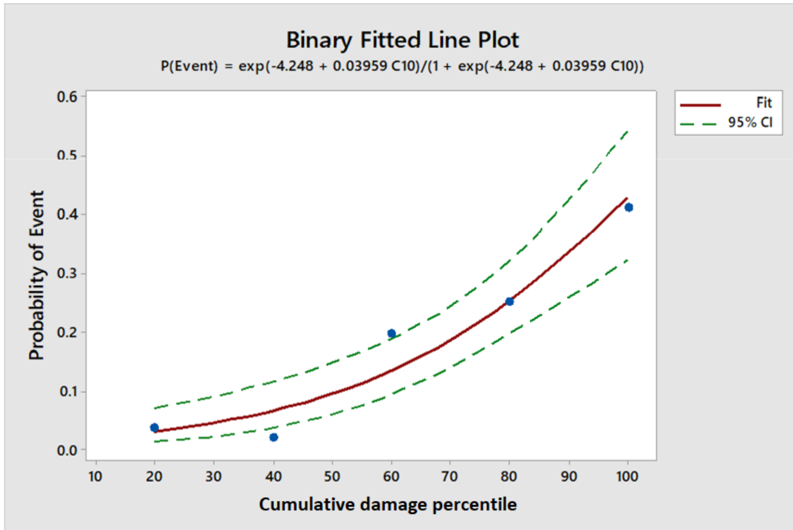

Figure 4.15: Logistic regression results between the shoulder CD measure and current shoulder pain (1&2 vs 4&5).

4.3.2.2 Current Shoulder Pain (1 vs 5) Outcome

For current shoulder pain (1 vs 5), a significant relationship was found for log CD ($p<0.0001$). None of the covariates demonstrated a significant relationship, however site did show a trend towards a significance level of 0.01 (table 4.14). The model explained 15.99% of the deviance. The odds ratio was 2.7705 with a 95% CI of (1.7060, 4.4994). Figure 4.16 illustrates the binary fitted line plot. Data points on the plot also seem to be scattered. Too many significant ORs can be observed between quintiles of risk per CD estimates (table 4.15). Figure 4.17 demonstrates the logistic regression relationship between CD percentile and the probability of a shoulder outcome.

Table 4.14: Deviance table for the logistic regression (current shoulder pain 1 vs 5).

Source	DF	Adj Dev	Adj Mean	Chi-Square	P-Value
Regression	9	36.282	4.0313	36.28	0.000
Log CD_	1	19.262	19.2619	19.26	0.000
Site_	5	9.325	1.8651	9.33	0.097
Age_	1	2.315	2.3150	2.32	0.128
Sex	1	0.782	0.7819	0.78	0.377
BMI_	1	0.001	0.0014	0.00	0.970
Error	251	190.689	0.7597		
Total	260	226.971			

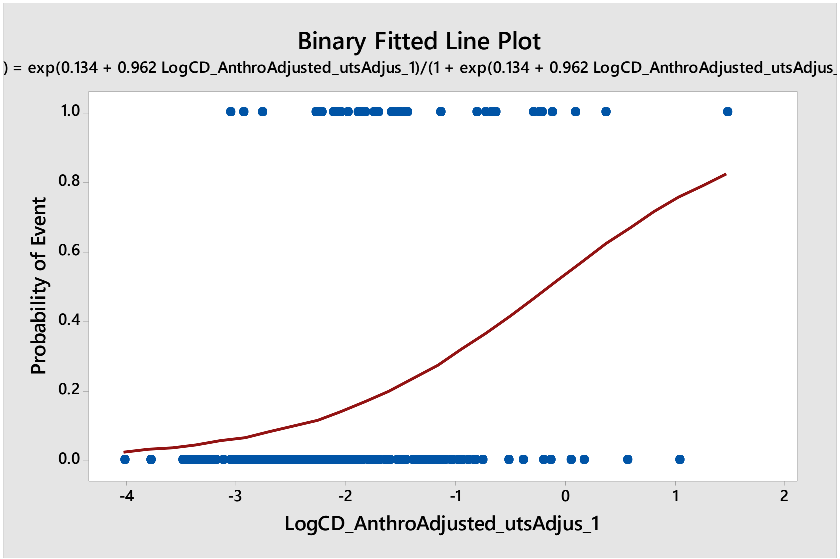

Figure 4.16: Binary fitted line plot (current shoulder pain 1vs 5).

Table 4.15: Odds ratios between quintiles of risk per CD estimates, starred values represent risk quintiles that are different from each other.

	40%	60%	80%	100%
20%	0.50 (0.043, 5.69)	6.07 (1.26, 29.25) *	7.65 (1.62, 36.16) *	11.33 (2.45, 52.37) *
40%		12.14 (1.49, 98.75) *	15.30 (1.91, 122.66) *	22.67 (2.88, 178.71) *
60%			1.26 (0.49, 3.24)	1.87 (0.75, 4.62)
80%				1.48 (0.62, 3.55)

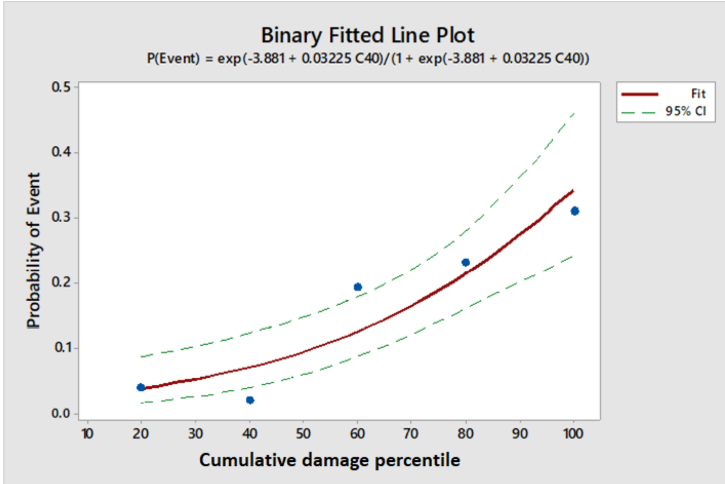

Figure 4.17: Logistic regression results between the shoulder CD measure and current shoulder pain (1 vs 5).

4.3.2.3 Shoulder Pain Last Year Outcome

For shoulder pain last year, a significant relationship was found, and log CD was significant ($p<0.0001$). None of the covariates did show a trend (table 4.16). The model explained 11.96% of the deviance. The odds ratio was 2.3036 with a 95% CI of (1.5917, 3.3341). Figure 4.18 illustrates the binary fitted line plot. A wider range of probability can be seen in this plot when compared to the self-reported outcomes. Significant ORs can be observed between quintiles of risk per CD estimates (table 4.17). Figure 4.19 demonstrates the logistic regression relationship between CD percentile and the probability of a shoulder outcome.

Table 4.16: Deviance table for the logistic regression (shoulder pain last year).

Source	DF	Adj Dev	Adj Mean	Chi-Square	P-Value
Regression	9	39.620	4.4023	39.62	0.000
Log CD	1	22.505	22.5050	22.50	0.000
Site	5	4.757	0.9513	4.76	0.446
Age	1	0.463	0.4625	0.46	0.496
Sex	1	0.447	0.4466	0.45	0.504
BMI	1	0.512	0.5120	0.51	0.474
Error	283	291.546	1.0302		
Total	292	331.166			

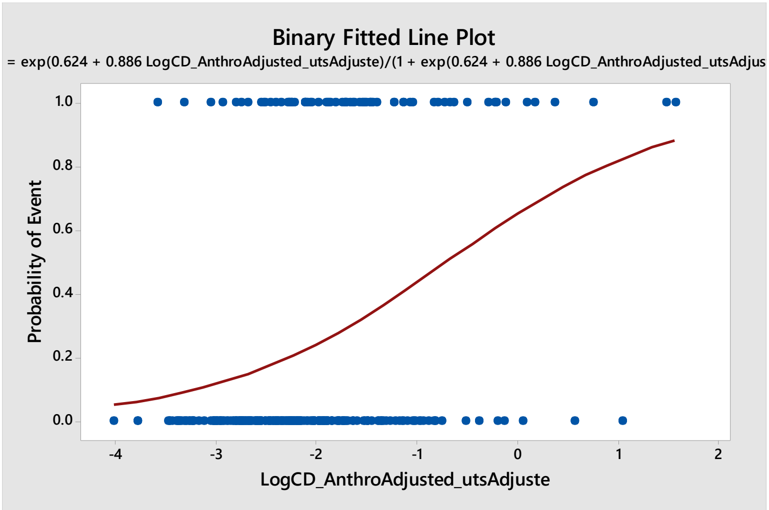

Figure 4.18: Binary fitted line plot (shoulder pain last year).

Table 4.17: Odds ratios between quintiles of risk per CD estimates, starred values represent risk quintiles that are different from each other.

	40%	60%	80%	100%
20%	1.69 (0.52, 5.52)	3.77 (1.27, 11.19) *	5.26 (1.81, 15.31) *	9.11 (3.19, 26.03) *
40%		2.22 (0.86, 5.75)	3.11 (1.23, 7.83) *	5.38 (2.1774, 13.29) *
60%			1.40 (0.63, 3.12)	2.42 (1.11, 5.27) *
80%				1.73 (0.82, 3.67)

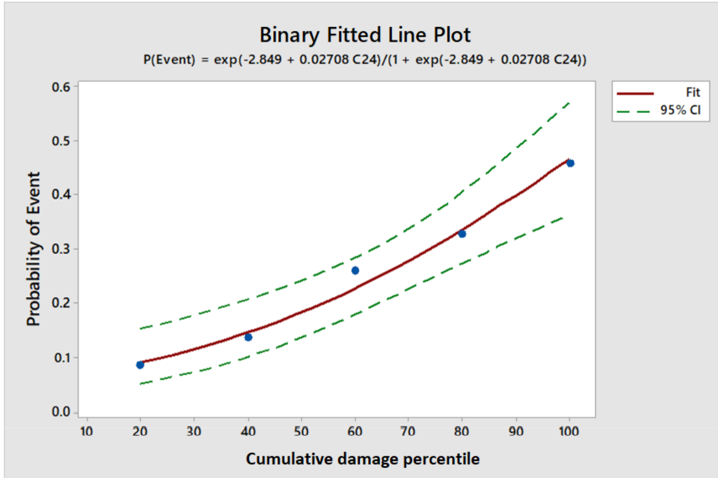

Figure 4.19: Logistic regression results between the shoulder CD measure and shoulder pain last year.

4.3.2.4 First Time Office Visits (FTOV) Outcome

For the FTOV injury record, the model and the CD were significant ($p<0.0001$). Site demonstrated a significant relationship ($p=0.015$) (table 4.18). The model explained 7.70% of the deviance. The odds ratio was 1.6658 with a 95% CI of (1.2171, 2.2800). For the binary fitted line plot, the data points are scattered, and the maximum of the prediction probability is around 75% (figure 4.20). Logistic regression results between the shoulder CD measure and FTOV injury record are displayed in figure 4.21, wide CI can be observed, and 40% and 80% percentiles seem to have about the same probability of a shoulder outcome. The ORs that are observed between quintiles of risk per CD estimates for FTOV outcome are shown in table 4.19.

Table 4. 18: Deviance table for the logistic regression (FTOV injury record).

Source	DF	Adj Dev	Adj Mean	Chi-Square	P-Value
Regression	6	25.82	4.303	25.82	0.000
Log CD	1	10.44	10.436	10.44	0.001
Site	5	14.06	2.813	14.06	0.015
Error	286	309.62	1.083		
Total	292	335.43			

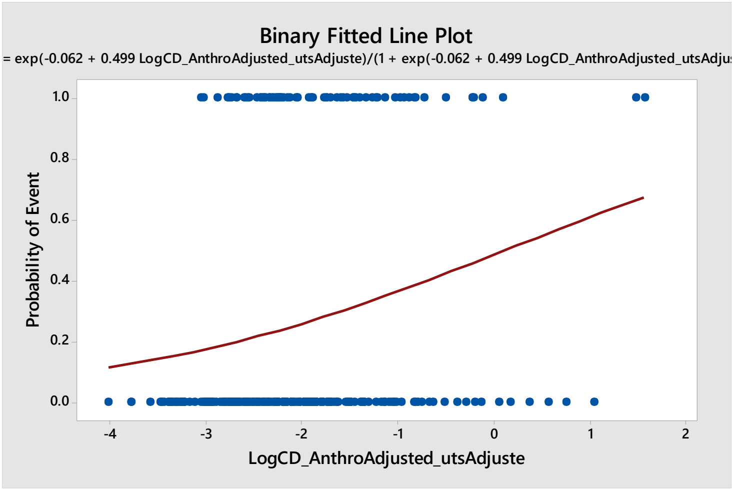

Figure 4. 20: Binary fitted line plot (FTOV injury record).

Table 4. 19: Odds ratios between Quintiles of risk per CD estimates, starred values represent risk quintiles that are different from each other.

	40%	60%	80%	100%
20%	2.75 (0.98,7.74)	4.30 (1.57,11.78) *	2.55 (0.90,7.26)	6.06 (2.25,16.32) *
40%		1.57 (0.70, 3.53)	0.93 (0.39,2.20)	2.20 (0.99, 4.87)
60%			0.59 (0.26, 1.35)	1.41 (0.66, 2.99)
80%				2.37 (1.06, 5.32) *

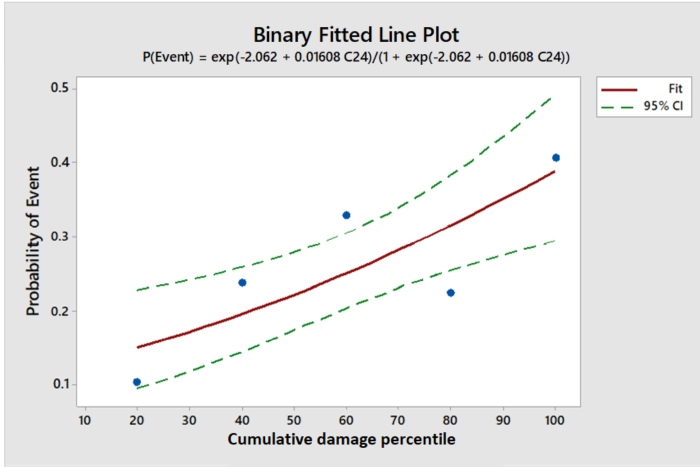

Figure 4.21: Logistic regression results between the shoulder CD measure and FTOV injury record.

4.3.2.5 Shoulder Pain Today Outcome

For the shoulder pain today, the model is significant and none of the covariates did show a trend, however, sex did show a trend towards a significance level of 0.10 (table 4.20). The model explained 11.30% of the deviance. The odds ratio was 1.6319 with a 95% CI of (1.1108, 2.3976). The binary fitted line plot is illustrated in figure 4.22, the maximum probability that can be observed from the plot is around 70%, so the predictive capability is decreased. Table 4.21 summarizes the Odds ratios between quintiles of risk per CD estimates. Figure 4.23 show the logistic regression results between the shoulder CD measure and shoulder pain today a good fit line can be observed from the plot. Table 4.22 summarizes the ORs for the different shoulder outcomes. Higher ORs are observed for the self-reported symptoms for current shoulder pain.

Table 4.20: Deviance table for the logistic regression (shoulder pain today).

Source	DF	Adj Dev	Adj Mean	Chi-Square	P-Value
Regression	9	28.777	3.1975	28.78	0.001
Log CD	1	6.347	6.3468	6.35	0.012
Site	5	7.381	1.4762	7.38	0.194
Age	1	0.276	0.2756	0.28	0.600
Sex	1	2.854	2.8542	2.85	0.091
BMI	1	1.137	1.1366	1.14	0.286
Error	283	225.931	0.7983		
Total	292	254.708			

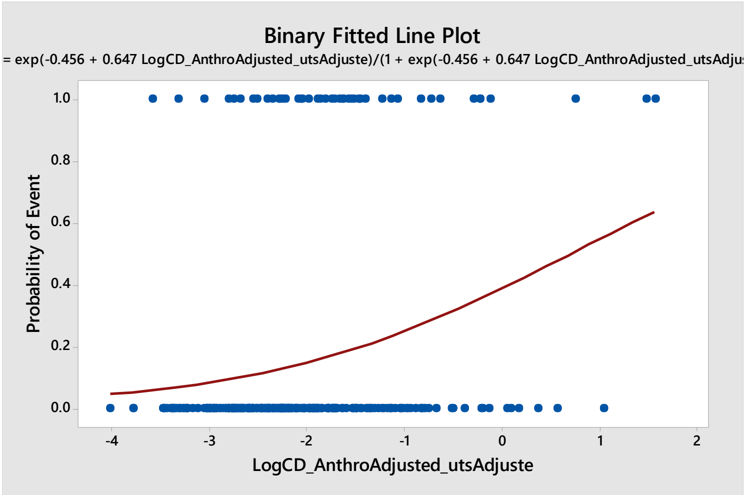

Figure 4.22: Binary fitted line plot (shoulder pain today).

Table 4.21: Odds ratios between quintiles of risk per CD estimates, starred values represent risk quintiles that are different from each other.

	40%	60%	80%	100%
20%	1.56 (0.42, 5.83)	2.20 (0.62, 7.75)	3.59 (1.08, 11.88) *	5.12 (1.59, 16.42) *
40%		1.41 (0.46, 4.36)	2.30 (0.80, 6.63)	3.29 (1.18, 9.12) *
60%			1.63 (0.61, 4.34)	2.33 (0.91, 5.96)
80%				1.43 (0.61, 3.36)

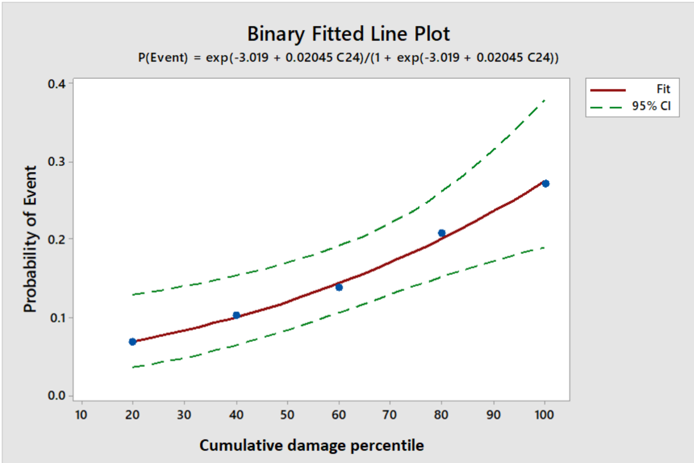

Figure 4.23: Logistic regression results between the shoulder CD measure and shoulder pain today.

Table 4.22: Summary of the crude and adjusted ORs for the different shoulder outcomes, N=total number, Var=various, df=degrees of freedom.

Outcome	**Analysis**	**Cases**	***N***	**Variable**	***df***	x^2	***p***	**OR**	**95% CI**
Pain today	Crude	46	293	Log CD	1	14.95	<0.001	1.9104	(1.372, 2.661)
	Adjusted			Log CD	1	6.35	0.012	1.6319	(1.111, 2.398)
				Age	1	0.28	0.600	0.8141	(0.376, 1.761)
				Sex	1	2.85	0.091	0.5232	(0.248, 1.103)
				BMI	1	1.14	0.286	0.6204	(0.252, 1.529)
				Site	5	7.38	0.194	Var	Var
Pain last year	Crude	74	293	Log CD	1	33.19	<0.001	2.4250	(1.746, 3.368)
	Adjusted			Log CD	1	22.50	<0.001	2.3036	(1.592, 3.334)
				Age	1	0.46	0.496	1.2543	(0.653, 2.409)
				Sex	1	0.45	0.504	0.7973	(0.412, 1.544)
				BMI	1	0.51	0.474	0.7676	(0.369, 1.596)
				Site	5	4.76	0.446	Var	Var
FTOV	Crude	76	293	Log CD	1	11.75	0.001	1.6468	(1.232, 2.201)
	Adjusted			Log CD	1	10.44	<0.001	1.6658	(1.217, 2.280)
				Site	5	14.06	0.015	Var	Var
1&2 VS 4&5	Crude	51	282	Log CD	1	40.61	<0.001	2.9868	(2.051, 4.351)
	Adjusted			Log CD	1	35.25	<0.001	3.3576	(2.146, 5.255)
				Age	1	1.95	0.162	1.7206	(0.804, 3.685)
				Sex	1	0.66	0.417	1.3977	(0.616, 3.170)
				BMI	1	1.10	0.294	0.6328	(0.264, 1.515)
				Site	5	6.87	0.231	Var	Var
1VS 5	Crude	41	261	Log CD	1	25.95	<0.001	2.6168	(1.767, 3.876)
	Adjusted			Log CD	1	19.26	<0.001	2.7705	(1.706, 4.499)
				Age	1	2.32	0.128	1.871	(0.833, 4.204)
				Sex	1	0.78	0.377	1.4916	(0.606, 3.671)
				BMI	1	0.00	0.970	0.9832	(0.401, 2.412)
				Site	5	9.33	0.097	Var	Var

4.4 Discussion

The analysis revealed that when the effect of personal characteristics is introduced into the model, strong associations between the CD and the shoulder MSD outcomes can be observed, which may help explain the etiology of these disorders. The dose-response associations were observed for the pain prevalence, the ORs were higher for the self-reported symptoms. For the binary fitted line plots, we can notice that higher values of log CD are associated with an increase in probability of a shoulder outcome. Some of the plots also show few extreme data points where a subject reported a shoulder outcome and one did not. Difference among individuals and their perception of pain might be the reason behind that. Also, the subject reporting an outcome does not need to be the one filmed doing the job. When adjustments for the personal characteristics are used for the moment calculations and sex is used to adjust for the ultimate strength, higher ORs can be observed. Whereas, adjusting for the moments and adjusting the ultimate strength for each subject yielded lower ORs. This can be explained by the differences among male and female subjects in terms of strength capabilities and introducing more variability in the CD estimates for female subjects. The predictive range for some of the shoulder outcomes such as FTOV decreased for the method of doing ultimate strength adjustments for each subject too.

Changes between the two analysis methods can be explained by the differences in the strength capabilities between male and female subjects which in turn will move the female subjects to the higher end of the CD because of their low strength capability compared to male subjects. This can be observed from the binary fitted line plots where too many data points can be seen at the higher end of the CD estimates. This pattern (more variability) can be observed to be dominant in the second method of analysis compared to the first one. Thus, introducing the effects of height and weight for female subjects increased the impact of the female subjects moving to higher end of CD estimates. For the covariates used in the analysis, sex demonstrated significant relationships for most of the shoulder outcomes, which can be explained by the methods used in the analysis to use sex to adjust for the moment and ultimate strength calculations. Site demonstrated significant relationships when the FTOV injury record is used in the analysis; this is affected by the differences in the policies among sites in reporting an injury record. Fewer numbers of reported cases (shoulder pain today) for jobs with high CD can be observed for shoulder pain today outcome in both methods of analysis. Differences in workers perception and reporting of a shoulder pain today can affect those cases. Self-reported symptoms demonstrated higher ORs when compared to other shoulder outcomes. Most of the workers reported either a “1” or “5” for that outcome and those values were used to define a case or non-case and demonstrated good results of association with the log CD estimate.

The strong associations between the CD and all shoulder outcomes support the notion that fatigue failure theory may be important in the etiology of MSDs. The current results indicate that application of the fatigue failure method also works extremely well in assessing the probability of association with shoulder outcomes. Although the personal characteristics introduced some variability in the CD estimates, strong associations can still be observed.

This study’s aim was to investigate the effect of the personal characteristics on the shoulder risk assessment tool based on the fatigue failure theory. In the current tool, dose-response relationships were observed between the CD and pain prevalence. The tool will provide a CD measure and an estimated outcome probability can be obtained for any given value. The CD can be easily summed for multiple tasks to get a daily dose of exposure, and the contribution of the various tasks will be easily estimated. The proposed tool investigated the impact of the personal characteristics, higher variability can be observed in estimates of the CD compared to the proposed model in chapter 3. Sex differences in the strength capability can explain the higher variability. Study limitations include the fact that only awkward postures were included in the analysis and other risk factors such as, speed of work and duty/rest cycles were not considered in the analysis. Personal habits, hobbies and previous injuries are not included in the analysis and could impact the investigated Shoulder outcomes. The ultimate strength was assumed to be associated with the height of the subjects and the population in 3DSSPP may not be representative of the subjects in the epidemiology dataset. An 8-hour shift is also included in the analysis, but shifts varied. Interaction with the ergonomics team might also impact the speed at which the workers are performing their tasks.

Chapter 5: Effect of Subjective Shoulder Strength Assessment on the Proposed Shoulder Risk Assessment Tool

5.1 Subjective Rating Scales

Individual, physical, and psychosocial risk categories are the leading causes for the development of MSDs. Risk factors within each category can be used to estimate their impact on MSDS development. Subjective ergonomic risk assessment tools are widely used to assess work-related risk factors. Some of the subjective assessments (e.g. posture, force) are made by direct observation or self-reporting. Most of the subjective assessment tools follow a straight-forward analysis process to compute a hazard score, which is used to provide guidance to improve the working conditions to prevent MSDs risk [155].

Subjective ratings have been extensively used to quantify the perception for an individual's physical demand of an activity [156]. Those subjective ratings are referred to as ratings of perceived exertion (RPE); examples include Likert, VAS, Borg, and OMNI [157]. Studies of steady state exercises have suggested that the subjective rating scales can be used to reproducibly measure pain and fatigue symptoms [158]. Perceived exertion helps to understand how the individuals can detect and respond to the physiological adaptations as a result of a physical demand [159]. Variable ratings in perceived exertions are based on the psychological notion of perceived exertion. Relating the physical demand with its correct corresponding perceived magnitude initiates the need for valid, reliable methods [160]. Borg scale is the most widely used RPE scale, it is considered as a psychophysical scale with different levels where those levels assume that the subjective range can be set nearly equal for all persons, where verbally anchored scales are available to give responses on ratio level data or an interval [160]. The subjective range is set to range from minimal to maximal exertions/intensity levels. Borg scales include the 6-20 original Borg RPE scale, the 0-10 category scale with ratio characteristics CR10 scale, and the fine graded CR100 scale or the centiMax scale which is followed by the CR10 scale (Figure 5.1). According to Borg a power function can describe the relationship between the physical intensity and the response intensity (equation 5.1):

$$R = a + c(S - b)^n \tag{5.1}$$

where *R* is the perceived magnitude, *S* is the physical stimulus, and *c* is a measure constant, a and b are the absolute thresholds. If the logarithmic transformation is implemented this relationship will be summarized by a linear relationship. The linear relationship has been constructed for the relationship between the RPE scale and the stimulus intensity, oxygen consumption and heart rate. This has been done for aerobic work on an ergometer bicycle for 4-6 minutes. The linear regression model can be described as:

$$R = a + cS \tag{5.2}$$

Where *R* is the perceived magnitude, *S* is the physical stimulus, and *c* is a measure constant [160]. Verbal anchors are placed congruently with the numbers for both the CR10 and CR100 scales.

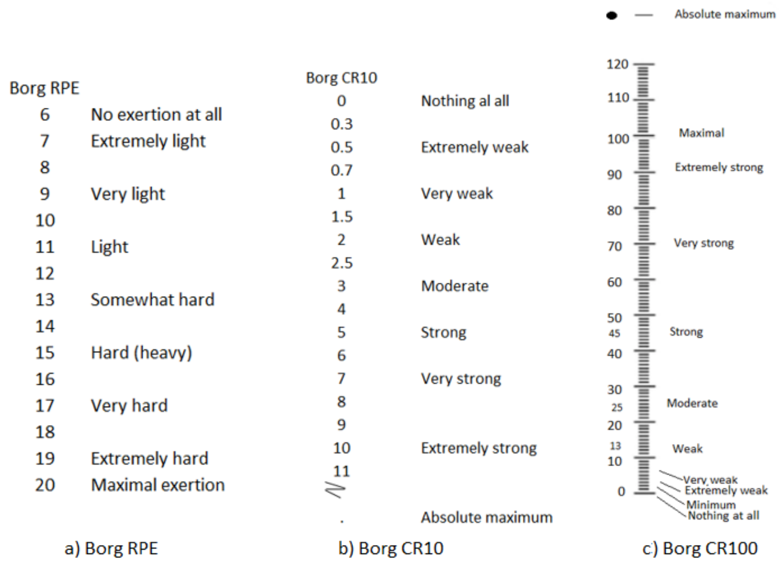

Figure 5.1: Borg RPE scales, a) Borg RPE original scale, b) Borg CR10 scale, c) Borg centiMAX CR100 scale [160].

The OMNI perceived exertion scale is another scale to rate the perceived exertions, the scale has been validated initially for use in children performing cycle ergometry and treadmill exercise (walking/running). The OMNI scale is 0 to 10 scale (Figure 5.2) and it has some pictorial formats such as walking/running, body resistance exercise for both the upper and lower body. The pictorial descriptor is congruently placed with the verbal anchors. [161] The OMNI resistance exercise scale OMNI RES has been established by measuring the RPE for eccentric and concentric resistance exercise. Separate upper and lower body resistance exercises performed by both male and female subjects were used.

0	Very easy
1	
2	Easy
3	
4	Somewhat easy
5	
6	Somewhat hard
7	
8	Hard
9	
10	Very Hard

Figure 5.2: OMNI-RES scale [161].

Criterion related validity, where a measure related to an outcome, has been used to describe how the RPE scales correlate with numerus physiological measures such as: blood lactate concentration, ventilatory drive, creatine, and heart rate. The Borg scale has been validated in exercise exertions against some physiological measures which include lactate concentration in blood and muscles, percent of maximum oxygen uptake, $\%\dot{V}O_{2max}$; and heart rate. [162] In submaximal exercises, the blood lactate concentration has been found to be correlated with the RPE. For the CR10 scale, the glycogenolytic metabolism resulting in lactate concentration was found to correspond well with the CR10 RPE. For the heart rate, the associations are highly variable. The heart rate was the physiological measure initially used by Borg to validate the original Borg RPE scale; the correlation was about 0.85 between the two. However, subsequent studies yielded different correlation coefficients [163]. For the maximum oxygen uptake, studies have shown that it has the highest correlation coefficient but under certain conditions such as swimming or subjects maximally exerting themselves [162]. Inconsistencies have been also found for the correlation among the Borg RPE and the various physiological measures such as heart rate [162]. For steady state type exercises, as the loads increase the incremental curve for perceived exertion also increases and this relationship can be depicted by a combination of the blood lactate concentration and the heart rate [164]. The three Borg scales have been compared for a bicycle ergometer exercise where a stepwise increase on the workload is implemented and the heart rate and blood lactate concentrations and the ratings of exertion were recorded and compared among the Borg RPE, Borg CR10 and CR100 centiMax scales. A linear regression was used to describe the data obtained with the Borg RPE with individual correlations of about 0.98. For the CR10, data obtained with the scale could be described with a linear regression and if a power function is used it gave an exponent of 1.2. Mean individual correlations were around 0.98. For the CR100 centiMax scale, data obtained could be described by a power function with mean exponents of 1.4. A deviation from linearity was observed between the heart rate and the RPE values [160].

The OMNI scale has been also validated, the RPE-OMNI was validated by correlating the scale with physiological responses such as: maximal oxygen uptake ($\%\dot{V}O_{2max}$), ventilation ($\dot{V}_E$), respiratory rate (RR), respiratory exchange ratio (RER), oxygen uptake ($\dot{V}O_2$)and heart rate. A validity test was implemented with all the previously mentioned physiological measures and the RPE-OMNI for the walking/running exercise on a treadmill with stepwise increases on the workload. The measurements were made every minute and results indicated that a positive linear function is found between all physiological measures and the RPE-OMNI ratings with a correlation coefficient ranging from 0.67-0.88 (P<0.05). No sex effect was observed for any of the correlations. A positive correlation was also found between the RPE-OMNI and the Borg-RPE scales with a correlation coefficient of 0.96 (P<0.01) [161]. For the OMNI-RES scale, a validation was employed for upper and lower body resistance exercises performing Knee extension and Bicep curls. The weight lifted and the blood lactate concentrations were used as criterion variables. Active muscle and overall body ratings were recorded. Positive linear regressions were found between the active muscle and overall body ratings with the weight lifted with correlation coefficients in the range 0.79-0.91 (P<0.01). The blood lactate concentration was positively correlated with the active muscle ratings in the bicep curls, with a correlation coefficient of 0.87 (P<0.01). No sex differences were found [165].

Studies also investigated the reliability and validity for different ratings of perceived exertion scales. In the study implemented by Pfeiffer et al., [166] both Borg RPE and RPE-OMNI were used in submaximal treadmill exercise conditions and the heart rate and $\%\dot{V}O_{2max}$ were measured continuously for 57 adolescent girls. ANOVA and single trial measures were used to assess the reliability of the scales. Pearson product moment correlations with $\%\dot{V}O_{2max}$ and $\%HR_{max}$ were used to test the validity of the scales. The reliability results indicated that the intraclass and single trial measures were higher for the RPE-OMNI when compared to the Borg RPE. Validity was also found to be higher for the RPE-OMNI.

Subjective ratings have been used in many studies to measure the forces, fatigue, and postural changes. In the study done by Troiano et al. [167] the force and fatigue of the upper trapezius muscle in isometric contractions was assessed using the Borg CR10 scale. Moreover, surface electromyography EMG indexes (e.g. root mean square value (RMS), fractal dimension (FD), mean frequency of power spectrum (MNF)) were used to assess the force and fatigue of the upper trapezius muscle to provide objective measures. Fourteen (14) total subjects were used in the study, equally divided between males and females. Isometric contractions of the muscle were implemented at 10-80% of the maximum voluntary contraction (MVC) in increments of 10% to represent the different force levels. A 50% MVC was used to represent the constant force level to measure the fatiguing contraction until exhaustion. Both objective and subjective measures provided information about the endurance time and the exerted forces. Borg ratings were also predictive of the RMS topographical maps of the upper trapezius muscle.

In another study implemented by Elisabet Borg and Gunnar Borg [168], 70 subjects (32 females, 38 males) were asked to produce a hand grip force using a hand dynamometer to represent the conception of strong followed by a maximal exertion on the Borg CR10 ratio scale. Relationships from the Borg CR10 were used to predict maximal performances using the power relationship and the 1:2 ratio between strong and maximal. The correlation between the actual performances and the predicted values was around 0.76 ($P \leq 0.001$) which supports the use of the verbal anchors in ratio scaling and indicates that Borg CR scales satisfies the requirements of ratio scaling.

In the study done by Kong et al. [169] a comparison for ratings of force levels, comfort and discomfort during some grip exertions were done. Seventy-two (72) subjects were recruited and each subject exerted ten levels of MVC and used a subjective rating scale (VAS) to rate their perceptions for the force levels to evaluate how comfortable or uncomfortable they were for five hand regions. Higher discomfort was reported when required forces increased. The results also show that the subjects' ratings were good as far as estimating when a change occurred regarding how comfortable they were. Comfortable ratings were obtained when subjects are asked to exert less than 65% MVC.

In the study done by Li and Yu [170], the perception of physical exertion under experimental conditions was quantified using the Borg CR10 scale. The grip force was tested on four levels of the CR10 scale. Twenty male subjects were recruited, two posture conditions and two hand conditions were used to measure hand exertions. The results indicated that at levels 2, 5 and 7 subjects tended to apply higher %MVC (power grip force) compared to what they perceived. Similar results were found for the posture conditions. Significant correlations were found between the subjective ratings and the grip force. The correlation coefficient between the grip force and the subjective ratings was 0.92 ($p<0.0001$).

Several ergonomic assessment tools used subjective rating scales to rate the force exertions. In DUET, estimation for the force experienced by the tissues was obtained by a subjective rating scale. The authors estimated the force exertion by using the OMNI-RES scale. The scale has been found to have strong construct validity and exertions were highly correlated with the Borg scale, which indicates the proper use of the scale to quantify exertions of resistance exercise. The force experienced by the distal upper extremities along with respective repetitions per workday were used in the tool to get estimates of the cumulative damage in a similar way to the suggested methodology in the current study [130]. Strong associations were found for the DUET CD measure and the DUE outcomes when validated against the epidemiological dataset used in the current study. Thus, the use of the fatigue failure theory in DUET indicated the role of the fatigue failure theory for the development of MSD risk.

The Strain Index (SI) is a job risk assessment tool that is based on the biomechanical, epidemiological and physiological principles. It calculates the risk of developing a distal upper extremity (DUE) disorder from a given task. It was created by J. Steven Moore and Arun Garg in 1995, the tool is generally used for hand intensive jobs [171]. Each task can be analyzed in terms of six job risk factors and exertions can be rated. These risk factors are: Intensity of exertion, duration of exertion, speed of work, duration of task per day, efforts per minute, and wrist/hand posture. A multiplier that correlates to the rating for each risk factor category is used. The product of these multipliers will give a SI score. Categories for the strain index score are established to indicate safe or hazardous jobs. A strain index of less than three is considered safe whereas an index of 7 or greater is hazardous and needs further actions [171]. The intensity of exertion in the

SI uses the Borg scale of perceived exertion (0-10) to represent exertions that are light, somewhat hard, hard, very hard, and near maximal. Good specificity and sensitivity results based on predictive validity studies were found for the SI and longitudinal studies have shown that the SI can be used to quantify the physical risk exposure for various upper extremity outcomes [172,173].

All previously listed studies highlighted the ease of use for the subjective ratings and how they are well correlated with the physiological measures. Similar results have been also found when direct assessment methods are used and compared with subjective ratings such as EMG. Moreover, tools using subjective ratings did show good results in terms of associations with MSD outcomes and specificity and sensitivity results. Thus, the aim of this study is to figure out the effect of subjective shoulder strength assessment on the proposed shoulder model. In the current study, the data from chapter 3 will be used to investigate the effect of using subjective ratings on the strength of the associations between the shoulder CD measure and the various shoulder outcomes. Subjective ratings will be used to replace the ultimate strength for each subject. The OMNI-RES scale will be used to categorize the ultimate strength for the subjects and inputs for the equation of the stress and number of cycles to failure will be categorical based on the scale rating.

5.2 Model logic

The required inputs for the shoulder model were based upon the data generated for chapter 3. The postural data and the loads carried (magnitude and direction) were used to obtain the moment at each shoulder joint. The University of Michigan's model (3DSSPP version 6.0.6) is used to estimate the shoulder moments.

Moments for both right and left shoulders were used. The ultimate strength was estimated by considering the shoulder strength capability estimates from 3DSSPP (50% male population, lifting standing) and the calculated shoulder moments for each task. The OMNI-RES scale is used to categorize the ultimate strength for each subject. The percentile rank for the ultimate strength is used to convert the values into the OMNI-RES scale. Minor values (0-5%) of the ultimate strength were estimated to have 0.5 on the OMNI-RES scale, values between 5%-10% were categorized as 1 on the OMNI-RES scale, values between 10-20% were categorized as 2, …etc. (Table 5.1). Categorical values are used as inputs to find the number of cycles to failure.

Table 5.1: Ultimate strength percentage and corresponding OMNI-RES scale value.

Ultimate strength percentage	Corresponding OMNI-RES scale value
0-5%	0.5
5-10%	1
10-20%	2
20-30%	3
30-40%	4
40-50%	5
50-60%	6
60-70%	7
70-80%	8
80-90%	9
90-100%	10

Numbers of cycles to failure for right and left shoulders are then obtained using equation 5.3.

$$S = 101.25 - 14.83 \log(N) \qquad (5.3)$$

Where S is the normalized stress as a percentage of the ultimate tensile strength (UTS) and N is number of cycles to failure. The damage per cycle (DPC) was then calculated using the reciprocal of the number of cycles to failure; the CD was then estimated by the multiplying DPC by the repetitions per minute. The job cumulative damage for the left and right shoulders were then calculated using equation (5.4).

$$Total\ CD = \sum_{i=1}^{j} DPC_i \times n_i \qquad (5.4)$$

Where *Total CD* is the daily dose for the cumulative damage for all tasks, DPC_i is the damage per cycle for task i, i is number of tasks in a job with a total of j tasks, n_i is the number of repetitions within task i. An assumption was made that the highest value for the cumulative damage between left and right shoulders was responsible for a higher probability for the development of shoulder MSDs.

5.3 Validation of the tool

The epidemiology database used in chapters 3 and 4 is employed to validate the tool when subjective ratings are used for the ultimate strength of the subjects. The database involved symptoms from a structured interview and historical records for injury data, for all jobs analyzed. Jobs analyzed included up to six tasks. Health outcomes used in the validation included pain today, pain last year, records for injury data for shoulder and subject attribution of job relationship. The FTOV were reported on the job level. A visual analog scale (VAS) was used by subjects to rate their pain for different body parts including the shoulder. Self -reports of discomfort and injury reports were included and self-reported symptoms on day of interview, and retrospectively for the previous year and subject attribution of job relationship too. Symptoms included in the study were self-reported and they fall into five groups: Category 1: Job-related where symptoms originated on the participant's job; Category 2: Job aggravated, symptoms not originating on job but aggravated by the participant's current job, Category 3: Symptoms not originating on job and no change or improvement in symptoms, Category 4: Symptoms improved on the job, symptoms improving but did not originate on job Category 5: No symptoms present.

Since multiple tasks were performed within the same job, the cumulative damage summation was used to produce an overall estimate for the damage for a job a daily dose. For the validation, definitions of cases and controls involved shoulder pain (category 1 only) vs shoulder pain (category 5 only); as well as shoulder pain (categories 1&2) vs shoulder pain (categories 4&5). Outcomes were considered for shoulder pain today and shoulder pain last year and FTOV injury record. To be as a case a VAS>15mm was considered (VAS ranged from 0-100 mm with 0= no pain at all and 100= worst pain imaginable). Once the cumulative damage was obtained, binary logistic regression was used to test model significance and get estimates of the odds ratios associated with the log of the continuous CD.

Binary logistic regression was used to test the model significance and to find odds ratios associated with the log of the CD and the different outcomes. The analysis considered multiple workers performing the same job. Covariates included sex, age, and BMI. Age and BMI and sex were dichotomized, with 1M, 0F for sex, 40 years for age and >=30 for BMI. Regression equations were used to determine the relationship between the log of CD measure and the probability of an outcome (positive case) using the following equation:

$$\mathrm{P(event)} = \exp(\mathrm{Y}')/(1 + \exp(\mathrm{Y}')) \qquad (5.5)$$

Where Y' relationship will be derived from logistic regression

$$\mathrm{Y}' = \beta 0 + \beta 1 \times \mathrm{Log\ CD} \qquad (5.6)$$

Thus, this regression equation can be used to get the probability of a shoulder outcome for each value of CD.

5.4 Results

5.4.1 Current Shoulder Pain (1&2 vs 4&5) Outcome

The logistic regression results indicated significant associations between log CD and all shoulder outcomes. For current shoulder pain (1&2 vs 4&5), a significant relationship was found ($p<0.0001$). Age demonstrated a significant relationship but was close to the boundary of the significance level. Sex did show a trend towards a significance level of 0.10 (table 5.2). The model explained 24.28% of the deviance. The odds ratio was 5.1416 with a 95% CI of (3.0169, 8.7626). The binary fitted line plot is displayed in figure 5.3. Table 5.3 shows the Odds ratios between quintiles of risk per CD estimates, too many significant ORs can be observed which increases the distinguish power for the logistic regression probability relationship. Figure 5.4 illustrates the CD measure and the probability of a shoulder outcome. Higher CD percentiles were associated with higher probability of a shoulder outcome.

Table 5.2: Deviance table for the logistic regression (current shoulder pain 1&2 vs 4&5).

Source	DF	Adj Dev	Adj Mean	Chi-Square	P-Value
Regression	9	64.732	7.1924	64.73	0.000
Log CD	1	50.358	50.3585	50.36	0.000
Age	1	3.869	3.8692	3.87	0.049
Sex	1	3.678	3.6784	3.68	0.055
BMI	1	0.018	0.0181	0.02	0.893
Site	5	6.130	1.2261	6.13	0.294
Error	272	201.860	0.7421		
Total	281	266.592			

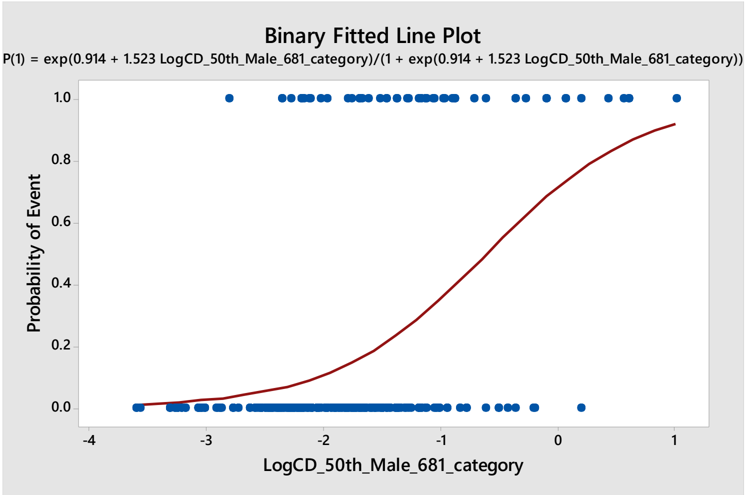

Figure 5.3: Binary fitted line plot (current shoulder pain 1&2 vs 4&5).

Table 5. 3: Odds ratios between quintiles of risk per CD estimates, starred values represent risk quintiles that are different from each other.

	40%	60%	80%	100%
20%	9.14 (1.10, 75.71) *	4.31 (0.47, 39.80)	13.69 (1.70, 110.05) *	52.14 (6.74, 403.26) *
40%		0.47 (0.13, 1.66)	1.50 (0.55, 4.06)	5.70 (2.29, 14.21) *
60%			3.18 (0.95, 10.68)	12.10 (3.89, 38.00) *
80%				3.81 (1.64, 8.84) *

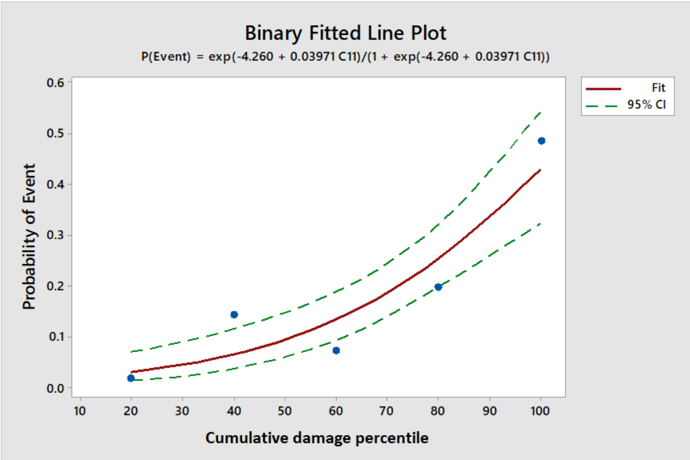

Figure 5.4: Logistic regression results between the shoulder CD measure and current shoulder pain (1&2 vs 4&5).

5.4.2 Current Shoulder Pain (1 vs 5) Outcome

For current shoulder pain (1 vs 5), the model was significant ($p<0.0001$) and log CD was also significant ($p<0.0001$). Age demonstrated a significant relationship but was close to the boundary of the significance level (table 5.4). The model explained 20.00% of the deviance. The odds ratio was 3.8487 with a 95% CI of (2.2303, 6.6413). The binary fitted line plot is displayed in figure 5.5; higher values of log CD were associated with a higher probability of a shoulder outcome. Table 5.5 summarizes the odds ratios between quintiles of risk per CD estimates. Significant ORs can be observed when all categories are compared with the 100% category. Logistic regression results between the shoulder CD measure and current shoulder pain (1 vs 5) are illustrated in figure 5.6.

Table 5.4: Deviance table for the logistic regression (current shoulder pain 1 vs 5).

Source	DF	Adj Dev	Adj Mean	Chi-Square	P-Value
Regression	9	45.400	5.0445	45.40	0.000
Log CD	1	28.380	28.3801	28.38	0.000
Age	1	3.981	3.9810	3.98	0.046
Sex	1	1.557	1.5574	1.56	0.212
BMI	1	0.828	0.8284	0.83	0.363
Site	5	8.776	1.7552	8.78	0.118
Error	251	181.570	0.7234		
Total	260	226.971			

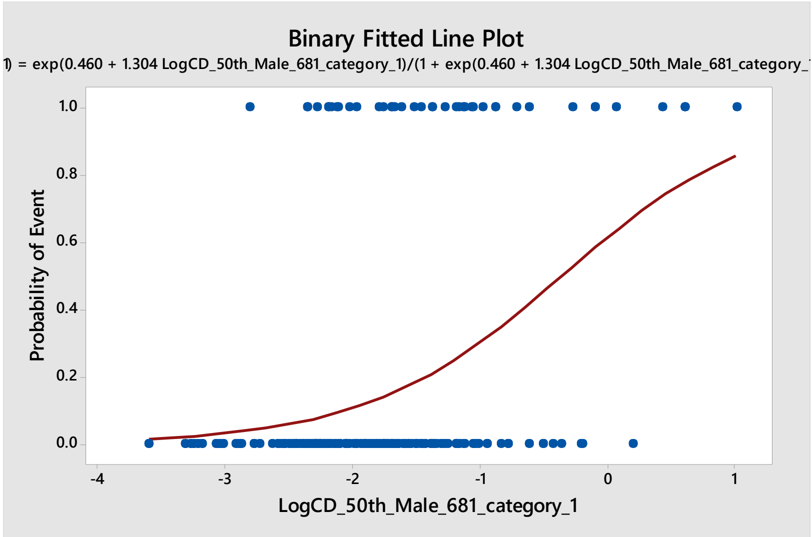

Figure 5.5: Binary fitted line plot (current shoulder pain 1 vs 5).

Table 5.5: Odds ratios between quintiles of risk per CD estimates, starred values represent risk quintiles that are different from each other.

	40%	60%	80%	100%
20%	9.45 (1.14, 78.55) *	4.33 (0.47, 40.14)	9.45 (1.14, 78.55) *	32.50 (4.16, 253.99) *
40%		0.46 (0.13, 1.63)	1.00 (0.34, 2.90)	3.44 (1.35, 8.78) *
60%			2.18 (0.61, 7.75)	7.50 (2.34, 23.99) *
80%				3.44 (1.35, 8.78) *

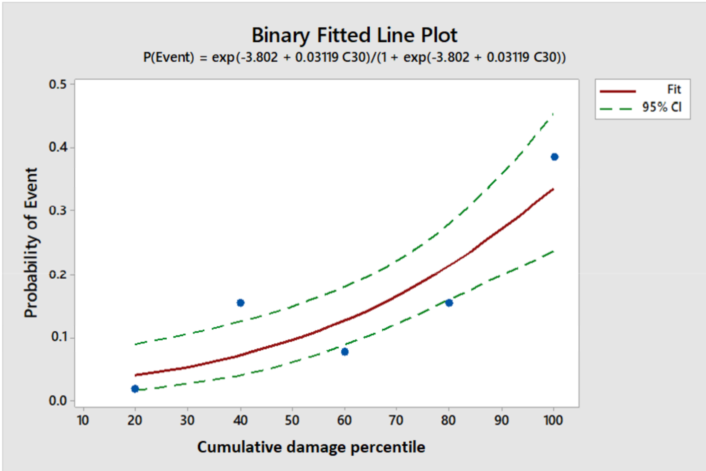

Figure 5.6: Logistic regression results between the shoulder CD measure and current shoulder pain (1 vs 5).

5.4.3 Shoulder Pain Last Year Outcome

For shoulder pain last year, the model was significant ($p<0.0001$) and log CD was significant too ($p<0.0001$). Sex demonstrated a significant relationship ($p=0.006$) (table 5.6). The model explained 13.26% of the deviance. The odds ratio was 2.6664 with a 95% CI of (1.7894, 3.9731). The binary fitted line plot demonstrated how the increase in log CD is associated with an increase of a probability of a shoulder outcome (figure 5.7). Table 5.7 summarizes the odds ratios between Quintiles of risk per CD estimates, when categories are compared with the 100% category significant ORs can be noticed. Figure 5.8 illustrates the logistic regression results between the CD measure and shoulder outcome. Similar probabilities can be observed at the 40 and 80 CD percentiles.

Table 5.6: Deviance table for the logistic regression (shoulder pain last year).

Source	DF	Adj Dev	Adj Mean	Chi-Square	P-Value
Regression	9	43.918	4.8798	43.92	0.000
Log CD	1	26.802	26.8025	26.80	0.000
Age	1	1.045	1.0450	1.04	0.307
Sex	1	7.542	7.5423	7.54	0.006
BMI	1	0.012	0.0119	0.01	0.913
Site	5	4.305	0.8611	4.31	0.506
Error	283	287.248	1.0150		
Total	292	331.166			

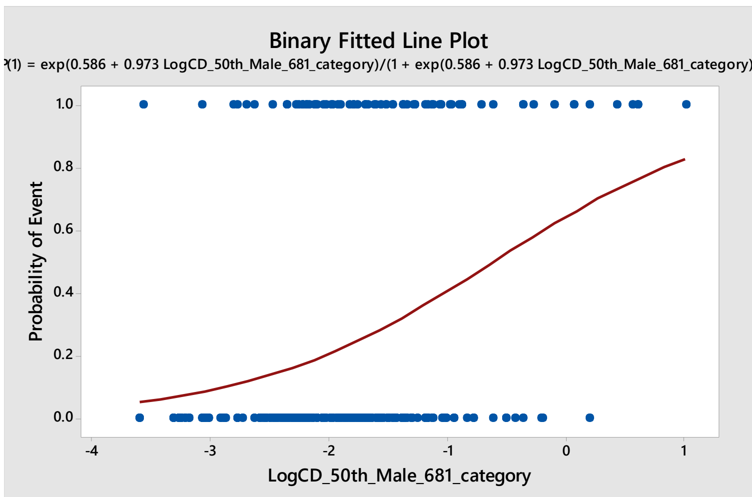

Figure 5.7: Binary fitted line plot (shoulder pain last year).

Table 5.7: Odds ratios between quintiles of risk per CD estimates, starred values represent risk quintiles that are different from each other.

	40%	60%	80%	100%
20%	2.09 (0.77, 5.71)	1.52 (0.53, 4.29)	2.36 (0.88, 6.37)	7.96 (3.10, 20.42) *
40%		0.72 (0.29, 1.81)	1.12 (0.48, 2.66)	3.79 (1.69, 8.46) *
60%			1.56 (0.63, 3.87)	5.25 (2.24, 12.32) *
80%				3.3673 (1.53, 7.43) *

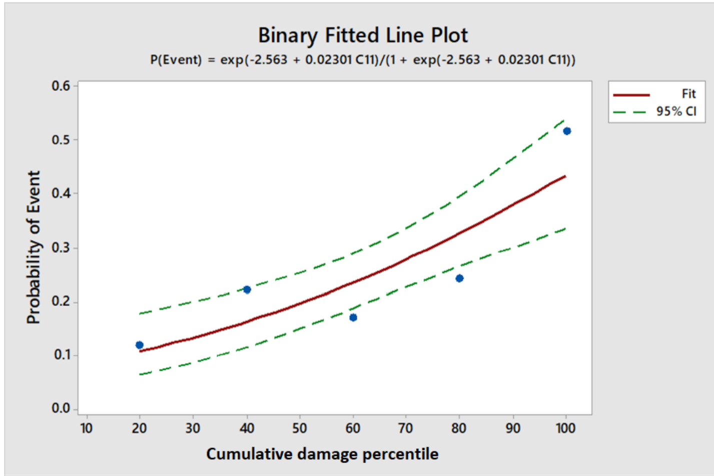

Figure 5.8: Logistic regression results between the shoulder CD measure and shoulder pain last year.

5.4.4 First Time Office Visit (FTOV) Outcome

For the FTOV injury record, the model and log CD were significant (p<0.0001). Site demonstrated a significant relationship (p=0.016) (table 5.8). The model explained 12.05% of the deviance. The odds ratio was 2.5454 with a 95% CI of (1.7208, 3.7653). The binary fitted line plot is displayed in figure 5.9; the maximum probability that can be predicted is around 80%. Table 5.9 shows the odds ratios between quintiles of risk per CD estimates. ORs demonstrated significant results between all categories when they are compared with the 100% category. Figure 5.10 illustrates the logistic regression results between the shoulder CD measure and FTOV injury record, few numbers of cases can be observed at the 80% percentile of the CD which explain the lowest probability associated with this percentile.

Table 5.8: Deviance table for the logistic regression (FTOV injury record).

Source	DF	Adj Dev	Adj Mean	Chi-Square	P-Value
Regression	6	40.40	6.734	40.40	0.000
Log CD	1	25.02	25.022	25.02	0.000
Site	5	13.97	2.793	13.97	0.016
Error	286	295.03	1.032		
Total	292	335.43			

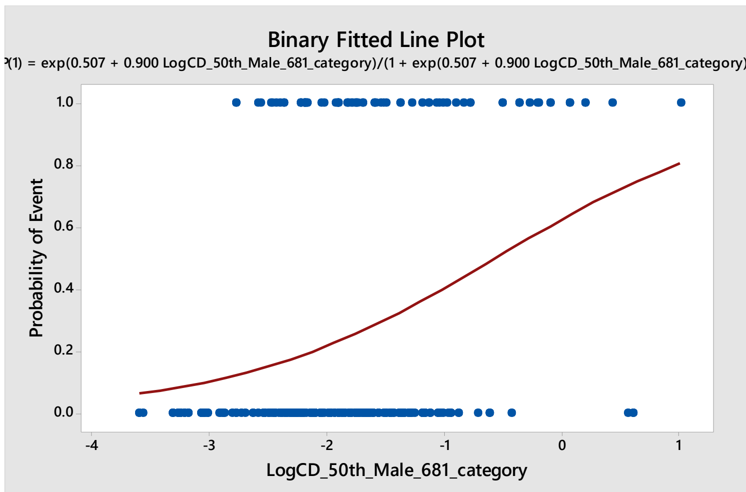

Figure 5.9: Binary fitted line plot (FTOV injury record).

Table 5.9: Odds ratios between quintiles of risk per CD estimates, starred values represent risk quintiles that are different from each other.

	40%	60%	80%	100%
20%	1.80 (0.69, 4.74)	2.58 (1.01, 6.57) *	1.33 (0.48, 3.65)	5.95 (2.40, 14.72) *
40%		1.43 (0.62, 3.29)	0.74 (0.29, 1.85)	3.30 (1.48, 7.37) *
60%			0.51 (0.21, 1.25)	2.31 (1.07, 4.95) *
80%				4.48 (1.91, 10.52) *

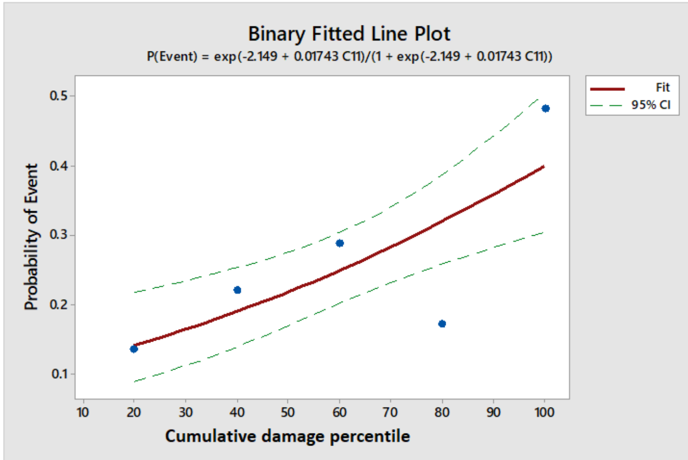

Figure 5.10: Logistic regression results between the shoulder CD measure and FTOV injury record.

5.4.5 Shoulder Pain Today Outcome

For shoulder pain today, the model and log CD were significant (p<0.0001). Sex demonstrated a significant relationship (p=0.003) (table 5.10). The model explained 13.62% of the deviance. The odds ratio was 2.1302 with a 95% CI of (1.3812, 3.2854). Figure 5.11 demonstrates the binary fitted line plot, a reduction in the maximum probability that can be predicted is observed. Fewer reported cases even at high CD values for this outcome reduces the prediction capability. This could be affected by differences in individuals in their report of pain and their pain perception. Table 5.11 summarizes the odds ratios between quintiles of risk per CD estimates; categories are significant when compared with the 100% category. Figure 5.12 shows the Logistic regression results between the shoulder CD measure and shoulder pain today, the 60% percentile of CD had a low probability as can be seen from the plot which can be explained by having fewer number of cases. Table 5.12 shows a summary of the ORs for the different shoulder outcomes. Higher ORs can be observed for the self-reported current shoulder pain.

Table 5.10: Deviance table for the logistic regression (shoulder pain today).

Source	DF	Adj Dev	Adj Mean	Chi-Square	P-Value
Regression	9	34.689	3.8543	34.69	0.000
Log CD_	1	12.259	12.2586	12.26	0.000
Age	1	0.062	0.0618	0.06	0.804
Sex	1	8.768	8.7685	8.77	0.003
BMI	1	0.397	0.3965	0.40	0.529
Site	5	6.652	1.3303	6.65	0.248
Error	283	220.019	0.7775		
Total	292	254.708			

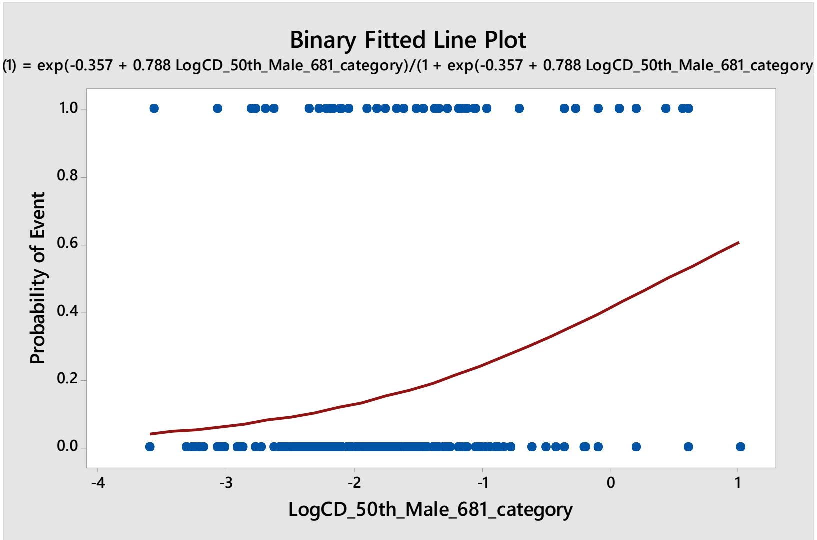

Figure 5.11: Binary fitted line plot (shoulder pain today).

Table 5.11: Odds ratios between quintiles of risk per CD estimates, starred values represent risk quintiles that are different from each other.

	40%	60%	80%	100%
20%	1.39 (0.45, 4.27)	0.64 (0.17, 2.41)	1.62 (0.54, 4.89)	4.30 (1.57, 11.78) *
40%		0.46 (0.13, 1.63)	1.17 (0.42, 3.28)	3.11 (1.23, 7.83) *
60%			2.53 (0.73, 8.72)	6.69 (2.11, 21.23) *
80%				2.65 (1.08, 6.51) *

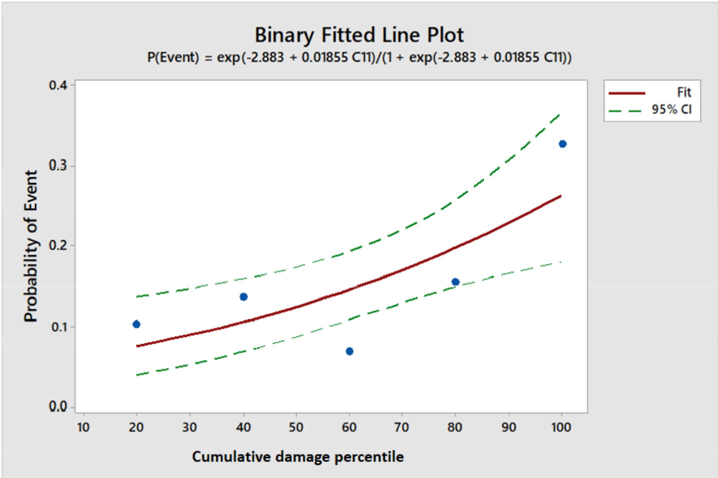

Figure 5.12: Logistic regression results between the shoulder CD measure and shoulder pain today.

Table 5.12: Summary of the ORs for the crude and adjusted ORs for the different shoulder outcomes, N=total number, Var=various, df=degrees of freedom.

Outcome	**Analysis**	**Cases**	***N***	**Variable**	***df***	x^2	***p***	**OR**	**95% CI**
Pain today	Crude	46	293	Log CD	1	15.83	<0.001	2.195	(1.481, 3.264)
	Adjusted			Log CD	1	12.26	<0.001	2.1302	(1.381, 3.285)
				Age	1	0.06	0.804	0.9053	(0.413, 1.987)
				Sex	1	8.77	0.003	0.3418	(0.168, 0.694)
				BMI	1	0.40	0.529	0.7540	(0.309, 1.840)
				Site	5	6.65	0.248	Var	Var
Pain last year	Crude	74	293	Log CD	1	29.93	<0.001	2.6458	(1.816, 3.855)
	Adjusted			Log CD	1	26.80	<0.001	2.6664	(1.789, 3.973)
				Age	1	1.04	0.307	1.4122	(0.729, 2.737)
				Sex	1	7.54	0.006	0.4188	(0.226, 0.778)
				BMI	1	0.01	0.913	1.0409	(0.507, 2.139)
				Site	5	4.31	0.506	Var	Var
FTOV	Crude	76	293	Log CD	1	26.44	<0.001	2.4600	(1.705, 3.549)
	Adjusted			Log CD	1	25.02	<0.001	2.5888	(1.721, 3.765)
				Site	5	13.97	0.016	Var	Var
1&2 VS 4&5	Crude	51	282	Log CD	1	52.28	<0.001	4.5871	(2.829, 7.437)
	Adjusted			Log CD	1	50.36	<0.001	5.1416	(3.017, 8.763)
				Age	1	3.87	0.049	2.2383	(0.997, 5.026)
				Sex	1	3.68	0.055	0.4714	(0.220, 1.010)
				BMI	1	0.02	0.893	1.0626	(0.440, 2.568
				Site	5	6.13	0.294	Var	Var
1VS 5	Crude	41	261	Log CD	1	32.71	<0.001	3.6856	(2.246, 6.047)
	Adjusted			Log CD	1	28.38	<0.001	3.8487	(2.230, 6.641)
				Age	1	3.98	0.046	2.3552	(1.007, 5.507)
				Sex	1	1.56	0.212	0.5926	(0.263, 1.335)
				BMI	1	0.83	0.363	1.5260	(0.620, 3.755)
				Site	5	8.78	0.118	Var	Var

5.5 Discussion

The analysis revealed that when the subjective ratings are used for the percentage of strength capability for the subjects, strong association between the CD and the shoulder MSD outcomes are still observed. The dose-response associations were observed for the pain prevalence, the ORs were higher for the self-reported symptoms. For the binary fitted line plots, we can notice that higher values of log CD are associated with an increase in probability of a shoulder outcome. Few extreme log CD points were observed in the binary fitted line plots; those points refer to jobs with higher risk as they were reported as a case for some outcome definitions. For shoulder pain today, the maximum prediction probability of a shoulder outcome to occur from the binary fitted line plot is less than the other shoulder outcomes. Fewer reported cases for this outcome definition when high CD measure are estimated can explain this pattern. Differences in individuals in their pain perception and in reporting this shoulder outcome can also affect the results. Although a recall bias can be associated with the shoulder pain last year, the results indicated better associations. For the logistic regression plots for percentile of CD measure and the various shoulder outcomes, some percentiles did show a low probability this can be explained by the fewer number of cases in that percentile. When subjective ratings are introduced similar results are obtained when compared to those using continuous ultimate strength for the subjects. The effect of site can be noticed when FTOV outcome is used in the analysis. FTOV is related to the injury records, thus this can be different based on the site policy.

The strong associations between the CD and all shoulder outcomes support fatigue failure theory and etiology of MSDs. The current results indicate that application of the fatigue failure method also works extremely well in assessing the probability of association with shoulder outcomes.

Strong associations can still be observed when the OMNI-RES scale is used for the ultimate strength when compared with continuous ultimate strength measures. Thus, the shoulder model can be further investigated to make the required inputs easily estimated by the user instead of requiring some direct measurements.

The study objective was to investigate the effect of the subjective ratings for the shoulder ultimate strength on the shoulder risk assessment tool based on the fatigue failure theory. In the current tool, dose-response relationships were observed between the CD and pain prevalence. The tool will provide a CD measure and an estimated outcome probability can be obtained for any given value. The CD can be easily summed for multiple tasks to get a daily dose of exposure, and the contribution of the various tasks will be easily estimated. The proposed tool investigated the impact of the subjective ultimate strength ratings in estimates of the CD measure, similar results are obtained when compared to the proposed model in chapter 3. Thus, using the OMNI-RES scale can compensate for some of the required model inputs to facilitate the use of the tool. Study limitations include the fact that only awkward postures were included in the analysis and other risk factors such as, speed of work and duty/rest cycles were not considered in the analysis. Personal habits, hobbies and previous injury are not considered as well and could impact the studied shoulder outcomes. Interaction with ergonomics team might also impact the speed at which the workers are performing their tasks. Recall bias and the temporal sequence of exposure and effect are other limitations for the self-reported symptoms in the epidemiology study. Subjective ratings have been also found to be biased [130] and quantitative methods are preferable, however the current results demonstrate a promise in the use of subjective ratings for assessment of ultimate strength and the use of the fatigue failure theory to understand the etiology of MSD risk. Further research is required to better understand the impact of the covariates on the model variability.

Chapter 6: Conclusion and Future Work

6.1 Conclusion

The shoulder joint is one of the most complex structures in the human body and shoulder injuries and illnesses are one of the most frequently occurring MSDs [3]. To better understand the etiology of shoulder MSD, the dose-response relationship needs to be better investigated. Cumulative loading appears to be a major contributing factor for the development of MSDs. Studies have suggested various methods for addressing cumulative loading however, most of them assume that low force, long duration and high force, short duration tasks have the same injury risk [8,9]. Several studies supported the use of the fatigue failure theory to explain the etiology of MSDs and the biological tissues were found to exhibit a pattern of force repetition interaction anticipated by fatigue failure theory [130].

In the presented studies a new shoulder risk assessment tool based on the fatigue failure theory is proposed where shoulder CD estimates are quantified and associations with various shoulder outcomes have been investigated. Video recordings from an existing epidemiology study were used to obtain the required inputs to build the shoulder risk assessment tool based on the fatigue failure theory. Postural estimates and repetitions for the tasks were estimated using the video analysis. Awkward postures were employed for the postural estimates. University of Michigan's model 3DSSPP (version 6.0.6) was used to estimate the moments of the shoulders. The ultimate strength for the shoulders was then based on the shoulder moments and strength capability. Tendons fatigue failure relationship was used to estimate the number of cycles to failure. Damage per cycle values are obtained and the CD for the tasks are estimated by considering both the damage per cycle and repetitions per workday. A job CD measure and an estimated outcome probability which can be obtained for any given value can be quantified. The CD can be easily summed for multiple tasks to get a daily dose of exposure, and the contribution of the various tasks can be easily estimated.

The database in the epidemiology study was used to validate the shoulder risk assessment tool. The database involved symptoms from a structured interview and historical records for injury data, for all jobs analyzed. The database contained jobs form a large US automotive manufacturer from six different sites. Five different outcomes are considered to validate the shoulder risk assessment tool. These outcomes are shoulder pain today, current shoulder pain (1&2 vs 4&5), current shoulder pain (1 vs 5), FTOV injury record and shoulder pain last year. The binary logistic regression was used to figure out the associations between the different shoulder outcomes and the shoulder CD measure. Sex, age, BMI and site were used as covariates in the analysis.

Different methods were used to adjust for the moments and shoulder strength capability. In the first study, the moments were calculated without any type of adjustments such as adjusting for the effect of the personal characteristics (e.g. height, weight, sex). The strength capability was also estimated for lifting while standing and no adjustments were made. In the second study, adjustments were made in two methods. The first method included adjustments for the moments based on height, weight and sex for subjects and only sex was used to adjust for the shoulder strength capability. In the second method, height, weight and sex for each subject were used to adjust for both the moments and the strength capability. Effects of the subjective ratings on the shoulder strength assessment were investigated in the third study. The OMNI-RES scale was used to estimate the ultimate strength for the shoulder based on the scale ratings. The analysis revealed that there is a strong association between the CD and the shoulder MSD outcomes, which may help explain the etiology of those MSDs. The dose-response associations were observed for the pain prevalence, the ORs were higher for the self-reported symptoms. When the effect of the personal characteristics is introduced into the model, more variability can be observed for the CD measure estimates which can be explained by the differences in the anthropometry and strength capability between male and female subjects. Those differences can lead to changes in moment calculations and the ultimate strength estimates which in turn affect the CD measure. When the OMNI-RES scale is used significant associations were also found with log CD when compared to continuous ultimate strength of the subjects. Those associations need to be further investigated to address the use of the subjective ratings for the proposed shoulder tool. Some of the shoulder outcomes demonstrated less predictive range for the probability of occurrence of a shoulder outcome which can be explained by fewer numbers of cases reported for jobs with high CD measure. The effect of the covariates on the model need to be further investigated; none of the covariates was significant among all outcomes. However, sex and site demonstrated significant relationships for some of the shoulder outcomes. No clear effect of BMI was observed. Some other unstudied factors might impact the associations such as hobbies.

The results of the first study demonstrated more significant relationships in terms of the R-squared and ORs. The R-squared and the ORs were the highest for the current shoulder pain (1&2 vs 4&5) among all studies. When subjective ratings are used in the third study, the model demonstrated significant relationships very close to the ones obtained in the first study (Chapter 3). Thus, the best results were obtained in the first study and they were very comparable with the results of the third study (Chapter 5).

The results of the studies demonstrated that the fatigue failure theory may help to explain the etiology of shoulder MSDs. Recently, material fatigue theory to assess MSD risk have been used to develop two new risk assessment tools, one for the distal upper extremity (the Distal Upper Extremity Tool, or DUET) and one for the low back, the lifting fatigue failure tool (LiFFT). Both LiFFT and DUET were validated using epidemiological studies including the database used here and they demonstrated significant results and significant odds ratios. The current results indicate that application of the fatigue failure method also works extremely well in assessing the probability of association with shoulder outcomes.

Current tools such as RULA and REBA fall short in terms of the impact of cumulative loading and they do not consider a variety of risk factors. Inability to deal with multitask jobs is another shortcoming of previous tools, as many jobs are multitasked in nature.

The results presented in this research will serve to better understand the dose-response relationships for MSDs. The proposed shoulder risk assessment tool will provide a CD measure and an estimated outcome probability can be obtained for any given value. The proposed tool is designed to be easy to use requiring inputs for moments (lever arm and load) and repetitions per workday for each task performed. The tool will be capable of analyzing jobs with load handling and pushing/pulling tasks (Appendix A). The tool is available in a web-based version at https://theshouldertool.pythonanywhere.com, a user's manual is also provided. To allow more functionality of the tool an Excel version will be available where data can be saved to a worksheet allowing the users to keep history data for future records.

Study limitations include the fact that only awkward postures were included in the analysis and other risk factors such as the speed of work and duty/rest cycles were not considered in the analysis.

Population in 3DSSPP might not be well representative for the population in the epidemiology database used in the current studies. Other covariates might impact the relationships such as personal habits, hobbies, previous injury and time at current job. Recall bias is another limitation of the epidemiology study used in validation, moreover it is hard to determine the temporal sequence of exposure and effect. An 8-hour shift is assumed in the analysis but shifts varied. Speed of work might be affected by the interaction with the ergonomics team. Further research is required to better understand the different associations and the applicability of the proposed shoulder risk assessment tool.

6.2 Future Work

Further future research would involve the use of different shoulder outcome definitions. Better ways to quantify the exposure could be further investigated and employed. Optimization methods could be used to find the optimal equation constant values for the relationship between stress and number of cycles to failure. The new relationship could be tested to figure out the associations with the different shoulder outcomes.

Other exponential relationships for tendons fatigue failure could be also used to figure out their impact on the strength of the association. Effects of the duration of tasks and duty/rest cycle for the analyzed jobs would be investigated. Different cumulative exposure methods could be employed such as the linear integration and the squared integration methods. Weibull or other reliability distributions might be another novel method to describe the fatigue behavior of the shoulder joint. A further extension is to implement a sensitivity analysis to investigate the impact of changes in some of the model variables such as changes in the strength capability and changes in the threshold values used for the cases definition in some outcomes. The analysis could be also implemented for the male and female subjects separately to investigate the impact of the sex on the developed relationships. Further future work might also include the use of the Data mining analysis methods to describe the behavior of the dataset and predict some patterns. For instance, Cluster analysis can be implemented to investigate the similarities for jobs that correspond to high and low risk categories.

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Appendix A

A.1 The Shoulder Tool

The Shoulder Tool is an ergonomic risk assessment tool to evaluate the risks related to shoulder intensive jobs. The tool is designed to be easy to use requiring simple inputs from the users. Three pieces of information are necessary for the shoulder tool which include: Weight of load carried in hand, distance from the acromion to center of load or hand (greatest distance), and repetitions in a workday for the analyzed tasks. The distance from the acromion to the load or hand can be horizontal, vertical or straight from the acromion to center of load depending on the type of task analyzed (i.e lifting, pushing, pulling) (Figures A.1-A.4). A Measuring tape can be used to get the measurement form the acromion to the load or hand. The tool provides analysis for each shoulder separately, thus the greatest lever arm for one shoulder does not need to happen at the same time for the other one. The tool can analyze both shoulders and one shoulder at a time based on the task analyzed.

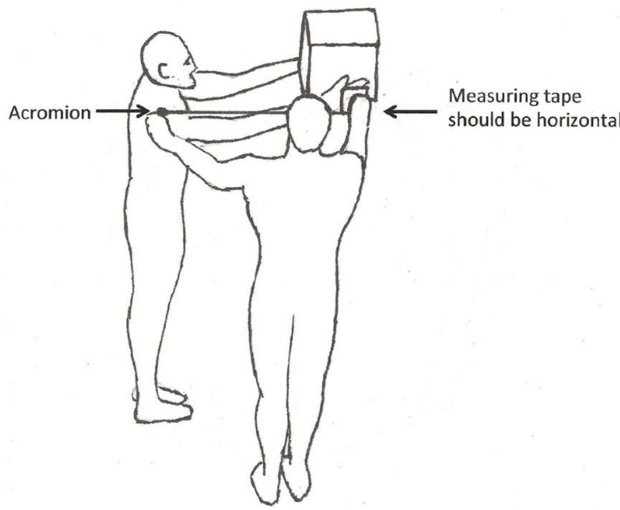


Figure A. 1: An illustration of the horizontal measurement for load handling, measurement is taken from the acromion to the center of load/hand.

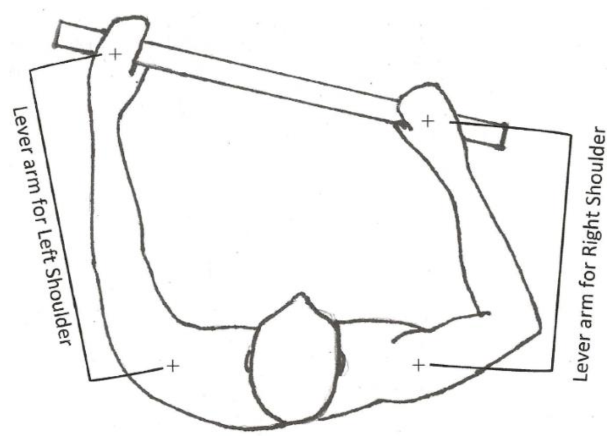


Figure A. 2: A manual handling task and measurements of the lever arms for both left and right shoulders. The weight of the object being handled may be divided between the hands done evenly or unevenly (i.e. one shoulder is bearing more weight) which can be estimated by the analyst.

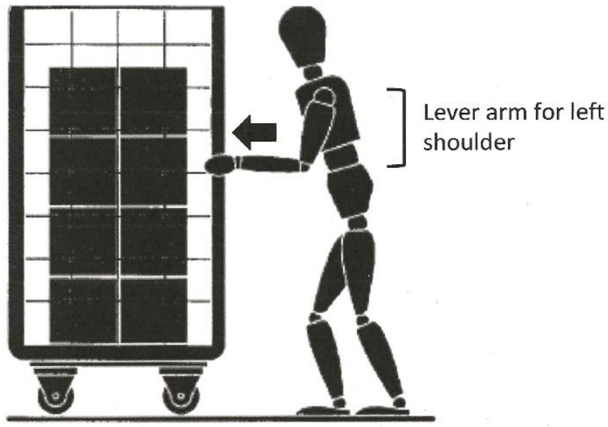


Figure A. 3: Vertical measurement for the lever arm for forward pushing/pulling backward tasks. Force gauges may be used to estimate the forces. Peak forces need to be estimated such as the forces required to get the cart to move.

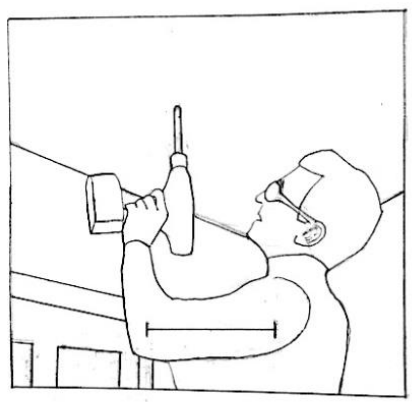
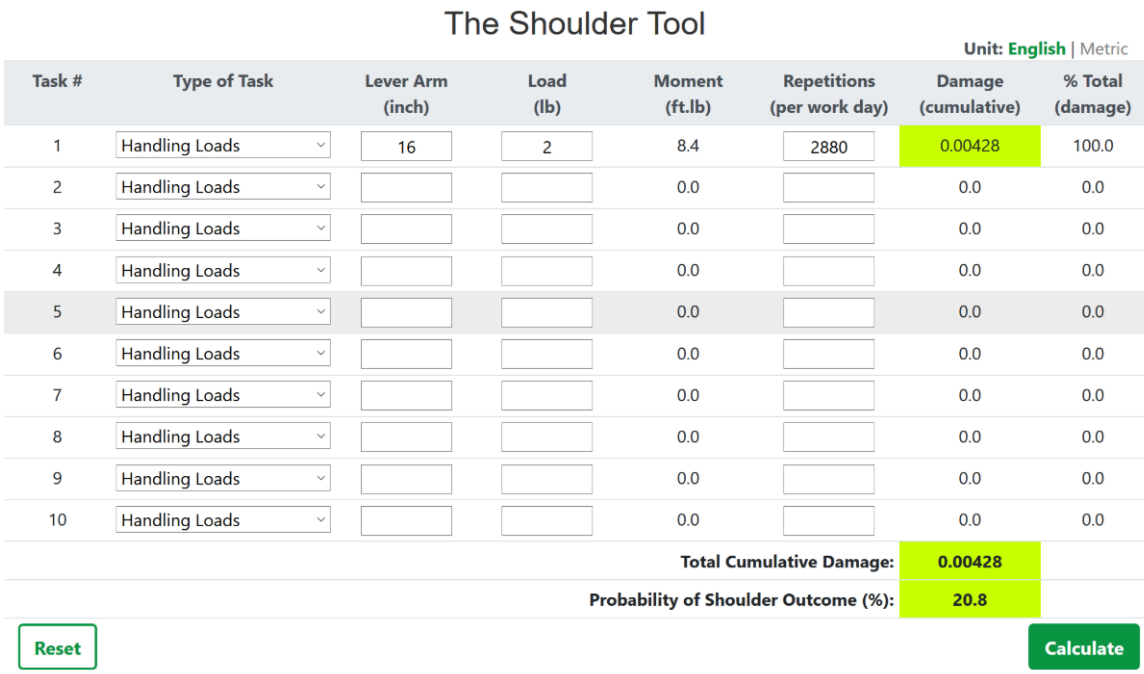


Figure A. 4:Lever arm measurement for an upward push task, a pulling down action under the same posture may be also analyzed using the same lever arm measurement.

A.1.1 Assessing Mono-Task Jobs

A shoulder intensive monotask, a task done repetitively throughout a workday, can be easily analyzed using the shoulder tool. An example is a task where a 2-pound load is handled using the right shoulder and the lever arm is 16 inches. The repetitions per workday is 2,880. Figure A.5 shows a screenshot of The Shoulder Tool for this task. The probability of a right shoulder outcome is 20.8%. The interpretation for the shoulder tool outcome is that the symptoms are critical for a medical attention to take place.



The Shoulder Tool

Unit: English | Metric

Task #	Type of Task	Lever Arm (inch)	Load (lb)	Moment (ft.lb)	Repetitions (per work day)	Damage (cumulative)	% Total (damage)
1	Handling Loads	16	2	8.4	2880	0.00428	100.0
2	Handling Loads			0.0		0.0	0.0
3	Handling Loads			0.0		0.0	0.0
4	Handling Loads			0.0		0.0	0.0
5	Handling Loads			0.0		0.0	0.0
6	Handling Loads			0.0		0.0	0.0
7	Handling Loads			0.0		0.0	0.0
8	Handling Loads			0.0		0.0	0.0
9	Handling Loads			0.0		0.0	0.0
10	Handling Loads			0.0		0.0	0.0
					Total Cumulative Damage:	0.00428	
					Probability of Shoulder Outcome (%):	20.8	

Reset Calculate

Figure A. 5:The Shoulder Tool results for the analysis of a monotask job.

Another example for a monotask where both hands are used, is a 10 lb. panel lifted from a conveyor to a rack. In this example the weight can be evenly distributed between hands (5lbs each). The repetition of the task is 4,800 times per shift. The lever arm is 18 inches. The risk associated with this task will be the same for each shoulder because of the even distribution of the load and the identical lever arms. Dominant hand strength is not included in the tool. A screenshot of the analysis is shown below, figure A.6.

The Shoulder Tool

Unit: English | Metric

Task #	Type of Task	Lever Arm (inch)	Load (lb)	Moment (ft.lb)	Repetitions (per work day)	Damage (cumulative)	% Total (damage)
1	Handling Loads	18	5	14.0	4800	0.03331	100.0
2	Handling Loads			0.0		0.0	0.0
3	Handling Loads			0.0		0.0	0.0
4	Handling Loads			0.0		0.0	0.0
5	Handling Loads			0.0		0.0	0.0
6	Handling Loads			0.0		0.0	0.0
7	Handling Loads			0.0		0.0	0.0
8	Handling Loads			0.0		0.0	0.0
9	Handling Loads			0.0		0.0	0.0
10	Handling Loads			0.0		0.0	0.0
					Total Cumulative Damage:	**0.03331**	
					Probability of Shoulder Outcome (%):	**37.6**	

Reset | Calculate

Figure A. 6: A screenshot of a monotask two-handed lift with even weight distribution.

A.1.2 Assessing Jobs with Multiple Shoulder Tasks

For jobs with variable tasks and various exertions, The Shoulder Tool provides a daily dose cumulative damage for each shoulder by summing the cumulative damage for each task. Moreover, the tool provides the percentage contribution for the total cumulative damage associated with each task. An example is provided in Figure A.7 below. In this example, task 3 is associated with the highest percentage of cumulative damage, thus a priority is given to task 3 in this job for ergonomic intervention strategies.

The Shoulder Tool

Unit: English | Metric

Task #	Type of Task	Lever Arm (inch)	Load (lb)	Moment (ft.lb)	Repetitions (per work day)	Damage (cumulative)	% Total (damage)
1	Handling Loads	18	5	14.0	1920	0.01333	32.5
2	Handling Loads	15	7.5	14.7	480	0.00400	9.8
3	Horizontal Push or Pull	16	20	26.7	96	0.02106	51.4
4	Handling Loads	18	1	8.0	1920	0.00258	6.3
5	Handling Loads			0.0		0.0	0.0
6	Handling Loads			0.0		0.0	0.0
7	Handling Loads			0.0		0.0	0.0
8	Handling Loads			0.0		0.0	0.0
9	Handling Loads			0.0		0.0	0.0
10	Handling Loads			0.0		0.0	0.0
					Total Cumulative Damage:	**0.04097**	
					Probability of Shoulder Outcome (%):	**39.6**	

Reset Calculate

Figure A. 7: A multitask job analyzed using The Shoulder Tool.

A.1.3 Assessing Highly Variable Shoulder Jobs

For jobs with highly variable shoulder intensive tasks, a binning procedure can be used. An example for the use of the Shoulder Tool using a binning procedure is a warehouse picker doing lifting for different items. Table A.1 demonstrates an example for a warehouse picking using the right shoulder to lift many items.

Table A. 1: An example for the use of the binning procedure in The Shoulder Tool.

Item	Lever arm (inches)	Load (pounds)	Moment (ft.lbs.)	Repetitions
1	12	8	8	30
2	18	14	21	25
3	20	15	24	35
4	21	10	17.5	50
5	15	4	5	55
6	16	8	10.7	32
7	24	14	28	45
8	15	7	8.8	72
9	18	10	15	40
…				

For this analysis tasks can be grouped into bins based on their peak moments and the repetitions for the tasks in the same bin can be summed to get the repetitions for each bin. It is preferred to narrow the range for the bins, so the probability of a shoulder outcome is not inflated too much. In this example, three bins will be used for the analysis, bin 1(0-10 ft.lbs.), bin 2 (11-20 ft.lbs.), bin 3 (21-30 ft.lbs.). Task will be then grouped into their corresponding bin and the repetitions will be summed for the tasks within each bin. For example, tasks 1,5 and 8 will be grouped into bin 1 and their corresponding repetition within that bin will be 157. This bin will represent the first task in the shoulder tool (10 lb. load and 12 in lever arm, 157 repetitions). The binning analysis for the other two bins will be done in a similar way. Thus, the second task in the shoulder tool will have (20lbs. and 12 in lever arm, 122 repetitions). The third task represents the third bin and the inputs for the analysis will be (30lbs load, 12 in lever arm, and 105 repetitions). While this binning procedure is easy to use, gives reasonably close results and simplifies the analysis, some inflation in the probability might result thus reasonable narrowest range for the bins is recommended. Figure A.8 shows a screenshot of the results.

The Shoulder Tool

Unit: English | Metric

Task #	Type of Task	Lever Arm (inch)	Load (lb)	Moment (ft.lb)	Repetitions (per work day)	Damage (cumulative)	% Total (damage)
1	Handling Loads	12	10	14.1	157	0.00112	0.6
2	Handling Loads	12	20	24.1	122	0.01338	7.0
3	Handling Loads	12	30	34.1	105	0.17764	92.5
4	Handling Loads			0.0		0.0	0.0
5	Handling Loads			0.0		0.0	0.0
6	Handling Loads			0.0		0.0	0.0
7	Handling Loads			0.0		0.0	0.0
8	Handling Loads			0.0		0.0	0.0
9	Handling Loads			0.0		0.0	0.0
10	Handling Loads			0.0		0.0	0.0
					Total Cumulative Damage:	**0.19214**	
					Probability of Shoulder Outcome (%):	**55.0**	

Reset | Calculate

Figure A. 8: An application of the use of the binning procedure for a highly variable shoulder intensive tasks.

Some limitations of the current version of the shoulder tool is that it does not account for all loading conditions such as when arm is held straight in line with the shoulder such as a push forward action, stress in the shoulder will be generated even though no moment is present. Another example is when arm is held directly above shoulder, although a low moment is created intensive muscle contraction is taking place and this loading condition will lead to physiological (and material) fatigue.

It is noteworthy that this is the third ergonomic risk assessment tool developed by ergonomists at Auburn University based on the fatigue failure model. As with previous fatigue failure-based risk assessment tools (LiFFT and DUET) developed by ergonomists at Auburn University, The Shoulder Tool demonstrated strong associations with outcomes, suggesting that fatigue failure may be an etiologically significant factor in several different types of MSDs.