Upper extremity kinematic changes and shoulder muscle fatigue during a repetitive goal directed task

by

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Author's Declaration

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

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Abstract

Repetitive workplace tasks are associated with fatigue induced changes to shoulder muscular behavior, which can alter glenohumeral joint kinematics and lead to chronic injury. However, accessible and reliable methods to detect shoulder muscle fatigue in the workplace are scarce. The overall purpose of this thesis was twofold. First to determine if changes in upper extremity joint angle across individuals during a workplace emulative repetitive task exhibit features that may be visually identifiable, and second, to characterize the relationship between potentially visually identifiable changes in thoracohumeral elevation and traditional indicators of shoulder muscle fatigue. Twenty-seven, young healthy individuals performed a seated repetitive manuals materials handling task requiring them to lift and lower a weighted bottle between two target locations to exhaustion. During the last five lift motions of each 2-minute interval during the repetitive task, a symbolic motion structure representation (SMSR) algorithm was used to identify the basic spatial-temporal structure of the time series upper extremity joint angle data (i.e. torso, thoracohumeral, elbow and wrist), followed by measures of selected shoulder muscle electromyography (EMG) mean power frequency (MPF) and ratings of perceived fatigue and discomfort (RPF/RPD). Joint angle SMSRs characterize motion as a sequence of directional changes in joint angle time series data, which are easier to visually identify by ergonomists, in comparison to joint angle magnitudes. Changes in joint angle SMSRs occurred across upper extremity joints for most participants (at least 24 of 27) in this repetitive task. A weak positive linear relationship existed between the onset of changes in thoracohumeral elevation SMSR and the onset of shoulder muscle fatigue (as identified by a decline in the EMG MPF from the infraspinatus muscle) (R^2 = 0.275, p = 0.02). Participants who varied the thoracohumeral elevation SMSR, in comparison to those who did not, exhibited a 7.45% greater decrease in anterior deltoid EMG MPF (p = 0.304), indicative of higher levels of muscle fatigue, throughout

the repetitive task. In principle, the results of this thesis indicate that upper extremity kinematic changes in a repetitive task may be visually identifiable as directional changes in joint motion identified by the SMSR algorithm. The relationship between anterior deltoid muscle fatigue and variability in thoracohumeral elevation SMSRs throughout the repetitive task provide a link between potentially visually identifiable directional changes in thoracohumeral elevation joint motion (SMSR) and shoulder muscle fatigue accumulation. These initial findings can inform future research endeavors aimed at developing heuristic guidelines for visually identifying variations in thoracohumeral joint angles as a more accessible method to identify local shoulder muscle fatigue in ergonomics assessments.

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Dedication

To my Mother, Dayle Whittaker, and my Grandma (mia Nonna), Palma Whittaker, who inspired me to pursue my love of learning and taught me the importance of hard work. I love you and am forever grateful for all you have done for me.

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3 INTRODUCTION

Shoulder musculoskeletal disorders (MSDs) are common, costly, and reoccurring pathologies in the workplace. The development of shoulder MSDs in the workplace negatively affects the individual, the employer, and society. For the individual, shoulder MSDs are not only associated with pain and discomfort (Madeleine, 2010), but can markedly influence the ability to complete activities of daily living (Hall et al., 2011), and impact quality of life (MacDermid et al., 2004). Although less common than low back injuries, shoulder injuries typically require a longer recovery period (Ijzelenberg et al., 2004). A long recovery period places a financial burden on the employer, given that the highest proportion of injury compensation is for the loss of earnings (WSIB, 2014). Shoulder MSDs are related to the development of chronic pain, dysfunction, and secondary health outcomes that place a continuing burden on the health care system long after the initial injury (Norlund & Ekberg 2004). To reduce the prevalence of shoulder MSDs in the workplace, research has focused on understanding their causation.

Task repetition is an important risk factor for the development of shoulder MSDs. Repetitive tasks require prolonged muscular activation, causing muscle fatigue; which is a time- and exposure-dependent biological process that begins shortly after the onset of exercise and reduces muscular force generating capacity (Barry & Enoka, 2007). Fatigue induced changes to shoulder muscular behavior alters joint kinematics, causing the loading of ill-suited structures (Kumar, 2001). Force decrements of the rotator cuff muscles due to muscle fatigue limits their ability to resist the upward pull of the deltoid muscles on the humerus, resulting in superior humeral head translation (Chopp et al., 2010). The kinematic alteration of superior humeral head translation is problematic as it decreases the size of the subacromial space. This increases the likelihood that tissues occupying the subacromial space, such as the supraspinatus tendon, will become compressed. Compressive loading of tissues in the subacromial space induces structural damage, leading to inflammation or rupture (Bey et al., 2007; Calis et al., 2000). Progressive degeneration of the rotator cuff muscles and associated tissues is the most common MSD of the shoulder region, with symptoms of subacromial impingement syndrome present in roughly half of reported shoulder complaints (Seitz et al., 2011; van der Windt et al., 1995). Rotator cuff muscle fatigue and subsequent changes to glenohumeral joint kinematics links/associates task repetition to the risk of shoulder MSDs.

Rotator cuff muscle fatigue has a direct effect on glenohumeral joint kinematics because a primary role of this muscle group is to maintain glenohumeral joint stability. The rotator cuff consists of the infraspinatus, supraspinatus, teres minor, and subscapularis muscles, all of which originate on the scapula and insert on the humerus. As a group, the rotator cuff muscles form a half circle around the head of the humerus and have lines of action that pull the head of the humerus into the glenoid fossa (Culham & Peat, 1993). These muscles are therefore effective glenohumeral joint stabilizers because they generate a combination of compressive and shear forces that maintain the position of the humeral head in the glenoid fossa (Veeger & van der Helm, 2007). As glenohumeral joint stabilizers, the rotator cuff muscles are active during a wide range of upper extremity tasks. In repetitive work, this is a considerable problem as the rotator cuff muscles are inherently active, while being relatively small, and are therefore more prone to fatigue in tasks requiring glenohumeral joint contribution. As rotator cuff muscles fatigue, alterations to glenohumeral joint kinematics increase the likelihood of compressing tissues in the subacromial space. Therefore, ergonomic interventions that focus on mitigating rotator cuff muscle fatigue, such as introducing periods of rest throughout repetitive work (Rohmert, 1973), may be an effective solution to reduce the risk of shoulder MSDs in the workplace.

The demands placed on the infraspinatus muscle as both glenohumeral joint external rotator and stabilizer indicate it may be one of the first rotator cuff muscles to fatigue in repetitive work. The infraspinatus muscle has the most favorable external rotation moment generating capacity at the glenohumeral joint throughout the range of motion (Ackland & Pandy, 2011; Kuechle et al., 2000). Therefore, the infraspinatus fatigues rapidly during tasks requiring glenohumeral external rotation (Ebaugh et al., 2006b; Mc Quade et al., 1998). Interestingly, infraspinatus muscle fatigue also develops in repetitive tasks consisting of glenohumeral elevation or those designed to fatigue scapulothoracic musculature, such as a modified push up task (Borstad et al., 2009; Ebaugh et al., 2006a; Mc Quade et al., 1998). This places importance on identifying the onset and development of infraspinatus muscle fatigue in upper extremity repetitive work tasks, as it may occur earlier than fatigue of the other rotator cuff muscles in tasks requiring external rotation. A robust method to identify infraspinatus muscle fatigue accumulation in repetitive work could be used to introduce periods of rest to allow fatigue recovery or prevent its onset.

Currently, accessible, reliable and non-invasive methods to detect shoulder muscle fatigue in the workplace are scarce. Electromyography (EMG) is frequently used to quantify fatigue experimentally, but is often infeasible in the workplace as it requires expensive equipment and intensive interpretation of the generated signals. Recent work suggests that during repetitive, upper extremity goal directed tasks, the neuromuscular system takes advantage of system redundancies to redistribute loads away from fatiguing tissues and enable task performance (Emery & Côté, 2012; Fuller et al., 2009; Lomond & Côté, 2011). Relative changes, between the start and end of the repetitive task, in thoracohumeral elevation angle (decrease) were negatively correlated with an electromyographic indicator of trapezius muscle fatigue across participants ($R^2 = 0.7$) (Fuller et al., 2011). The onset of the kinematic changes occurred at around half (43-53%) of the total task endurance time, suggesting that upper extremity kinematic changes during repetitive work may be indicative of an intrinsic preventive reaction to glenohumeral joint muscle fatigue, well before complete exhaustion. A temporal relationship between local muscle fatigue at the shoulder and changes in thoracohumeral kinematics has the potential to guide ergonomic intervention in repetitive tasks and reduce the risk of shoulder MSDs.

Increases in joint movement variability during repetitive tasks may also provide a kinematic based guide to ergonomic intervention. In repetitive goal directed tasks that elicit fatigue at the glenohumeral joint, motor variability increases across joints within the upper extremity. Trial to trial variability of upper extremity average joint angles and segment positions increases during the latter portion of a repetitive goal directed task, when compared to baseline (Fuller et al., 2011). Despite an increase in upper extremity joint movement variability with fatigue in repetitive goal directed tasks there is no concurrent change in endpoint position variability (Fuller et al., 2009, 2011; Gates & Dingwell, 2011). Thus, an increase in upper extremity joint motion may represent individuals exploring alternative movement strategies, to redistribute loads away from fatiguing tissues and enable task performance (Emery & Côté, 2012; Fuller et al., 2009; Lomond & Côté, 2011). A relationship between local muscle fatigue at the shoulder and increases in upper extremity movement variability also has the potential to guide ergonomic intervention in repetitive upper extremity tasks.

For use in the workplace, kinematic indicators of shoulder muscle fatigue must be visually identifiable to an observer and not require sophisticated equipment. Research on existing observational based UE ergonomic tools suggest that directional (i.e. flexion vs. extension) in comparison to magnitude based (i.e. >30° flexion) changes in joint motion during repetitive work are easier to visually identify by ergonomists (Lowe & Krieg, 2009). Further, shoulder joint motion, in comparison to elbow or wrist, is easier to visually identify as it consists of the relative angle between larger body segments (i.e. torso and humerus) than the former (Lowe, 2004). Current analysis of the upper extremity kinematic changes in repetitive tasks have identified that these kinematic changes indicate a change in movement strategy, rather than simply the consequence of deleterious effects of muscle fatigue (Fuller et al., 2011; Gates & Dingwell, 2008). Park et al. (2005) created a symbolic motion structure representation (SMSR) algorithm to identify 'invariant features' of joint motion, analogous to the generalized motor program used by the central nervous system as a template for movement planning (Schmidt, 1965). A change in movement strategy during the repetitive task, by using a different generalized motor program, should theoretically coincide with a change in the SMSR characterization of joint angle data. Further, the invariant features of joint motion identified by the SMSR are slope based, and therefore reflect directional changes in joint motion. In repetitive tasks, characterizing joint angle data using the SMSR algorithm may provide information about upper extremity kinematics that are likely visually detectable.

Another advantage of using a simplistic representation of upper extremity joint motion, such as the SMSR, is that it may help reduce between subject kinematic variability. Between-subject kinematic variability of descriptive values of joint angle data (i.e. maximum angle, range of motion, etc.) are often greater than the within-subject kinematic variability of these data (Frost et al., 2015). Thus, the group mean of descriptive values of joint angle data are often unrepresentative of individuals within the sample population (Frost et al., 2015). The purpose of generalized motor programs is to reduce the memory capacity within the central nervous system by storing only the necessary information required to perform a given movement (Schmidt, 1965). Thus, by using the SMSR algorithm to reduce joint motion to its basic elements, similarities between individuals may become more clear and less convoluted by variance attributed to subject specific modifications of a basic motion template used to perform a given task. The ability to generalize upper extremity kinematic changes, indicative of local muscle fatigue, across a population is necessary to reflect diverse occupational populations. The use of joint angles SMSRs instead of descriptive values of joint angle data could therefore be quite suited to identify generalizable features of upper extremity kinematics within a population.

Although there is considerable research on the relationship between shoulder muscle fatigue, upper extremity kinematics, and chronic injury, few have explored potential methods to translate this knowledge effectively into the workplace. Directional changes in upper extremity joint motion during repetitive tasks, in contrast to recent focus on joint angle magnitudes, may be visually identifiable to an observer. The SMSR algorithm provides a systematic approach to identify the basic structure of joint angle data based on directional changes in joint motion. Characterization of a potential relationship between directional changes in upper extremity joint motion and shoulder muscle fatigue, especially that of the rotator cuff, may provide a visually identifiable, generalizable, and non-invasive method for detecting localized muscle fatigue at the shoulder during repetitive tasks. Visual detection of upper extremity kinematic changes as an indicator of shoulder muscle fatigue in the workplace could cue ergonomic intervention focused on enabling mitigation or elimination of the deleterious consequences of shoulder muscle fatigue with the intent of reducing the prevalence of shoulder MSDs in the workplace.

4 PURPOSE & HYPOTHESES

The overall purpose of this thesis was twofold. First to determine if the basic structure of upper extremity joint angle data, characterized by the SMSR algorithm, changes across individuals during a workplace emulative repetitive task. Joint angle SMSRs characterize motion as a sequence of directional changes in joint angle time series data (Park et al., 2005), which can be visually identified by ergonomists (Lowe & Krieg, 2009). Second, to characterize the relationship between changes in thoracohumeral elevation SMSRs, and traditional indicators of shoulder muscle fatigue. In comparison to other upper extremity joint angles, the repetitive task studied requires a large range of thoracohumeral elevation joint motion. Thus, a change in upper extremity kinematics to redistribute loads away from fatiguing tissues at the shoulder and enable task performance should certainly involve a change in thoracohumeral elevation joint motion (Fuller et al., 2009, 2011, Gates & Dingwell, 2008, 2011; Lomond & Côté, 2011). The specific objectives, research questions and accompanying hypotheses are stated below.

1. **Objective:** To determine if multi-joint upper extremity kinematic changes with muscle fatigue, during a workplace emulative repetitive task, consist of potentially visually identifiable features represented by changes in joint angle SMSRs.

Research Question: In a healthy, university-aged population, are there changes in the SMSRs across upper extremity joint angles during a workplace emulative repetitive task?

Hypothesis: The changes in SMSRs of upper extremity joint angles will identify changes in movement strategies across upper extremity joints (i.e. torso, thoracohumeral, elbow and wrist), associated with the development of muscle fatigue during an emulative repetitive task. In response to muscle fatigue at the shoulder, the CNS will exploit the abundant degrees of freedom across joints within the upper extremity, employing a multi-joint strategy, to redistribute loads away from fatiguing tissues and enable task performance (Emery & Côté, 2012; Fuller et al., 2009; Lomond & Côté, 2011). This hypothesis is based on current research that has identified changes in average joint position and angles across upper extremity joints during fatiguing repetitive upper extremity tasks (Emery & Côté, 2012; Fuller et al., 2009; Lomond & Côté, 2011). With fatigue, a multi-joint approach to upper extremity movement reorganization is likely to cause a change in movement strategy, which is hypothesized to be captured by the SMSR representations of joint angle data across upper extremity joints during the repetitive task.

2. **Objective:** To determine the potential generalizability of SMSR representations of joint angle data by examining the variability of upper extremity joint angle SMSRs between participants during a workplace emulative repetitive task.

Research Question: Within the sample population of healthy university-aged individuals, is there variability in the SMSR of upper extremity joint angle data during a candidate workplace emulative repetitive task?

Hypothesis: The SMSRs of upper extremity joint angles will be the same across participants at a given joint angle. The SMSR will act as a 'filter' of the kinematic variability between participants by identifying the basic structure of time series joint angle data. Assuming that the basic motion structure identified by the SMSR algorithm represents the generalized motor program used by the CNS, the SMSR will characterize motion features that align with the goal equivalent manifold of the task (Cusumano & Cesari, 2006; Latash et al., 2002). That is, the SMSR will identify elements of joint motion that are instrumental to enabling task performance, with less emphasis on variations in joint motion that are not goal related and contribute to between-subject variability (Gates & Dingwell, 2008). Thus, the single criterion of a change in SMSR string, representing a change to the basic structure of motion, will provide a method to detect "meaningful" kinematic changes with muscle fatigue that are generalizable across participants.

3. **Objective:** To investigate whether the onset of potentially visually identifiable changes in thoracohumeral elevation joint angles, as identified by a change in SMSRs, can be used to identify the onset of infraspinatus muscle fatigue, as identified by a decline in the mean power frequency of the muscle's electromyogram (EMG), during a workplace emulative repetitive task.

Research Question: What is the temporal relationship between the onset of changes in thoracohumeral elevation SMSRs and the onset of EMG indicators of infraspinatus muscle fatigue?

Hypothesis: An EMG-based indication of infraspinatus muscle fatigue onset will precede the onset of changes in the thoracohumeral elevation SMSRs. This hypothesis comes from the existing theory that in repetitive upper extremity tasks, upper extremity kinematics change to redistribute demands away from fatiguing tissues to enable task completion (Cantú et al., 2014; Côté et al., 2002, 2005; Emery & Côté, 2012; Fuller et al., 2011; Lomond & Côté, 2011). As both a glenohumeral joint external rotator and stabilizer, in this repetitive task requiring external rotation, infraspinatus should be the first muscle at the glenohumeral joint to fatigue. With the assumption that fatigue drives the transition to a different movement strategy, a change in thoracohumeral elevation SMSRs will occur after the development of infraspinatus muscle fatigue.

4. **Objective:** To investigate whether a series of potentially visually identifiable changes in thoracohumeral elevation joint angles, as identified by a several intermittent changes in SMSRs, are related to local muscle fatigue at the shoulder, as identified by a decline in the mean power frequency of the muscles' EMG signals, during a workplace emulative repetitive task.

Research Question: Is there a relationship between the variability of thoracohumeral elevation angle SMSRs and indicators of muscle fatigue?

Hypothesis: Participants exhibiting more variability of thoracohumeral elevation angle SMSRs will have greater muscle fatigue accumulation. In repetitive goal directed tasks that elicit fatigue at the glenohumeral joint, motor variability increases across joints within the upper extremity (Fuller et al., 2009, 2011; Gates & Dingwell, 2011). This increase in motor variability with fatigue does not inhibit task performance, but may represent individuals exploring alternative movement strategies to redistribute demands away from fatiguing tissues (Gates & Dingwell, 2011; Madeleine et al., 2008). Thus, variability in thoracohumeral elevation angle SMSRs will be associated with local shoulder muscle fatigue induced by the repetitive task.

5 LITERATURE REVIEW

This literature review consists of six main sections. The first provides an overview of the shoulder complex, focusing on the boney, cartilaginous, and muscular elements of the shoulder complex, with a specific focus on their contributions to joint mobility and stability. The second section discusses muscle fatigue, and how it is measured, which is followed by a third section focused on the methods to identify changes in joint kinematics. The next two sections integrate the first three, in a discussion which highlights the current literature on joint kinematic changes with muscle fatigue. The final section provides a summary of the main points from the literature review and existing gaps.

5.1 Part 1: The Shoulder Complex

The human shoulder complex is an intricate mechanical system, consisting of the interactions between the thorax, scapula, clavicle and humerus. Precise control of these elements gives the upper extremity a very large range of motion, covering nearly 65% of a sphere (Enging & Chen, 1986). In fact, the large range of motion at the human shoulder complex has been proposed to have an evolutionary role in facilitating vertical climbing (Isler, 2005), and/or encouraging bipedal motion to carry objects (Latimer, 2005). However, in comparison to other terrestrial animals, the high range of motion at the human shoulder comes at the cost of low intrinsic stability of the joint complex (Veeger & van der Helm, 2007). The goal of this section is to provide a brief overview of the boney, cartilaginous, and muscular elements of the shoulder complex, with a specific focus on their contributions to joint mobility and stability.

5.1.1 Shoulder Girdle

5.1.1.1 Articulations

The clavicle, scapula and torso form a closed chain system referred to as the shoulder girdle. The primary function of the shoulder girdle is to position the glenoid fossa of the scapula, which articulates with the head of the humerus to form the glenohumeral joint, throughout the arm's range of motion (Veeger & van der Helm, 2007). Scapular motion, which occurs along the ribcage, is the result of the combined motion at the sternoclavicular and acromioclavicular joints (Van der Helm, 1994). Evidently, intricate muscular control is required to facilitate scapular movement, given the closed chain nature of the system. A force applied to one element of the system will have a direct effect on the others, facilitating movement or requiring compensatory reaction forces to maintain a static position. For example, motion at the sternoclavicular joint will result in scapular motion, unless compensated by motion at the acromioclavicular joint. The purpose of this section is to describe the articulations between the clavicle, scapula, and torso that form the shoulder girdle.

The sternoclavicular joint is a plane synovial joint formed between the medial end of the clavicle, the sternum, and the cartilage of the first rib. Joint integrity is maintained by an articular disc, the joint capsule, and ligaments. The articular disc, which spans from the upper portion of the medial clavicle to the sternum and first rib, prevents medial translation of the clavicle relative to the sternum (Peat, 1986). Anterior and posterior movement between the joint surfaces is limited by the anterior and posterior sternoclavicular ligaments, respectively (Peat, 1986). The costoclavicular ligament between the clavicle and first rib prevents excessive posterior rotation of the clavicle about the long axis of the thorax, referred to as protraction (Culham & Peat, 1993). Downward motion of the clavicle relative to the sternum is limited by the interclavicular ligament (Culham & Peat, 1993).

The articulation between the lateral end of the clavicle and the acromion process of the scapula forms the planar, synovial, acromioclavicular joint. In combination with the sternoclavicular joint, this joint forms the link between the appendicular and axial skeleton, connecting the upper extremity and the torso. Acromioclavicular joint stability is maintained by the superior and inferior acromioclavicular ligaments, and the weak joint capsule (Culham & Peat, 1993). The coracoclavicular (CC) ligament, between the coracoid process of the scapula and the clavicle, helps to maintain the relative position of the clavicle and scapula (Peat, 1986). The trapezoid portion of the CC ligament prevents the lateral end of the clavicle from sliding over the anterior surface of the acromion process (Peat, 1986). The conoid portion of the CC ligament plays an important role in facilitating posterior rotation of the clavicle during arm elevation (Veeger & van der Helm, 2007).

The thin, flat scapula bone is positioned over ribs two to seven on the posterior lateral aspect of the rib cage to form the scapulothoracic gliding plane. The articulation between the scapula and ribcage is not considered a joint because there are no fibrous, cartilaginous, or synovial tissues binding the two bones (VanPutte et al., 2009). In the absence of boney or ligamentous attachments between the anterior surface of the scapula and the ribcage, the articulation is maintained by the peri-scapular musculature or, in some circumstances, the external load applied to the hand (Veeger & van der Helm, 2007).

5.1.2 Glenohumeral Joint

5.1.2.1 Articulation

The glenohumeral joint is a multiaxial di-arthrodial joint that consists of the articulation between the head of the humerus and the glenoid fossa of the scapula. Internally, the humeral head is surrounded by a labrum which borders the glenoid fossa and externally by the coracohumeral, superior, middle and inferior ligaments, and the tendons of the rotator cuff musculature, which form the glenohumeral joint capsule (Peat, 1986). The concave, articular surface of the glenoid fossa is only $1/3^{rd}$ the size of the convex humeral head (Culham & Peat, 1993). This allows for high mobility at the glenohumeral joint, as only part of the humeral head is in contact with the glenoid fossa throughout the range of motion of the arm (Veeger & van der Helm, 2007). However, high mobility comes at the cost of low intrinsic stability.

From a mechanical perspective, an unstable glenohumeral joint is attained when the humeral head is dislocated from, or no longer articulating with, the glenoid fossa. Therefore, any process that contributes to maintaining the articulation between the humeral head and glenoid fossa contributes to glenohumeral joint stability. A fundamental characteristic of glenohumeral joint stability is the ratio between the shear and compressive force components of the net joint reaction force vector acting on the head of the humerus (Lippitt & Matsen, 1993). The net joint reaction force vector represents the sum of all muscle, ligamentous, and external forces acting on the humeral head. Dickerson et al., 2007, used available cadaveric data (Lippitt & Matsen, 1993) to develop a series of linear equations that give the glenohumeral joint dislocation ratio threshold along 8 equally spaced directions perpendicular to the glenoid fossa. If the glenohumeral joint shear to compressive force ratio exceeds the joint dislocation ratio threshold, the net joint reaction force vector at the center of the humeral head points outside of the glenoid fossa, excessive humeral translation relative to the glenoid fossa occurs, and glenohumeral joint becomes unstable.

At the glenohumeral joint, during activities of daily living, passive (ligamentous) tissues contribute only modestly to the joint reaction forces required to maintain glenohumeral joint stability. Throughout the mid-range of motion at the glenohumeral joint, moment contributions from the joint capsule are negligible. Maximum moments from the capsule only occur nearing the end range of motion (last 20°) (Blasier et al., 1997). The labrum also has very modest effects on maintaining the position of the humeral head in the glenoid fossa. Labrum resection on cadaveric specimens only reduced the shear to compressive force ratio by 10% (Halder et al. 2001). As a result, the role of the labrum is unlikely a mechanical means to maintain the articulation, but instead plays an important role in joint lubrication (Veeger & van der Helm, 2007). Evidently, glenohumeral joint stability during activities of daily living is maintained primarily through coordinated muscular control.

Although several muscles crossing the glenohumeral joint can contribute to maintaining joint stability, the rotator cuff muscles are primarily responsible. The rotator cuff muscles consist of the teres minor, supraspinatus, infraspinatus and subscapularis muscles. As a group, the rotator cuff muscles are particularly effective at maintaining glenohumeral joint stability for two reasons: 1) their line of action pulls the humeral head into the glenoid fossa, thus increasing the compressive joint reaction force, and 2) small moment arms, reducing potential counterproductive moments to joint motion (Veeger & van der Helm, 2007). Muscles with larger moment arms, such as the pectoralis major or latissimus dorsi can contribute to joint stability, but when active, may contribute a large counterproductive moment (opposite to the direction of motion) (Veeger & van der Helm, 2007). A more detailed description of the muscles acting on the shoulder complex and their mechanical functions will be described in detail in section 0.

5.1.2.2 Kinematics: Measurement

In contrast to bones of the shoulder girdle, the humerus is much larger and easier to collect position data using surface markers. However, to reduce error in the position data resulting from skin motion, cluster markers consisting of three reflective markers secured on a rigid plate, are typically secured approximately mid-length along the shaft of the humerus. Skin motion artifact is largest when surface markers are placed over anatomical landmarks at the joint, as the skin in these regions is stretched more during motion in comparison to areas further from the point of rotation (Cappozzo, 1997). Static calibration trials, in which the participant holds a posture or series of postures within the range of motion of the dynamic task, are used to develop an anatomical calibration matrix describing the position of the anatomical landmarks within the cluster coordinate system (Winter, 2009). With the assumption that this relationship remains constant, a direction cosine matrix between the global co-ordinate system and the humeral coordinate system is created using the position of the cluster markers, instead that of surface markers placed over the anatomical landmarks(Winter, 2009). Relative angles between the humeral and either scapular or thoracic coordinate systems can be calculated using this direction cosine matrix.

5.1.2.3 Kinematics: Relative Orientations

The orientation of the humerus is reported either with respect to the torso, referred to as thoracohumeral angles, or the scapular, referred to as glenohumeral joint angles. Glenohumeral joint angles require kinematic position data from both the scapula and humerus. Kinematic analysis of glenohumeral joint angles in combination with acromioclavicular, and sternoclavicular joint motion is useful in understanding the relative contribution of each joint within the shoulder complex to humeral motion. However, it can be quite difficult to accurately measure scapular and clavicular motion using surface techniques, which are subject to skin motion artifact due to the small and irregular shapes of these bones (McClure et al., 2001). On the other hand, thoracohumeral angles require position data from the humerus and torso, which is advantageous not only because they are easier to obtain using surface techniques, but they are also easy to observe and therefore applicable across clinical settings (van Andel et al., 2008). Local co-ordinate systems for the humerus, scapula and torso are computing using position data from anatomical landmarks on the segment. These coordinate systems are used to create a direction cosine matrix that describes the relative orientation of the distal segment (humerus) to the proximal segment (torso or scapula). The direction cosine matrices are then decomposed, using an Y-X-Y Euler sequence of rotation, to give three joint angles.

5.1.3 Musculature

At the simplest level of organization, there are 16 muscles acting on the shoulder complex. More commonly, however, 23 “muscles” are reported, as muscles, such as the deltoid or trapezius, are further divided based on the various orientations of fibers within the muscle (Van der Helm, 1994). The high mobility at the glenohumeral joint makes it difficult to classify muscular functions anatomically based simply on origin and insertions in a standard posture. Several muscle actions behave biphasically, such that for a given range of motion the muscle may have varying functions at the joint. For example, the infraspinatus muscle produces an elevation moment below 50° of elevation and depression moment above 50° of elevation (Kuechle et al., 1997). For parsimony, this initial section introduces the muscles acting on the shoulder complex based on their anatomical origin/insertion points. Muscular function is discussed in the subsequent section (Section 5.1.4).

5.1.3.1 Anatomical Origins and Insertions

Muscles of the shoulder complex that originate on the thorax, and have insertion points on the clavicle and scapula play an important role in scapular or clavicular motion. Muscles with scapular insertions are the serratus anterior, levator scapulae, rhomboids, middle trapezius, lower trapezius and pectoralis minor muscles (Table 1). The upper trapezius, and subclavis muscles insert on the clavicle (Table 1). Only two muscles, the sternal part of the pectoralis major and latissimus dorsi, originate on the thorax, but insert on the humerus (Table 2).

Table 1: The muscles of the shoulder complex that originate on the thorax, with insertion points either on the clavicle or scapula. Physiological cross sectional areas for each muscle as listed, and have been taken from Veeger et al., 1991.

Muscle	Physiological Cross Sectional Area (cm^2)	Origin	Insertion
Subclavius	-	Thorax	Clavicle
Upper Trapezius	15.99		
Middle Trapezius			Scapula
Lower Trapezius			
Serratus	13.93		
Levator Scapulae	2.82		
Rhomboids	6.27		
Pectroalis Minor	3.74		

The remaining muscles have an insertion point on the humerus and origins on the scapula or clavicle (Table 2). Muscles with a scapular origin consist of subscapularis, middle deltoid, posterior deltoid, supraspinatus, infraspinatus, teres major, teres minor, and coracobrachialis muscles. The anterior deltoid and clavicular portion of the pectoralis major muscle originate on the clavicle. Lastly, the biceps and triceps muscles originate on the scapula, but insert on radius and ulna, respectively.

Table 2: The muscles of the shoulder complex that insert on the humerus or forearm, with origins on the thorax, clavicle or scapula. Physiological cross sectional areas for each muscle as listed, and have been taken from Veeger et al., 1991.

<table>
<tr><th>Muscle</th><th>Physiological Cross Sectional Area (cm^2)</th><th>Origin</th><th>Insertion</th></tr>
<tr><td>Latissimus Dorsi</td><td>8.64</td><td rowspan="2">Thorax</td><td rowspan="12">Humerus</td></tr>
<tr><td>Pectoralis Major (Thoracic Part)</td><td rowspan="2">13.65</td></tr>
<tr><td>Pectoralis Major (Clavicular Part)</td><td rowspan="2">Clavicle</td></tr>
<tr><td>Anterior Deltoid</td><td rowspan="3">25.9</td></tr>
<tr><td>Middle Deltoid</td><td rowspan="10">Scapula</td></tr>
<tr><td>Posterior Deltoid</td></tr>
<tr><td>Subscapularis</td><td>13.51</td></tr>
<tr><td>Supraspinatus</td><td>5.21</td></tr>
<tr><td>Infraspinatus</td><td>9.51</td></tr>
<tr><td>Teres Minor</td><td>2.92</td></tr>
<tr><td>Teres Major</td><td>10.02</td></tr>
<tr><td>Coracobrachialis</td><td>2.51</td></tr>
<tr><td>Biceps Brachii (Medial Part)</td><td>3.08</td><td rowspan="3">Forearm</td></tr>
<tr><td>Biceps Brachii (Lateral Part)</td><td>3.21</td></tr>
<tr><td>Triceps Brachii</td><td>6.84</td></tr>
</table>

5.1.3.2 Physiological Properties

The effect of joint position on the function of muscles acting on the shoulder complex is primarily related to changes in moment arm size and not changes in muscle length. Muscles of the shoulder complex tend to be small with large fascicle lengths and large moment arms, in comparison to leg musculature (Klein Horsman et al., 2007; Langenderfer et al., 2004; Kuechle et al., 1997; Kuechle et al., 2000). Large fascicle lengths give the shoulder muscles long active force trajectories, as they are less sensitive to changes in overall muscular length. Thus, for a given change in total muscle length, the change in length of each fascicle, relative to its total length, is smaller. As a result, joint position has little effect on muscular force generating capacities as they operate near the middle of their force length curve throughout most of the joint range of motion (Veeger & van der Helm, 2007). However, joint position has a tremendous effect on the muscular moment generating capacity, dictating both the muscular line of action, and moment arm size.

5.1.3.3 Physiological Cross Sectional Area

Physiological cross sectional area is another characteristic that is important in understanding the function of each muscle. Previous work on determining the physiological cross sectional areas of shoulder muscles has been primarily on cadaveric specimens. To determine a muscles physiological cross sectional area, the volume of the muscle is divided by the length of the muscle fiber or fascicle. The muscle of interest is carefully dissected from the upper limb, and its volume is measured using a water displacement technique. Recently, the tendon of the muscle was removed prior to this, and its cross sectional area measured separately. Muscle fiber or fascicle lengths are measured using a micrometer (Bassett et al., 1990), or, in recent work, derived from the measurement of sarcomere lengths using laser diffraction (Langenderfer et al., 2004, 2006).

The relationship between a muscle’s physiological cross sectional area, and maximal force generating capacity is influenced by its architecture. In fusiform muscles, where the orientation of the muscle fascicles align with the distal and proximal tendons, the physiological cross sectional area is related linearly to its maximal force generating capacity (De Luca & Forrestt, 1973). However, this is not the case for muscles of the shoulder complex. With the exception of the biceps brachii muscle, the muscle fascicles are oriented on an angle (pennation angle) relative to the line connecting the distal and proximal tendons (Langenderfer et al., 2004). To account for this, muscular force generating capacity is therefore calculated as the product of the muscle's physiological cross sectional area and the cosine of the pennation angle. Typically, muscle pennation angles are measured using a goniometer on cadaveric specimen (Langenderfer et al., 2004, 2006). After the muscle and tendon has been carefully removed from the specimen, the angle between the muscle fascicles, relative to the line connecting the proximal and distal tendons is recorded to the nearest degree (Langenderfer et al., 2004, 2006).

5.1.3.4 Potential Moments

In order to deduce the function of a given muscle at a joint, the muscle's maximum potential moment generating capacity must be considered. This metric provides a biomechanical basis to interpret the muscles that are most capable of producing a given joint moment as it considers both the magnitude of the muscular force exerted along the muscular line of action, and the size of the moment arm about the joint of interest (Bassett et al., 1990). A moment arm is defined as the distance between the muscle's line of action and the joint center of rotation, about a given joint. The maximum potential moment that can be generated by a muscle is the product of its moment arm size, physiological cross sectional area, and the cosine of its pennation angle (Langenderfer et al., 2004; Murray & Johnson, 2004). Analyses that only consider muscle force (physiological cross sectional area) or moment arm size in determining muscular function can be very misleading. For example, at the shoulder, teres minor often has a slightly larger external rotation moment arm than infraspinatus at the glenohumeral joint, but due to a larger physiological cross sectional area, infraspinatus has a larger external rotation potential moment than the teres minor muscle (Kuechle et al., 2000).

Accurate estimates of muscle moment arms are important in determining a muscles' potential moment at a given joint. Several methods have been used to estimate moment arm size of shoulder muscles. In vitro measurement of moment arms consist of digitization of radiographs (Poppen & Walker, 1978) or 3D approximation using a reconstruction from MRI images (Graichen et al., 2000). In vivo techniques include reconstruction of cadaveric cross sections, and tendon excursion methods. Tendon excursion methods are the most common in vivo technique used to measure the moment arms of the shoulder musculature (Ackland & Pandy, 2011; Ackland et al., 2008; Kuechle et al., 1997, 2000). Moment arms are calculated on cadaveric data by measuring tendon displacement at various joint angles, and assuming that the slope of the tendon length and joint angle curve represents the instantaneous moment arm length of the muscle. Recent shoulder models have incorporated mathematical representations of bone and muscle geometry, and a combination of cylindrical and spherical muscle wrapping techniques to estimate muscle moment arm sizes in various postures (Dickerson et al., 2007; Webb et al., 2014). Mathematical approximations of rotator cuff moment arm sizes are comparable to available empirical data (mostly tendon excursion methods) (Gatti et al., 2007). This is advantageous as it allows for estimates of moment arm sizes in postures that have not been measured experimentally and makes it possible to determine the relative effect of specific moment arm sizes on biomechanical variables of interest (i.e. muscle activation).

5.1.4 Muscle Functions

A number of factors, such as the moment generating capacity, line of action, and contribution to maintaining joint stability, dictate a muscle's function at a given joint. The close chain mechanism of the shoulder girdle and the high mobility at the glenohumeral joint make it difficult to isolate the function of shoulder musculature. The large mobility at the glenohumeral joint results in muscle moment arm sizes that vary significantly with changes in joint position (Ackland & Pandy, 2011; Ackland et al., 2008; Kuechle et al., 1997, 2000). As a result, a given muscle may have the capacity to generate a moment in opposite directions (i.e. flexion vs. extension) depending on glenohumeral joint position. Muscular function is further complicated by the coupling between joints of the shoulder complex, in that activation of one muscle may cause moments at accessory joints. For example, activation of the latissimus dorsi muscle to generate an abduction moment at the glenohumeral joint also causes abduction moments at the acromioclavicular and sternoclavicular joints (Veeger & van der Helm, 2007). Despite the intention to abduct the humerus, unless counteracted by the neuromuscular system, scapular motion will also result.

At the glenohumeral joint, muscles with both large moment arms physiological cross sectional areas are considered prime movers. The following four muscles are commonly given this title: 1) deltoid, 2) pectoralis major, 3) latissimus dorsi, and 4) teres major. The anterior and middle deltoid muscles generate elevation moments about the glenohumeral joint, while the posterior deltoid primarily generates horizontal extension moments about the glenohumeral joint (Kuechle et al., 1997, 2000). The pectoralis major muscle contributes to both horizontal extension and internal rotation moments about the glenohumeral joint (Kuechle et al., 1997, 2000).. Depending on joint position, the pectoralis major muscle can also create a depression moment, however the muscles primarily responsible for this are the teres major and latissimus dorsi muscles (Kuechle et al., 1997, 2000). The coupling of the prime mover muscles at the glenohumeral joint to a given joint moment, as presented in this paragraph, is certainly not definitive. As discussed previously, muscle function is highly dependent on joint position. Further, it is quite unlikely that the line of action these muscles aligns with a single axis of rotation at the glenohumeral joint, meaning that each muscle will generate moments about multiple axes. For these reasons, biomechanical models of the shoulder complex are essential to understanding the task-dependent function of the muscles at the glenohumeral joint.

The rotator cuff muscles, with small physiological cross sectional areas and moment arms are considered glenohumeral joint stabilizers. This classification is not based on the moment generating capacities of these muscles, but rather their line of action (Veeger & van der Helm, 2007). Forming a half circle around the head of the humerus, the infraspinatus, supraspinatus, teres minor, and subscapularis muscles pull the head of the humerus into the glenoid fossa. These muscles generate a compressive force at the glenohumeral joint, pulling the humeral head into the glenoid fossa. Glenohumeral joint stability requires the maintenance of a certain a shear to compressive force ratio, dictated by the direction of the shear force (Lippitt & Matsen, 1993). By generating a compressive force, the rotator cuff muscles serve to reduce the shear to compressive force ratio, and mitigate the risk of glenohumeral joint dislocation.

Although the primary role of the rotator cuff muscles is to maintain glenohumeral joint stability they also contribute modestly to joint moments. However, given the proximity of these muscles to the glenohumeral joint center, their moment generating capabilities are arguably even more position dependent than the prime movers. Supraspinatus and teres minor contribute to glenohumeral joint elevation and depression, respectively (Ackland et al., 2008; Kuechle et al., 1997). Infraspinatus and subscapularis can act as either glenohumeral joint elevators or depressors, depending on the joint position (Ackland et al., 2008; Kuechle et al., 1997). Subscapularis is the only rotator cuff muscle to contribute to horizontal flexion at the glenohumeral joint, as the other muscles create horizontal extension moments (Kuechle et al., 1997). In contrast to modest contributions from the rotator cuff muscles in elevation/depression and horizontal flexion/extension at the glenohumeral joint, the infraspinatus muscle is the most efficient glenohumeral joint external rotator (Ackland & Pandy, 2011; Kuechle et al., 2000; Langenderfer et al., 2006). The teres minor muscle also generates an external rotation moment, but this is smaller than that generated by the infraspinatus muscle due to the small physiological cross sectional area of this muscle (Ackland & Pandy, 2011; Kuechle et al., 2000; Langenderfer et al., 2006). Supraspinatus typically generates a small external rotation moment at the glenohumeral joint, while subscapularis generates a large internal rotation moment at the glenohumeral joint (Ackland & Pandy, 2011; Kuechle et al., 2000; Langenderfer et al., 2006). Despite modest contributions to glenohumeral joint moments in two out of three planes of motion, the rotator cuff muscles, especially infraspinatus, are significant contributors to humeral axial rotation.

5.2 Part 2: Muscle Fatigue

Muscle fatigue is a time and exposure dependent process has widespread effects within the neuromuscular system. By definition muscle fatigue is a biological process that begins soon after the onset of neuromuscular activity and causes a transient decline in the maximal force generating capacity of skeletal muscle (Enoka & Duchateau, 2008). In tasks composed of repetitive or sustained submaximal efforts, muscle fatigue increases an individuals' perceived effort and eventually leads to the inability to produce the required force (Enoka & Stuart, 1992).The processes contributing to muscle fatigue are dependent on several task characteristics such as: the muscle group(s) involved, the intensity of the contraction, whether the effort is continuous or intermittent, and subject characteristics such as motivation, age, and gender (Barry & Enoka, 2007).

The neuromuscular processes contributing to skeletal muscle fatigue are classified as either central or peripheral factors, according to the location of the process along the neuromuscular pathway. Central muscle fatigue is defined as “a progressive reduction in voluntary activation of muscles during exercise” (Gandevia, 2001). Specifically, central fatigue includes processes, proximal to the neuromuscular junction, that inhibit the neural drive to motor neurons. With fatigue, both transcranial (targets motor cortex) and motor point (targets motor neuron) stimulation increase an individual’s maximum force output, indicating that central muscle fatigue occurs at both the spinal and supraspinal levels (Gandevia et al., 1996). Peripheral muscle fatigue includes any change to processes at and distal to the the neuromuscular junction that contribute to excitation-contraction coupling failure (Enoka, 2000). Most notably, at the individual muscle fiber level fatigue results in changes to intercellular metabolites that reduce the sensitivity of the fibers to Ca^{2+} (Allen et al., 2008). A reduction in Ca^{2+} sensitivity decreases the number of cross bridge cycles that can be initiated, thus reducing the contractile ability of the muscle fiber (Allen et al., 2008).

5.2.1 Measurement of Muscle Fatigue

Several measures of muscle fatigue exist, with varying sensitivities to the spectrum of neuromuscular processes involved in muscular contraction. Therefore, it is important to understand the breadth of information provided by each method. Further, it is quite common to take a multitude of measures of muscle fatigue, that in combination, can help provide an account of the site(s) of transient impairment.

5.2.1.1 Maximum Force Generating Capacity

Muscle fatigue is most commonly measured as a reduction in maximum voluntary force (MVF), following exercise. A comparison of the pre-fatigued MVF, with that measured throughout or following fatiguing efforts, provides an indication of the overall level of muscle fatigue (Vøllestad et al., 1997). Further, this metric provides an indication of the "sum" of all impairments, either central or peripheral, due to the decline in muscle force generating capacity. The relative contribution of central factors to the muscle force impairment is identified by comparing an individual's maximal voluntary force output with that measured when an external electrical stimulus is applied to the muscle of interest. An increase in force, resulting from the electrical stimuli delivered to an individual who is contracting maximally, indicates a decline in voluntary activation of the muscle and serves as evidence of central fatigue (Gandevia et al., 1996).

5.2.1.2 Electromyography(EMG)

With muscle fatigue, changes to the EMG signal occur in the time and frequency domains. In sustained isometric efforts, the amplitude of EMG signal increases as fatigue accumulates (Jørgensen et al., 1988). Controversy exists regarding the mechanisms behind the increase in EMG amplitude with fatigue. Some authors suggest the increase in signal amplitude represents recruitment of additional motor units within a muscle to compensate for the fatigue induced force impairment, while others suggest it is the result of increased firing rate or motor unit synchronization with fatigue (Dimitrova & Dimitrov, 2003). Alternatively, a decrease in the mean or median power frequency of the EMG signal is used to indicate muscle fatigue. The shift in the spectral characteristics of the EMG signal with fatigue has been attributed to the following: 1) a decrease in the conduction velocity of the action potentials along the muscle fiber, 2) drop out of the faster motor units (shorter duration motor unit action potentials), and 3) motor unit synchronization (Winter, 2009).

Spectral characteristics of the EMG signal, such as the mean or median power frequency (MPF; MDPF), are also used to detect muscle fatigue. In comparison to EMG signal amplitude, changes in EMG MPF or MDF can provide a more direct indicator of muscle fatigue in repetitive work. The amplitude of the EMG signal is influenced by load (%MVC) and muscle fatigue accumulation (Bartuzi & Roman-Liu, 2014; Oberg et al., 1991; Roman-liu & Konarska, 2009; Roman-liu et al., 2004). Thus, motor adaptations in repetitive work that redistribute the load between muscles can make it difficult to identify whether an increase in EMG amplitude represents fatigue, an increased contribution (load) to joint torque, or both. However, EMG MPF and MDPF have little sensitivity to changes in load (%MVF) at low to moderate intensity levels (Bartuzi et al., 2015; Roman-Liu & Konarska, 2009). In particular, EMG MPF and MDPF from the trapezius, biceps brachii and triceps brachii muscles during sustained efforts do not vary with changes in load at low levels typical of repetitive work (10-30% MVF) (Bartuzi & Roman-Liu, 2014; Roman-liu & Konarska, 2009). Although either measure does not vary significantly with changes in load, there is evidence that EMG MPF is even less sensitive to changes in load (%MVF) in sustained efforts than EMG MDPF (Roman-Liu, 2016). Ultimately, this suggests EMG MPF, in comparison to EMG amplitude measures, provides an indication of muscle fatigue accumulation that is independent of effort intensity in efforts of 10% MVF or greater.

Although EMG MPF is not influenced by effort intensity above 10% MVF, there are other factors, aside from muscle fatigue, that can influence the EMG MPF of the signal. A major factor to consider is joint position as differences in joint position can change muscle lengths. A longer muscle length, in comparison to shorter muscle lengths, reduces the conduction velocity of action potentials within the muscle (Roman-Liu, 2016). Thus, the longer the muscle is the lower the values of EMG MPF. To mitigate this potential confounding factor, when using EMG MPF to indicate muscle fatigue, a static reference task in which individuals assume the same posture to complete a sustained isometric effort is used to obtain muscle EMG MPF values.

At joints that include several muscle synergists and have a large range of motion, it can be difficult to obtain a static reference task that eliminates the potential effects changes in joint position on muscle lengths and subsequently muscle EMG MPFs. Oberg et al., (1990,1991) reported a +/- 8.8% of baseline change in EMG mean power frequency of the trapezius muscle when static efforts were performed at different joint positions ranging from 30°-135° and with two different loads (~20%MVF and ~40% MVF). Despite the fact that this study focused on a single muscle at the shoulder, several authors have utilized a decline in mean power frequency greater than 8.8% of the initial value, as an indicator of muscle fatigue that is not related to changes in joint position or load based on the recommendations of Oberg et al., (1990,1991). The authors also recommend multiple measurements or regression analysis, especially with regards to obtaining a baseline value of a muscles' EMG MPF, to reduce random variation in the mean power frequency of the signal.

5.2.1.3 Perceived Ratings

Psychophysical ratings scales are commonly used to infer the level of muscle fatigue accumulation, especially in settings where laboratory equipment is not available, such as the workplace. Psychophysics is the study of the relationship between perception and physical intensity (Stevens & Mack, 1959). Subjective ratings provide information about a participant's experience that may be difficult to measure physically or physiologically, which is commonly obtained using one of Borg's Scales; either the rating of perceived exertion (RPE) scale, or the category ratio scale (Borg, 1990). The RPE scale ranges from 6-20 and is often used to obtain perceived effort during tasks where a comparison of the scale rating to physiological measures, such as heart rate and blood lactate concentration, are of interest (Borg, 1990). The category ratio scale ranges from 1-10 and is designed to give an indication of direct intensity levels of the exertion and can be compared across individuals or groups of people (Borg, 1990). Theoretically, RPE ratings can provide insight into muscle fatigue accumulation as the perception of perceived muscular effort depends on the required force and duration of the effort, both of which also influence muscle fatigue accumulation (Stevens & Cain, 1970).

Variations of the category ratio scale, such as ratings of perceived discomfort or fatigue, have also been used in fatigue research. These measures use the same basic structure as the category ratio scale but include modifications to the verbal instructions provided to participants (Wiker et al., 1990). Ratings of perceived fatigue and discomfort are valuable to assess an individuals' capacity to perform overhead work, which is not related to their upper-extremity strength capabilities (Wiker et al., 1990).

5.2.1.4 Kinematics

Joint kinematic changes with muscle fatigue are both task dependent and exhibit large between subject variability. However, proper analysis of these changes can provide valuable information regarding the effects of muscle fatigue on joint mechanics and neuromuscular control. A thorough discussion of joint kinematics and muscle fatigue will follow in the remaining sections of this literature review.

5.2.2 Sex Differences

Sex differences in muscle fatigue response are multifactorial. In sustained isometric tasks scaled to individuals' maximal strength, women are less fatigable than males as they exhibit longer endurance times (Clark et al., 2003; Yoon et al., 2007). The magnitude of the difference between the sexes is dependent on effort intensity, with larger differences at lower relative intensities (Hunter, 2009). A proposed mechanism for the sex differences in sustained isometric efforts is the fact that men exert a greater absolute force than women when the effort intensity is scaled to individuals' maximal strengths (Hunter, 2009). Higher absolute force levels in males result in higher intermuscular pressure which causes blood flow occlusion leading to more rapid accumulation of metabolites and reduced oxygen delivery to the muscle (Hicks et al., 2001; Yoon et al., 2007). Therefore, in sustained isometric efforts scaled to individuals' maximum strength, absolute strength differences between the sexes contributes to differences in the fatigue response between men and women.

In intermittent isometric efforts, periods of rest prevent continuous blood flow occlusion to working muscles, yet there is still a sex difference in the fatigue response suggesting alternative mechanisms. In a task comprised of intermittent elbow flexion efforts (50% MVC) at a duty cycle of 50% (5s effort, 5s rest) females exhibited longer endurance times as well as a slower rate of decline in maximal force generating capacity as compared to males (Hunter et al., 2004) . A primary mechanism behind this sex difference may be that males have a greater proportional area of type II muscle fibers in the elbow flexor muscles as compared to females

(Hunter et al., 2006). Type II fibers generate more force and are more fatigable than type I muscle fibers (Allen et al., 2008).

In upper extremity, repetitive, goal directed tasks an absence of sex differences in fatigue metrics (i.e task endurance time) may be attributed to sex differences in muscle activation strategy. In a repetitive reaching task performed until failure, men had a relatively larger and smaller increase in upper trapezius and biceps muscle activation variability, respectively (Srinivasan et al., 2016). The authors build on previous hypotheses that suggest that sex differences in motor control strategies during low to moderate force level repetitive tasks may explain why there is no difference in task endurance time between sexes (Côté, 2012; Hunter, 2014; Srinivasan et al., 2016). Nonetheless, sex differences in muscular activation patterns during repetitive tasks are important to study to understand potential injury risk over time.

5.2.3 Recovery of Muscle Fatigue

Recovery of muscle fatigue is the reversal of fatigue-related changes back to their baseline state. Recent work has shown that in addition to periods of complete rest, recovery is possible during continuous tasks with variations in the submaximal effort level (Sonne et al., 2015; Yung et al., 2012). The rate of recovery also differs between fatigue measures. Typically, myoelectric changes return to baseline sooner than the recovery of muscular force generating capacity (Baker et al., 1993). Further, the duration of the task influences the recovery of muscular force generating capacity such that the longer the task, the longer the recovery, but this does not hold true for the recovery of myoelectric changes with fatigue (Baker et al., 1993).

5.3 Part 3: Kinematic Analyses of Joint Motion

Kinematic analysis of joint motion provides valuable information regarding the neuromuscular control and biomechanics of human movement. Often, researchers use kinematic analyses to infer the effect of a given variable on neuromuscular function. Such experimental designs require the use of a threshold or boundary criteria that distinguishes between typical kinematic variability, and that which is "significant" or "meaningful" (Frost et al., 2015). The purpose of this section is to discuss the current approaches used to determine significant differences in joint kinematics.

5.3.1 Group Analyses

Most commonly, multifactorial repeated measures analysis of variance (ANOVA) are used in kinesiological research to determine the effect of independent variable(s), and their interactions, on the group mean of a dependent variable. The independent variable can be considered a "condition", and measures of the dependent variable are taken from each participant under each condition. The repeated measures design is advantageous because it: 1) reduces variability among subjects as each serves as their own control and 2) requires a fewer number of subjects (Daniel, 1999). In a repeated measures ANOVA, the effect of independent variable(s) on a dependent variable is considered significant if the differences in group means associated with the tested independent variable(s) are larger than the variability within the group. Quite commonly, kinematic variables (i.e. joint angles) exhibit large between subject variability in the sample population (Frost et al., 2015). Further, given that the variability within any individual is less than that at the group level, meaningful adaptations in joint kinematics within individuals are difficult to identify using a repeated measures ANOVA (Frost et al., 2015).

5.3.2 Within Subject Variability

As an alternative to analysis of group means, significant kinematic changes (i.e. joint angles) within individuals, can be identified using between-trial kinematic variability. Frost et al., (2015), proposed a method to identify a limit of participants' biological variability; the 25 trial mean +/- 2SD. If the magnitude of the kinematic variable exceeds this boundary, the change is considered significant. Further, the authors established a relationship between the upper limits of an individual's variability and the number of trials used to compute the mean (sequential mean) which was consistent across participants. Overall, this approach is advantageous in that it provides a method to identify within-subject changes in joint kinematics, using within subject variability, without having to collect a vast number of data samples.

5.3.3 Movement Strategy

Time series analyses of joint angle data often aim to identify different movement strategies for a given task. In general, these approaches cluster joint angle time series data using predefined mathematical algorithms. Several methods require a priori specification of the movement characteristics used to group the data (Park et al., 2005b). These models are not able to account for movement progression or variability, but instead sort the joint angle time series data on the basis of the conditions defined a priori (Choudry et al., 2013). In contrast, Choudry et al., (2013) recently developed an approach that can identify movement strategies without requiring a priori assumptions. This approach consists of training strategy specific hidden Markov models using a divisive clustering technique. Ultimately, data are partitioned in a hierarchal tree structure that contains a node for each movement strategy identified within the data set. Then, differences between a given pair of movement strategies (nodes) can be discerned using a degrees of freedom analysis. Essentially, through a process of elimination, joint angles are removed from the observation distribution functions (represent the joint angle data within the cluster) until the one which results in the greatest dissimilarity between the two hidden Markov models remains. This joint angle is the most different between the movement strategies. This major strength of this technique is that it can identify whole body movement strategies from a series of time series joint angle data, without a priori assumptions about which features of movement define each strategy.

The generalized motor program theory has also been used as a foundation guiding time series analyses of joint angle data. The generalized motor program theory suggests that generalized motor programs (GMPs) exist as memory structures within the central nervous system that are used as a template for movement planning (Schmidt, 1965). Each GMP consists of fixed (invariant) features and parameters (variant features) that can be modified according to the task requirements (Park et al., 2005b). The use of GMPs does not require an infinite memory capacity within the central nervous system, and provides an explanation as to how novel motions can be easily executed (Schmidt, 1965).

Kinematic analyses of human motion using repeated measures designs, have identified both variant and invariant features of movements, supporting the GMP theory. Typically, individuals perform a variety of tasks with characteristics that differ either spatially or temporally from one another. Kinematic similarities and differences in the motions used to complete each task are interpreted as variant and invariant features of the GMP, respectively (Park et al., 2004). In tasks that maintain the same spatial characteristics, but differ temporally (task duration), the central nervous system compresses the motion in the time domain (ie. joint angle vs. time graph) (Carter & Shapiro, 1984; Park et al., 2005b; Schmidt, 1965). Although overall movement speed changes, when expressed relative to total movement time, both the duration of motion segments as well as the time at which peak velocity is attained remain constant. Therefore, the relative timing of motion segments is an invariant feature of GMPs but speed is a variant feature. Park et al., (2005) created a symbolic motion structure representation (SMSR) algorithm to identify 'invariant features' of time series joint angle data, analogous to the GMPs used by the central nervous system. The motivation behind the development of the SMSR algorithm was to identify the basic features of motion that can be used to predict upper extremity movement in seated reaches, given the start and end positions of the hand. The SMSR algorithm identifies the basic structure of a motion in the joint angle-time space by creating a string of characters representing the monotonically increasing (***U***), decreasing (***D***), or stationary (***S***) segments determined using physiologically based criteria. Park et al., (2005) then created a computational model which uses "stored" SMSR strings, representative of a set of joint angle trajectories, to predict novel motions which differ spatially from the "stored" movement. A motion modification algorithm is used to generate the joint angle trajectory of a novel motion using the SMSR string of an existing motion as a motor template (GMP analogy) and new initial and final joint postures. The motion modification algorithm changes variant features of the joint angle time series data but maintains the SMSR string and therefore the sequence of motion segments. Using this procedure, Park et al., (2005) accurately predicted time series joint angle data for a set of tasks across individuals.

Although intended for motion prediction, the SMSR algorithm may be useful to identify different movement strategies, within an individual, from time series joint angle data. In comparison to the approach outlined by Choudry et al., (2013), the SMSR algorithm is much simpler to apply to time series joint angle data. However, this simplicity does come at a cost. The SMSR algorithm must be applied to each joint angle trajectory individually and will provide limited descriptive data about a given movement strategy. The SMSR algorithm segments the time series joint angle data to establish the basic structure of the movement, which is outputted as a character string. In doing so, the SMSR string is not sensitive to segment amplitudes (variant features), yet instead is concerned with the slope (invariant feature). It is likely that the SMSR string will be much less variable across individuals, than joint angle data, as it will not account for between subject differences in segment amplitudes (magnitudes of joint angles). With these limitations, the SMSR algorithm should not be used to identify different movement strategies between individuals. However, it may provide a very useful method to detect a change in movement strategy within an individual. By comparing the frequency of each string segment across a series of movements performed at baseline, and then following an intervention or perturbation of the neuromuscular system (i.e. muscle fatigue accumulation), a change in movement strategy can be detected. The SMSR string provides limited quantitative information about each movement strategy, limiting its use in assessing injury risk, its strength is the simplicity of the method in detecting a change in movement strategy within an individual. The same criterion of a change in the SMSR string relative to baseline, to identify a change in movement strategy, can be applied across individuals in a population.

5.4 Part 4: Local Muscle Fatigue & Glenohumeral Joint Kinematics

5.4.1 Joint Kinematics of the Shoulder Complex

Local fatigue protocols, designed to preferentially fatigue a subset of muscles, induce an imbalance in moment generating capacities at the joint of interest. The local fatigue protocols are designed to reduce the degrees of freedom available to the neuromuscular system to maintain task performance, thus requiring the overuse of the targeted muscles until task failure. Individual joint kinematic changes observed during a reference task, between rested and fatigue states, are interpreted with EMG indicators of muscle fatigue to deduce the mechanical implication of a transient impairment to the function of these muscles. This section highlights key findings of this body of research, which have been divided on the basis of the fatigue protocol.

5.4.1.1 Glenohumeral Elevation

The observed kinematic changes with muscle fatigue induced by repetitve arm elevation tasks appear to be related to the complexity of the fatiguing protocol. Mc Quade et al., (1998), had participants complete maximal arm elevations from rest to the end of their range of motion in the scapular plane (2s duration), while seated until exhaustion. A significant decline in the MPF of the EMG, indicative of muscle fatigue, was present in all recorded muscles: the trapezius (upper and lower), middle deltoid and serratus anterior muscles. The observed increase in scapular upward rotation, between the start and end of the task, was correlated with the changes in EMG MPF of each muscle. Ebaugh, et al., (2006a), used a more complex elevation fatigue protocol incorporating both static and dynamic elevation tasks across glenohumeral joint plane of elevation. Participants completed consecutive cycles composed of a 2 minute manipulation of small objects while maintaining 45° of elevation, and 40 reps of elevation (20% MVF), 20 in the scapular plane and 20 diagonally across the body until exhaustion. Rested and fatigued joint motion during seated arm elevation in the scapular plane was compared before and after the fatigue protocol. This protocol fatigued the upper trapezius, deltoid (anterior and posterior), serratus anterior, and infraspinatus muscles, but not the lower trapezius muscle. The following angle dependent kinematic changes occurred: 1) scapular upward rotation increased (60,90,120°, max), 2) scapular external rotation increased (90, 120°, max), 3) scapular posterior tilt decreased (minimum elevation position), 4) clavicular retraction increased (60,90,120°, max), and 5) clavicular elevation increased (90°). Across all elevation angles, humeral external rotation angle decreased with fatigue. These studies demonstrate that regardless of the complexity of the fatiguing protocol, increased scapular upward rotation was a mechanical consequence of glenohumeral elevation induced muscle fatigue. Further, Ebaugh et al., (2006a), showed that a fatigue protocol which includes multi-planar elevation results in kinematic changes across all three planes of scapulothoracic gliding plane motion. They also observed kinematic changes at the sternoclavicular and glenohumeral joints, which were not measured by McQuade et al., 2008.

5.4.1.2 Glenohumeral Axial Rotation

Similar to elevation fatigue protocols, variability in the fatigue response exists with a variation in external rotation fatigue protocols. Tsai, McClure, & Karduna, (2003), had participants performed repetitive external rotation against the resistance of a medium Thera-band, alternating between 45° of internal rotation and neutral at 1Hz frequency. The authors decided that the fatiguing task would terminate when there was a 25% decline in external rotation isometric torque, as this corresponded to infraspinatus muscle fatigue (decline in MPF) during a pilot study. A total of 18 subjects, who did not participate in the pilot study, completed the fatigue protocol until they reached a 25% reduction in external rotation isometric torque.

Joint kinematics during elevation in the scapular plane were tracked before and after the external rotation fatigue protocol. The observed changes in scapular kinematics were elevation angle dependent as follows: 1) decreases in scapular posterior tilt (0-90deg), 2) decreases upward rotation (0-60°) and 3) increased internal rotation (0-120°). Ebaugh, McClure, & Karduna, (2006b) studied kinematic changes following a external rotation fatigue protocol consisting of cycles of both static and dynamic external rotation tasks. Laying on their non-dominant side, in 10-20° of glenohumeral joint abduction in the frontal plane, participants were asked to maintain 0° of external rotation while manipulating small objects in their hand for 2 minutes. This was followed by 20 reps of resisted external rotation (20% MVF) starting with their hand across their body, until it was parallel to the floor. Consecutive cycles of these two tasks were completed until exhaustion. Consistent with the findings of Tsai et al., (2003), decreased scapular posterior tilt was observed with infraspinatus fatigue. However, scapular upward rotation increased (at 60&90° of elevation) and there was a trend of increased scapular external rotation, opposite to what was observed by Tsai et al., (2003). Ebaugh et al., (2006b) also observed kinematic changes at the sternoclavicular and glenohumeral joints, which were not measured by Tsai et al., (2003). Clavicular retraction and humeral external rotation decreased with fatigue. A possible explanation for the difference in kinematics observed between these two studies is the level of fatigue attained during the external rotation tasks. Tsai et al., (2003) did not record EMG from the participants who completed the external rotation fatiguing task or report perceived ratings of fatigue or task duration. This makes it difficult to compare with Ebaugh et al., (2006b), in which infraspinatus fatigue was confirmed by changes to EMG MPF, the average fatigue protocol duration was 14 min and 45s, and the average RPE at the end of the fatigue protocol was 19.6/20.

The most likely explanation for the kinematic changes observed by Tsai et al., (2003), in comparison to Ebaugh et al., (2006b), is that the external rotation fatigue protocol was not specific to infraspinatus, and resulted in fatigue to other muscles, as well. Chopp, Fischer, & Dickerson, (2011), repeated the same external rotation fatigue protocol on ten subjects, using a task termination criteria of a rating of perceived exertion of 10 on the Borg CR-10 scale, which is considered exhaustion (Borg, 1990). The external rotation fatigue protocol was interrupted every minute and subjects completed a 5s submaximal static hold of a water bottle that was weighted at 15% of their external rotation MVF. This submaximal effort was used to compute EMG MPF of the supraspinatus, infraspinatus, upper trapezius, serratus anterior, and middle deltoid muscles throughout the fatiguing task. In contrast to the findings of Tsai et al., (2003), they reported that none of the muscles had a significant change in EMG MPF indicative of muscle fatigue, and concurrently, no significant changes in scapular kinematics.

The diversity of fatigue repsonses following the external rotation fatigue protocols provides insight into the mechanical function of the infraspinatus muscle. Regardless of the external rotation fatigue protocol, when infraspinatus was fatigued, scapular posterior tilt decreased (Ebaugh et al., 2006b; Tsai et al., 2003). Further, when infraspinatus fatigue was not induced by an external rotation protocol there were no changes in posterior tilt (Chopp et al., 2011). The link between infraspinatus fatigue and scapulothoracic posterior tilt is suprising, as the infraspinatus muscle acts on the glenohumeral joint as an external rotator, and scapular tilting is attributed to scapulothoracic muscles, such as serratus anterior, with favorable moment arms (Borstad et al., 2009). However, infraspinatus fatigue does influence the SHR by reducing external rotation of the humerus with elevation in the scapular plane. It is possible that these changes in SHR elicit a compensatory response in the scapulothoracic musculature, which is responsible for the changes in scapulothoracic gliding plane motion (decreased posterior tilting) (Ebaugh et al., 2006b).

5.4.1.3 Scapulothoracic Musculature

Following a fatigue protocol which required a significant contribution from both the serratus anterior and infraspinatus muscles (>70% MVE), changes in both scapular tilt and internal rotation were observed. Borstad et al., (2009), designed a modified push-up plus task in which participants held the position assumed when the arms are extended at the start of a push up, with the following alterations: 1) engaging in a concious effort to protract their scapula, and 2) a 90 degree angle between the trunk and humerus facilitated by raising participant's feet off the ground onto a step. The task was completed until exhaustion, when participants could not longer maintain the required posture, and kinematics (scapulothoracic and glenohumeral joints) were measured during scapular plane elevation before and after the push-up plus task.The serratus anterior, trapezius (upper and lower) and infraspinatus muscles all had reductions in MPF indicative of muscle fatigue. The authors suggested that the observed increase in the internal rotation of the scapula was primarily attributed to serratus anterior and lower trapezius muscle fatigue as they serve to maintain external rotation of the scapula during arm elevation. This finding provides additional evidence that suggests that the increases in scapulothoracic gliding plane internal rotation following an the external rotation task reported by Tsai et al., (2003), may have resulted from fatigue to the scapulothoracic musculature in addition to the infraspinatus muscle. The authors also found increased posterior tilt of the scapula with infraspinatus fatigue, consistent with previous reasearch (Ebaugh et al., 2006b; Tsai et al., 2003). It appears that changes to the SHR with fatigue of the infraspinatus muscle may be multi-planar, influencing both scapular posterior tilt, and internal rotation (when combined with scapulothoracic muscle fatigue) (Borstad et al., 2009).

5.4.1.4 Summary

Overall, this body of research suggest that infraspinatus has as an important mechanical role within the shoulder complex. A change in glenohumeral joint motion, namely decreased external rotation with infraspinatus fatigue, is suggested to elicit a compensatory response in the scapulothoracic and sternoclavicular musculature, altering scapulothoracic and sternoclavicular joint motion (Ebaugh, et al., 2006a; Ebaugh et al., 2006b). Regardless of whether the fatiguing task consists of arm elevation, external rotation, or a modified push-up plus tasks, when the infraspinatus muscle is fatigued, a reduction in scapular posterior tilt is also present. Further, when an external rotation protocol does not successfully fatigue infraspinatus, scapulothoracic gliding plane kinematic changes are not observed. The push-up plus task (Borstad et al., 2009), suggests that infraspinatus fatigue, in combination with scapulothoracic muscle fatigue, may also influence scapular internal rotation. Ultimately, research on local fatigue of glenohumeral joint musculature demonstrates the intricate mechanical links between the joints of the shoulder complex (closed chain system). Although infraspinatus has a moment generating capacity at the glenohumeral joint, fatigue of this muscle is associated with kinematic changes at the glenohumeral, scapulothoracic, and sternoclavicular joints.

5.5 Part 5: Muscle Fatigue & Upper Extremity Kinematics

In response to fatigue within the shoulder complex, the mechanical redundancies present at the joint level (muscle synergists) or at the multi-joint level (upper extremity), provide mechanisms by which the neuromuscular system can respond to enable task performance. In the previous section, the fatigue protocols were designed to preferentially fatigue a target group of muscles by limiting the degrees of freedom available to the neuromuscular system to maintain task performance. However, repetitive tasks encountered in daily life are typically goal directed, for example lifting an object from one location to another, and impose constraints on the overall (multi-joint) motion of the arm (e.g. timing, object avoidance, precision, or external force requirements), with limited constraint on how the goal is achieved at the individual joint level. Evidence suggests that in repetitive goal directed tasks, the neuromuscular system takes advantage of the abundant degrees of freedom to reduce the load on fatiguing tissue and enable task performance. The focus of this section is to summarize research that has characterized how the neuromuscular system responds during goal directed tasks that induce fatigue at the glenohumeral joint.

5.5.1 Multi-Joint Response

During repetitive, upper extremity goal directed tasks, the neuromuscular system alters the relative contribution of individual joints to task performance in a means to reduce the load at the glenohumeral joint and enable task performance. Fuller et al., (2009) had participants reach between two targets placed at 30 and 100% of reach length in front of the body's midline, while simultaneously maintaining their arm above a mesh barrier at shoulder height. The task was terminated when participants could no longer maintain the 1Hz frequency of movement, or reached an RPE of 8/10 on the Borg CR-10 scale. Local muscle fatigue at the glenohumeral joint was confirmed by an increase in upper trapezius EMG RMS, coupled with a reduction in maximum glenohumeral joint elevation strength. In the last minute of the task, participants' shoulder joint position was more superior, medial and posterior, and both elbow and wrist positions were more posterior as compared to the first minute of the task. These kinematic changes indicate that participants leaned toward their non-reaching side, resulting increasing the distance between the reaching arm and the mesh barrier, allowing for a slight decrease in humeral abduction angle and the resulting moment at the shoulder (Fuller et al., 2009). The posterior shift of the shoulder, elbow and wrist with fatigue suggests an increased contribution of the torso to the reaching task, thus, reducing the distance between the arm and torso when the arm is extended. This is another mechanism to reduce the glenohumeral joint moments. Importantly, despite kinematic changes across joints and planes of motion with fatigue, there was no change in endpoint position, and therefore task performance. Studies of repetitive sawing (Côté et al., 2002; Gates & Dingwell, 2011), hammering (Côté et al., 2005), lifting (Sparto et al., 1997), and reaching tasks (Cantú, et al., 2014; Fuller et al., 2011; Lomond & Côté, 2011) have reported similar findings, supporting the notion that kinematic changes in the presence of muscle fatigue serve to reduce the load on fatiguing tissues while maintaining task performance.

During repetitive goal directed tasks, to maintain task performance, the CNS must elicit a movement strategy that is not only sensitive to changes in muscular force generating capacity, but also to changes in joint proprioception. Emery & Côté, (2012) had participants complete two position sense tasks, one involving the glenohumeral joint, the other the whole arm (representative of endpoint position sense), before and after the repetitive reaching task described above (Fuller et al., 2009). To test shoulder position sense participants were seated, with their right elbow flexed to the side and right dominant index finger touching the manubrium of their sternum. With their eyes closed, in one ballistic movement at their preferred speed, they abducted their shoulder until they perceived the upper arm was horizontal (90° of shoulder abduction). To test endpoint position sense subjects were shown a target, at their shoulder height, 60% of reach length in front of their midline. Then, with their eyes closed, they were asked to move their hand, from the same start position as the shoulder position sense (index finger touching manubrium), to where they perceived the target was located. Following the repetitive reaching task, significant differences in participant's shoulder position sense, but not endpoint position sense were observed. In combination, these results suggest that despite the impairment of position sense at the fatigued joint (shoulder position sense), multi-joint adjustments, which compensate for the changes in shoulder position sense, allow for the maintenance of end point position (endpoint position sense). Therefore it appears that upper extremity kinematic changes with fatigue mitigate both mechanical and sensory impairments to the neuromuscular system.

5.5.1.1 Intersegment Coordination

Further analysis of the changes in upper extremity kinematics with muscle fatigue indicates a change in the relative motion between limb segments (intersegment coordination). Fuller et al. (2011) calculated the peak velocity occurrence of the whole body center of mass, shoulder, elbow and endpoint (expressed as a percentage of the task duration) on kinematic data obtained during a repetitive reaching task (Fuller et al., 2009). Peak velocity occurred in the following order: endpoint, elbow, center of mass, shoulder. This sequence was unchanged with fatigue, however, endpoint peak velocity was reached later in the motion, such that there was no longer a significant difference between endpoint and elbow peak velocity occurrence. A change in the relative timing of motion segments with muscle fatigue has been identified as an invariant feature of a GMP thus suggesting a transition to a different GMP. These findings suggest time series analyses which characterize the invariant features of joint motion, such as the SMSR algorithm, may help to identify the apparent transition between motor programs with muscle fatigue.

5.5.1.2 Temporal Occurrence

Interestingly, multi-joint kinematic changes with muscle fatigue occur much before exhaustion is reached. Fuller et al., (2011) analyzed the kinematic and EMG variables which changed during a repetitive reaching task (Fuller et al., 2009). The effected variables consisted of anterior-posterior elbow position, medial-lateral whole body center of pressure position, medial-lateral whole body center of mass position, medial-lateral shoulder position, superior-inferior shoulder position, shoulder abduction angle, and upper trapezius EMG RMS. The authors used participants' within-subject variability, determined from the first 5 reaches at the start of the task, to indicate the time each variable deviated from the baseline mean +/- 2SD. All of kinematic variables deviated from baseline within the first 53% of the total task duration. The upper trapezius RMS deviation followed the kinematic changes with fatigue, occurring at 65.5% of total task duration. The authors suggested that perhaps "changes at the main agonist muscle site trigger whole body changes in a feed forward manner", before fatigue manifests in the EMG signal. However, they also stated that the 2SD criteria they selected may not be sensitive enough to distinguish changes in the EMG RMS with fatigue, and therefore are not directly comparable to the kinematic data.

5.5.2 Motor Variability

Variability in the contributions of individual joints to task performance, referred to as “movement variability”, can provide transient reductions in the mechanical loads placed on fatiguing tissues. Motor variability is defined as the variability within an individual, across time, at any level of movement execution (Srinivasan & Mathiassen, 2012). Motor variability can be represented by task performance characteristics (e.g. movement time, endpoint precision), kinematics (joint angles or velocities), kinetics (joint torques), muscle activity or recruitment, or inter-joint coordination (relative phase angles) (Srinivasan & Mathiassen, 2012). In contrast to the previous section (section 5.5.1), which discussed the spatial-temporal changes in joint kinematics with fatigue, research on movement variability with fatigue focuses on the standard deviations or coefficient of variation of the kinematic variables.

With muscle fatigue, motor impairments such as increased variability of muscular force and delayed reaction time suggest that task performance should be compromised. Interestingly, in repetitive goal directed tasks that elicit fatigue at the glenohumeral joint, motor variability increases across joints within the upper extremity. Fuller et al., (2011), indicated changes in reach to reach variability both at the site of fatigue (glenohumeral joint), as well as distally (whole body center of mass), during a repetitive reaching task (Fuller et al., 2009). Gates & Dingwell, (2011) also found that muscle fatigue elicited increased variability at the shoulder, elbow and wrist joints following a repetitive sawing task. Further, this increase in motor variability with fatigue did not inhibit task performance, leading the authors to conclude that it may represent individuals exploring alternative movement strategies, instead of simply a consequence of muscle fatigue.

5.5.3 Clinical Populations

The upper extremity kinematic response to local glenohumeral muscle fatigue during a repetitive goal directed task is also influenced by the initial state of the system, such as the presence of pain or injury. The repetitive reaching task described in section 5.5.1 (Fuller et al., 2009) was performed by 16 participants with chronic neck/shoulder pain (PAIN group), and 16 asymptomatic participants (CRTL group)(Lomond & Côté, 2011). In comparison to the CRTL group, the PAIN group had a shorter task endurance time, and adopted a more rigid movement pattern in which their arm was more fixed (limited elbow and shoulder movement) requiring increased whole body COM motion to compensate. Previous work, investigating joint kinematics during a repetitive hammering task in healthy and shoulder injured populations, also supports the notion that with injury, a more rigid, less variable inter-joint coordination pattern exists (Côté et al., 2005). Lomond et al., (2011) also reported the following similarities between groups: 1) shoulder joint position was brought closer to the targets, superior (elevated) and medial (towards non-reaching side), 2) elbow position was more posterior, and 3) shoulder abduction angle decreased. These adaptations, which were not modified by injury, may highlight the basic elements that guide the selection of different motor programs with fatigue.

The nature of the pain experienced, chronic or acute, influences the level of motor variability during repetitive tasks. Madeleine et al., (2008) found that acute pain in a healthy population (experimentally induced) resulted in greater motor variability, during a simulated cutting task, when compared to individuals suffering from chronic, injury related pain. The authors suggested that the increased movement variability with acute pain represents an individual's attempt to explore movement strategies that will enable task performance while reducing pain. Further, supporting previous research, participants with chronic injury related pain adopted a more rigid control strategy to reduce pain at the site of injury (Côté et al., 2005; Lomond & Côté, 2011; Madeleine et al., 2008). Under such constraints, the neuromuscular system appears unable to use the range of postural flexibility available to uninjured populations, which results in a reduction in task endurance time.

5.5.4 Summary

In response to fatigue induced by repetitive goal-directed tasks, kinematic changes occur across multiple joints and planes of motion. These kinematic changes mitigate fatigue related mechanical and sensory impairments to the neuromuscular system to maintain task performance. Further, changes to intersegmental coordination also occur, suggesting that the kinematic changes represent the transition to a new generalized motor program within the CNS. Although, in injured populations the CNS selects a more rigid movement strategy that reduces pain at the site of injury, shared characteristics exist with the movement strategy observed in an asymptomatic population. These similarities may represent invariant features that guide the selection of different motor programs with fatigue. Ultimately, this body of research suggest that in repetitive, multi-joint tasks, the neuromuscular system can respond by spatially and temporally modifying the relative contribution of individual joint degrees of freedom to upper extremity motion (Emery & Côté, 2012). Thus, changes in joint kinematics can be used to indicate muscle fatigue accumulation during repetitive tasks.

5.6 Literature Review Summary

Although there is considerable research on the relationship between shoulder muscle fatigue, upper extremity kinematics, and chronic injury, few have explored potential methods to translate this knowledge effectively into the workplace. Fatigue induced changes to shoulder muscular behavior alters joint kinematics, causing the loading of ill-suited structures which can lead to the development of shoulder MSDs (i.e. subacromial impingement syndrome). In repetitive work, upper extremity kinematic changes occur to redistribute loads away from fatiguing tissues and enable task performance. Identifying a generalized change in upper extremity movement strategy, during a repetitive task, in contrast to participant specific deviations in joint angles, could provide a method to detect kinematic changes across individuals within a population. A relationship between shoulder muscle fatigue, especially that of the rotator cuff, and upper extremity kinematics may provide a practical, non-invasive method to visually detect the onset of shoulder muscle fatigue repetitive work.

6 METHODS

6.1 Participants

A total of 27 right-hand dominant participants (14 male, 13 female), free of any upper extremity, neck, or back injuries in the last year were recruited from the university population to participate in the study. This sample size is larger than previous studies on multi-joint kinematics with muscle fatigue, which have typically ranged from 10-20 participants (Cantú et al., 2014; Emery & Côté, 2012; Fuller et al., 2011; Gates & Dingwell, 2008, 2011). This sample size was sufficient to obtain a power value approaching 0.8 for the statistical analyses performed on these data sets (Cohen, 1992). The study was approved by the office of research ethics at the University of Waterloo, and participants provided informed consent prior to participating in the experiment. The investigator ensured participants refrained from upper extremity and torso resistance training in the week prior to the scheduled session. This provision was to ensure sufficient recovery of possible muscle soreness or strength impairments that accompany moderate to high intensity exercise (Byrne et al., 2004).

6.2 Experimental Design

The study required participants come to the lab for a single session to complete the experimental protocol. The experimental protocol consisted of three phases and took approximately 2-3 hrs to complete (Figure 1).

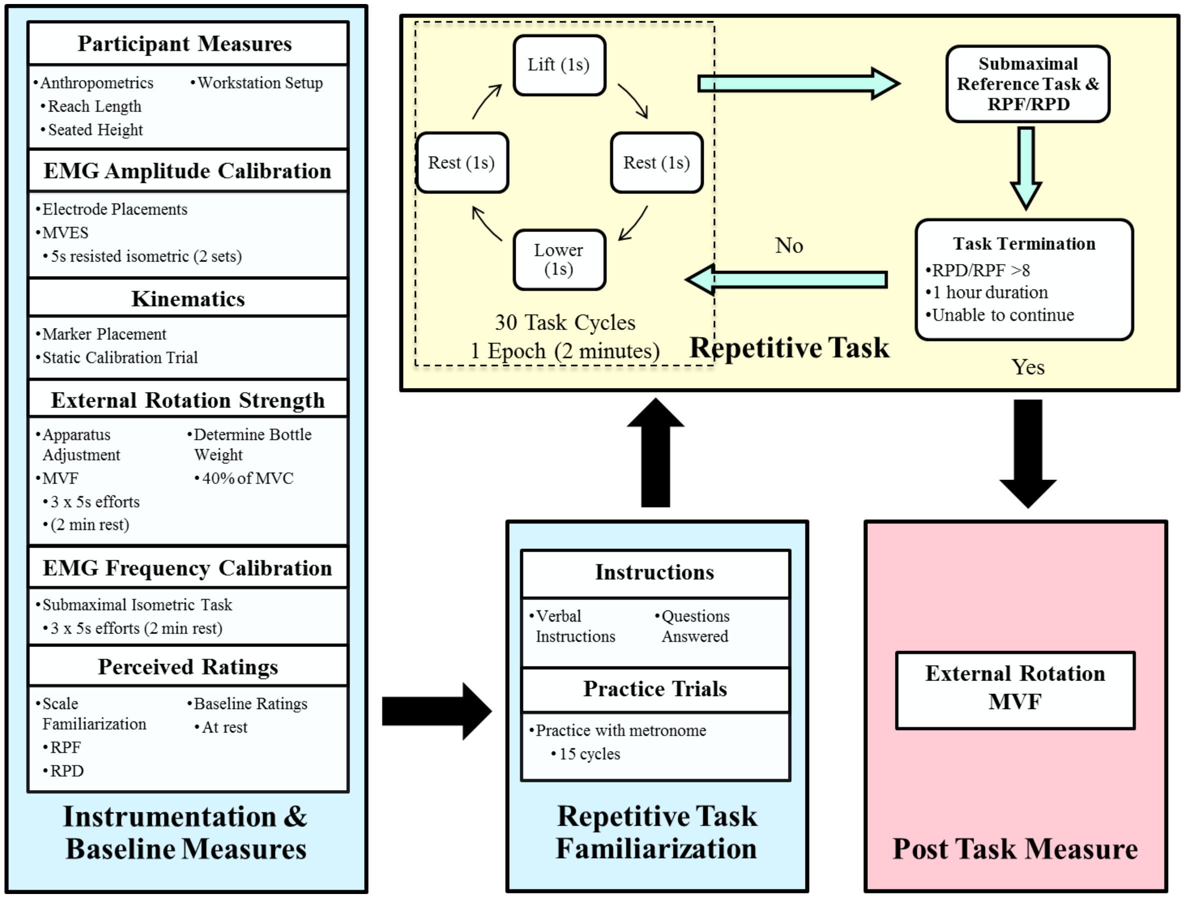


Figure 1: An overview of the experimental protocol. First, instrumentation and baseline measures were performed. Following this, participants were familiarized with the repetitive task before beginning the repetitive task portion of the experiment. The repetitive task consistied of 2 minute epochs, composed of 30 cycles that include a lift, and lower motion with rest interdispersed between each. Immediately following each 2 minute epoch participants completed a submaximal effort and provided rating of percieved fatigue (RPF) and discomfort (RPD) values. If the task termination criteria was reached the participant peformed a final external rotation maximum voluntary force effort (MVF), otherwise, they continued with subsequent epochs of the repetitive task until they fulfilled the task termination criteria.

6.3 Instrumentation and Data Acquisition

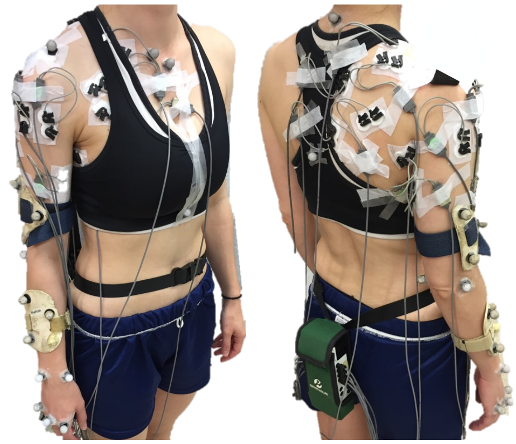
6.3.1 Motion Capture

Three dimensional position data of the right upper limb and torso were recorded for every 2 minutes during the repetitive task using an 8 camera (2MP) optoelectronic VICON MX20+ motion tracking system (VICON Motion system, Oxford, UK) at a sample rate of 50 Hz. The cameras were positioned around the collection area and calibrated using Vicon Nexus 1.2 software (VICON Motion system, Oxford, UK) prior to each data collection. The origin of the space was positioned on the floor, behind and to the left of where the participant was seated to complete the task.

A total of 13 spherical shaped (diameter 9 mm) reflective markers were placed on each participant's arms and torso over anatomical landmarks outlined in the published ISB recommendations for reporting motion of the upper extremity (Table 3) (Wu et al., 2005). To reduce skin motion artifact, rigid cluster markers were placed securely, using double-sided adhesive tape, overtop of the skin approximately mid-length along the humerus and forearm segments. Skin motion artifact is largest when markers are placed over anatomical landmarks at the joint in comparison to areas further from the point of rotation (Cappozzo, 1997). A static calibration trial, in which the participant was seated, in the rest position during the repetitive task, was used to develop an anatomical calibration matrix describing the position of the anatomical landmarks on the humerus and forearm within the respective cluster coordinate systems (Winter, 2009).

Table 3: Locations of the surface markers on the participants, grouped according to body segment. On the right, there is an image of a participant with the surface markers placed on the relevant anatomical landmarks.

Body Segment	Marker Location	Acronym
Thorax	Xiphoid Process	XP
	Suprasternal Notch	SS
	Cervical Vertebrae 7	C7
	Thoracic Vertebrae 8	T8
	Acromion Process	AP
Humerus	Upper Arm Cluster	UA1,UA2,UA3
	Medial Epicondyle	ME
	Lateral Epicondyle	LE
Forearm	Lower Arm Cluster	LA1,LA2,LA3
	Radial Styloid	RS
	Ulnar Styloid	US
Hand	Metacarpal Joint 2	MCP2
	Metacarpal Joint 3	MCP3
	Metacarpal Joint 5	MCP5



ANTERIOR VIEW **POSTERIOR VIEW**

6.3.2 Force Data

Force data were recorded during maximal external rotation efforts using an AMTI 6 degree-of-freedom force transducer (Force cube; MC3A, AMTI, MA, USA). The force cube was mounted on an adjustable stand. In short, participants performed isometric external rotation, while simultaneously limiting humeral abduction (Section 6.4.1.4). During the maximal external rotation efforts force data were amplified (1000x), sampled simultaneously with the sEMG data at 1500Hz, and converted to a digital signal using a 12 bit A/D card using Vicon Nexus software.

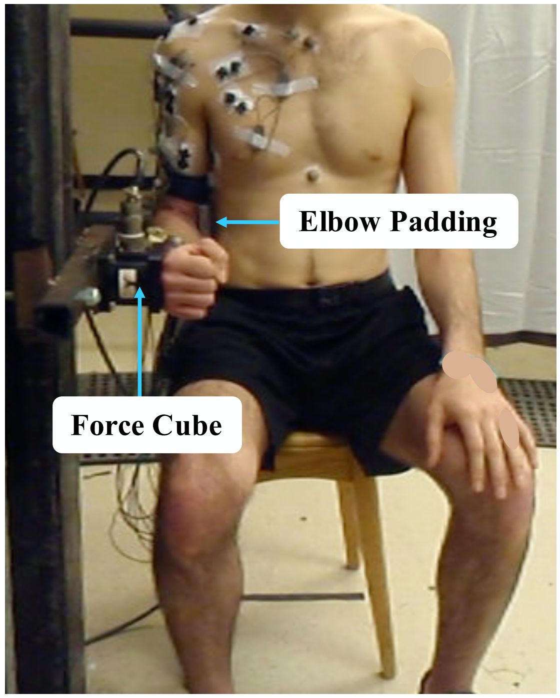


Figure 2: A participant completing the external rotation maximum voluntary force effort. The participant sat comfortably on a stool, with their arm by their side, and elbow in 90° of flexion. They were instructed to externally rotate their arm, to exert a maximal force with the back of their right hand against the flat surface of the force cube. To minimize humeral abduction, participants were asked to hold an elbow pad consisting of high density foam between their torso and humerus.

6.3.3 Surface Electromyography (EMG)

Surface electromyography (sEMG) data were measured from 12 sites over muscles of the right shoulder complex. sEMG was recorded from 8 muscles that cross the glenohumeral joint: deltoid (anterior, middle and posterior), infraspinatus, supraspinatus, pectoralis major (sternal and clavicular) and latissimus dorsi (Table 4). sEMG was also recorded from the following 4 scapulothoracic muscles: trapezius (upper, middle, and lower), and serratus anterior (Table 4).

Bipolar Ag-AgCl dual surface electrodes (Noraxon, Arizona, USA) with a fixed 2.0 cm inter-electrode distance were used to detect sEMG signals. The skin overlying these muscles (total of 12 sites) was shaved and wiped with an alcohol swab prior to placing the electrodes to facilitate adhesion and reduce electrical impedance. Electrode placement followed previous work and was confirmed through palpation (Table 4) (Daniels & Worthingham, 1986; Cram and Kasman, 1998; Kelly et al., 1996). A reference electrode was placed over the clavicle. sEMG data were collected using a Noraxon T2000 telemetered system (Noraxon, Arizona, USA). Raw EMG signals were passed through a differential amplifier (common-mode rejection ratio >100 dB at 60 Hz, input impedance 100 MΩ), sampled at 1500Hz, and converted to a digital signal (16-bit A/D card, maximum +/- 10 V range).

Once the electrodes were placed, participants completed submaximal exertions (80% of their maximum voluntary force) targeting each muscle to verify the electrode placements (Table 5). These efforts were also used to determine the required level of amplification needed to increase the digital resolution (+/- 10V per 16 bits) of the signal, given that the voltage recorded by surface electrodes is on the scale of 0.5-4 mV (Winter, 1980).

Table 4: A description of electrode placements used to measure the electromyography of the 12 muscles studied in this experiment. Placements are similar to those suggested in Daniels & Worthingham (1986); Cram & Kasman (1996). * indicates placements similar to those suggested in Kelly et al., 1996.

Muscle	Placement
Anterior Deltoid	3.5 cm below the anterior angle of the acromion, parallel to the muscle fibers*
Middle Deltoid	3 cm below the lateral rim of the acromion, midway between the deltoid tuberosity and the acromion process
Posterior Deltoid	2 cm below the posterior lateral surface of the acromion, (parallel to muscle fibers)*
Supraspinatus	Midpoint and two finger breadths anterior to the scapular spine
Serratus Anterior	Anterior midaxillary region over 5th and 6th ribs, anterior to the latissimus dorsi muscle positioned obliquely upward and posterior
Upper Trapezius	2cm lateral to the midpoint between the spinous process of C7 and the posterior tip of the acromion process along the line of trapezius (approximately 55° oblique angle)
Middle Trapezius	2/3 on the line between the trigonum spinae and the 8th thoracic vertebrae, 4 cm from muscle edge, at approximately a 55° oblique angle.
Lower Trapezius	Positioned obliquely upward and lateral along the line of intersection of the spine of the scapula and with the vertical border border of the scapula and the spinous process of T7
Infraspinatus	Two finger breadths (4cm) below the midpoint of the scapular spine, overtop the infraspinatus muscle belly in the infrascapular fossa, and angled toward the infraspinatus insertion (located just inferior to the humeral head on the lateral border)
Latissimus Dorsi	Three finger breadths (6cm) below the inferior angle of the scapula, parallel to the lateral border of the scapula
Pectoralis Major (Clavicular)	2cm below the clavicle half way between the sternoclavicular joint and coracoid process (oriented on a downward and lateral angle)
Pectoralis Major (Sternal)	6cm above the nipple, parallel to the muscle fibers

6.3.4 Perceived Ratings

Participants provided ratings of overall perceived discomfort (RPD) and fatigue (RPF) during the repetitive task using modified Borg scales (Borg, 1990). Similar to the Borg CR-10 scale, both the RPD and RPF scales ranged from 0-10. On each scale, ‘0’ indicated no discomfort or fatigue and ‘10’ indicated the worst imaginable discomfort or complete exhaustion. Printed copies of the scales were displayed for participants during the repetitive task when they were asked to provide RPF and RPD ratings (Appendix A). Previous research focused on multi-joint kinematic changes with muscle fatigue has used a rating of perceived exertion scale, based on the Borg CR-10 scale, to determine the point of exhaustion and thus task completion (Côté et al., 2002, 2005; Emery & Côté, 2012; Fuller et al., 2009; Gates & Dingwell, 2008). However, ratings of perceived fatigue and discomfort are more frequently used in upper extremity fatigue research as subjective indicators of muscle fatigue, exhibiting a linear relationship with other fatigue measures such as strength, task endurance time, and changes in muscle EMG MPF (Frey Law et al., 2010a; Iridiastadi & Nussbaum, 2006; Oberg et al., 1994b; Rose et al., 2000, 2014). Although both perceived effort and discomfort increase with muscle fatigue accumulation, given the applied focus of this study, ratings of perceived fatigue and discomfort were chosen as subjective measures of muscle fatigue accumulation. A rating of task difficulty of 8/10 for the shoulder region has been used to determine the point of exhaustion and therefore task completion (Côté et al., 2002, 2005; Emery & Côté, 2012; Fuller et al., 2009; Gates & Dingwell, 2008). This study used the same criterion to allow for comparisons with existing literature.

6.3.5 Participant Anthropometrics

The investigator used a cloth measuring tape to measure participants' reach lengths. The participants were seated upright with their right arm in 90°of forward flexion at the shoulder, full extension at the elbow and a neutral wrist posture during the reach length measurement. Reach length was defined as the distance between participants' acromion process and the third metacarpal joint of their right hand (La Delfa et al., 2014).

6.4 Experimental Protocol

The experimental protocol for this study was divided into 4 stages (Figure 1). The purpose of this section is not only to provide a description of the procedures in each stage, but also to outline the rationale behind the repetitive task design.

6.4.1 Baseline Measures & Calibrations

6.4.1.1 EMG Amplitude

Prior to the start of the experiment, participants completed two sets of maximum voluntary isometric contractions (MVICs) to obtain a measure of maximum voluntary excitation (MVE) from each muscle recorded (n =12). Each MVE consisted of a maximal isometric effort requiring a significant contribution from the muscle of interest to generate force against resistance applied by the investigator (Cram & Kasman, 1996) (Table 5). Participants were instructed to ramp up to their maximum effort, hold it for 1s and ramp back down to rest. Verbal encouragement was provided during each maximal effort and sEMG data were recorded for 5s to capture maximal muscle activations.

Table 5: A description of the resisted, isometric efforts participants will complete to obtain a maximal level of activation for subsequent processing of the electromyogram recorded during the experiment. The listed efforts are similar to those in Cram & Kasman (1996); Brookham et al., (2010).

Participant Position	Muscle	Description of Maximal Effort
Seated	Anterior Deltoid	The participant will be seated, with the shoulder at 90° of shoulder abduction, elbow extended and their thumb pointing towards the ceiling (upward). The participant will asked to attempt further shoulder abduction against upward resistance created by the investigator.
	Middle Deltoid	The participant will be seated, with the shoulder at 90° of shoulder abduction, elbow extended and their thumb pointing anteriorly. The participant will asked to attempt further shoulder abduction against upward resistance created by the investigator.
	Posterior Deltoid	The participant will be seated, with the shoulder at 90° of shoulder abduction, elbow extended and their thumb pointing posteriorly. The participant will asked to attempt further shoulder abduction against upward resistance created by the investigator.
	Pectoralis Major (Clavicular)	The participant will be seated with shoulder and elbow flexed at 90 degrees. The participant will horizontally adduct and flex the shoulder while the investigator is applying resistance from above in a outward and downward direction.
	Latissimus Dorsi	The participant will be seated, with the arm at 90° of shoulder abduction and the elbow flexed to 90°. The participant will be instructed to pull their elbow downward to the floor (adduction) against resistance created by the investigator.
Laying	Supraspinatus	The participant will lie on their side on a therapist's table, with the left arm resting under their head and the right arm resting on their side. The investigator will lift the active arm to 10° of shoulder abduction and support it until the trial begins. The participant will be asked to abduct their shoulder against resistance created by the investigator.
	Infraspinatus	The participant will lay on their left side. Arm is at the side, and elbow is bent to 90 degrees. Lateral rotation of the humerus is resisted by the investigator.
	Pectoralis Major (Sternal)	The participant will lie supine on a therapist's table, with their arm out to the side and flexed so that their hand points toward the ceiling. The participant will be instructed to try and bring their arm through forward flexion against resistance created by the investigator.
	Upper Trapezius	The participant will lie prone on a therapist's table, with the shoulder at 90° of shoulder abduction, elbow extended and their thumb pointing anteriorly (toward the floor). The participant will be instructed to horizontally extend their arm against resistance provided by the investigator.
	Middle Trapezius	The participant will be asked to abduct (~ 120 degrees) and forward flex (~45 degrees) their arm. An investigator will place their hands on the participants humerus and elbow joint, asking the participant to push upward into resistance.
	Lower Trapezius	The participant will lie prone on a therapist's table, with the shoulder at 90° of shoulder abduction, elbow extended and their thumb pointing posteriorly (toward the ceiling). The participant will be instructed to depress their arm against resistance.
Standing	Serratus Anterior	The participant will be asked to forward punch, (resisted) at 90 degrees of shoulder abduction and 105 degrees of horizontal extension

6.4.1.2 EMG Mean Power Frequency (MPF)

After the MVE trials, participants completed three static reference tasks. The purpose of the static reference task was to obtain a baseline measure of the mean power frequency (MPF) of the EMG signal recorded from each muscle. Further, the same reference task was used intermittently (every 2 minutes) during the repetitive task to identify changes in MPF, relative to that at baseline, indicative of shoulder muscle fatigue. Thus, the static reference task was designed to enable a quick transition from the repetitive task to the static reference task and vice versa. A quick transition between tasks minimizes potential muscle fatigue recovery, which may occur during periods of reduced demand or rest. Participants were seated and held the weighted bottle used in the repetitive task (scaled to 40% of their external rotation MVF) slightly above the P1 target location in the repetitive task for 5s (Section 6.4.2). Similar static reference tasks have been used in other studies to identify changes in MPF indicative of shoulder muscle fatigue (Chopp et al., 2010b, 2011; Noguchi et al., 2013).

6.4.1.3 Kinematic Static Calibration Trials

One static calibration trial was recorded and used to develop an anatomical calibration matrix describing the position of the anatomical landmarks on the humerus and forearm within the respective cluster coordinate systems (Winter, 2009). Participants were seated upright on a stool with their hand on the bottle as it rested in the P2 target position (Section 6.4.2). The position of the surface markers placed over the anatomical landmarks of the humerus and forearm relative to the rigid clusters will be obtained from the first static calibration trial. The calibration position was selected based on its relevance to the repetitive task and high kinematic marker visibility.

6.4.1.4 Maximum Voluntary Force (MVF)

After the kinematic static calibration trials participants completed 3 maximum voluntary force (MVF) external rotation efforts, separated by 2 minutes of rest, to obtain a baseline maximal force value. Participants also performed an MVF effort immediately following the repetitive task to provide a measure of the level of muscle fatigue at task termination.

The MVF effort consisted of a modified version of a commonly used clinical strength test, which "relatively isolates" the infraspinatus muscle (Brookham et al., 2010a). Participants were instructed to maximally exert force against the force cube by externally rotating at the shoulder, while holding an elbow pad, made from high density foam, between their torso and humerus. The height of the force cube was aligned with the dorsal side of the participants' right hand when they were seated with their right arm at their side and their elbow in 90° flexion (Figure 2). To maintain the position of the elbow pad on their torso, participants had to minimize humeral abduction moments at the shoulder and thus rely on external rotation moments to generate force at the hand. The maximal external rotation efforts were 5s in duration, allowing participants to ramp up to their maximum effort, hold it for 1s and return to rest.

6.4.2 Repetitive Task

The repetitive task was designed to place a moderate demand on the glenohumeral joint external rotators with minimal movement constraints. The goal of the repetitive task was to fatigue the glenohumeral joint external rotators while maintaining neuromuscular degrees of freedom that can contribute to task performance. The abundance of neuromuscular degrees of freedom enable changes in upper extremity kinematics with fatigue (Emery & Côté, 2012; Fuller et al., 2011; Gates & Dingwell, 2008).

6.4.2.1 Overview

Participants lifted and lowered a weighted bottle, set to 40% of their rested maximum external rotation strength, between two target locations at a 1Hz frequency. The lift and lower movements were 1s in duration and separated by 1s of rest. A metronome helped participants adhere to these movement times. Every 2 minutes, the repetitive task was stopped and participants completed the static reference task (Figure 5, Section 6.4.1.2). Immediately following the static reference task participants provided ratings of perceived discomfort and fatigue (Figure 5). The repetitive task was terminated when at least one of the following 4 criteria were met: 1) rating of perceived discomfort or fatigue greater than or equal to 8/10, 2) inability to perform the repetitive task or the static reference task, 3) verbal indication they were no longer able to continue the task, 4) a total task duration of 60 minutes. If the termination criteria were not met, participants continued the repetitive task for another 2 minutes after which they performed another static reference task and provided RPF/RPD (Figure 5). Consecutive 2 minute intervals, termed ‘epochs’ were performed by participants until the fatigue criterion was met.

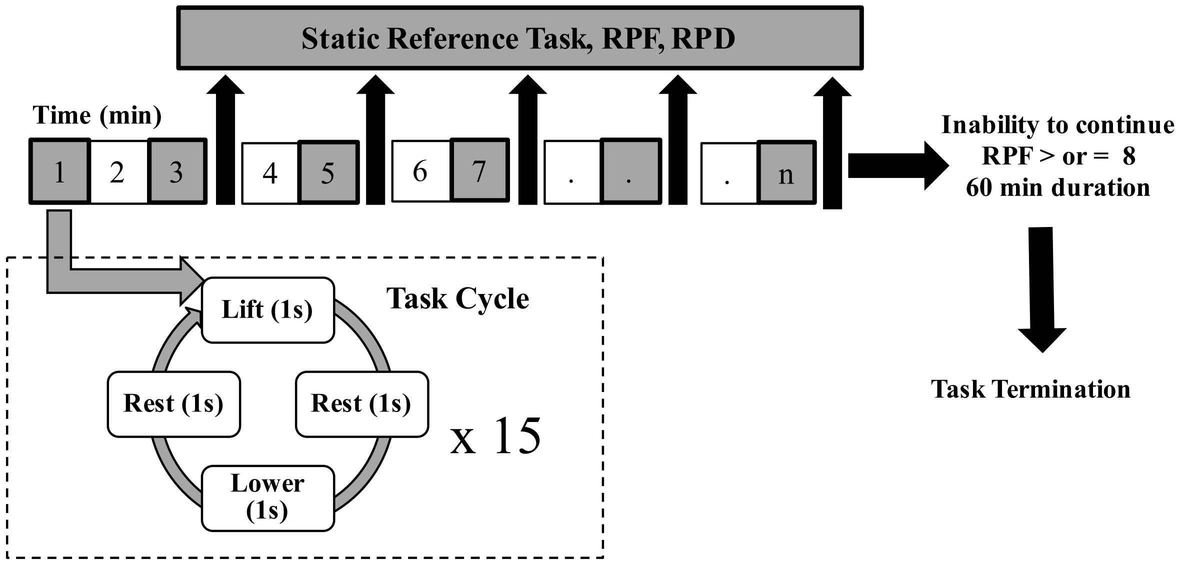


Figure 3: A schematic representation of the repetitive task. Participants completed 15 task cycles, consisting of a lift lower and rest, per minute during the repetitive task. Kinematic data were recorded during the first minute, and then every second minute of the repetitive task as indicated by the grey shaded boxes above. Every 2 minutes during the repetitive task participants completed the static reference task and provided ratings of perceived fatigue and discomfort. If the participant was unable to continue the repetitive task, had an RPF or RPD greater than or equal to 8/10 or reached a total task duration of 60 minutes, the task was terminated.

6.4.2.2 Workstation Design

The repetitive task was performed while seated, in order to eliminate the effects of whole body posture on upper extremity demands (Chopp, Fischer, & Dickerson, 2010). Participants sat on a height adjustable stool that facilitated a comfortable sitting posture with their knees at approximately 90° of flexion and their feet resting flat on the floor. The position of the two target locations, which defined the range participants lifted and lowered the weighted bottle within, varied from one another in all three (x,y,z) Cartesian planes. The multi-planar design of the repetitive task was intended to promote flexibility within the neuromuscular system in terms of the relative contribution of motion in each plane to maintain task performance.

The distances between participants' right acromion process and both target locations (P1 and P2), in which participants lifted and lowered the weighted bottle between, were scaled to participants' reach lengths. This relative scaling was used to mitigate potential differences in individuals' capabilities attributed to anthropometric differences (i.e. longer vs. shorter arms). The P1 and P2 target locations were set at 65% and 75% of the participants' reach lengths, respectively. These distances fit comfortably within participants' reach envelopes (Das et al., 1995).

The angles between the target locations and the participants' frontal and sagittal planes of motion were the second and third constraints used to determine the position of the target locations. The target locations P1 and P2 were oriented at 40° and 90° anterior to the frontal place of motion, respectively. Relative to the sagittal plane of motion the P1 and P2 target locations were oriented 80° and 70° anteriorly. These angles were selected in conjunction with feedback from and observation of pilot participants to produce a task that involves both glenohumeral elevation and external rotation, but the relative amounts of which can vary, as the location of the two positions differ in all three Cartesian planes. In addition, this task was also designed to minimize overhead work. Overhead postures are an occupational risk factor related to injury development through several pathways, including more rapid muscle fatigue accumulation in comparison to tasks performed below shoulder height (Dickerson et al., 2011).

6.4.2.3 Post-Task MVF

Immediately following the repetitive task, participants completed a final external rotation MVF effort (Section 6.4.1.4). The investigator ensured a timely transition from the repetitive task to the external rotation MVF effort to minimize fatigue recovery during this period.

6.5 Data Analysis

The following sets of raw data were processed to derive the dependent variables of interest in this thesis: 1) surface electromyography (sEMG), 2) 3D upper extremity segment positions (kinematic data), 3) ratings of perceived fatigue and discomfort (RPF, RPD) and 4) maximum external rotation force (ER-MVF).

6.5.1 Electromyography (EMG)

Although the frequency content of the EMG signal was the primary variable of interest in this thesis, the amplitude of the EMG signal during the three baseline efforts was processed and used as a 'screen' to identify the muscles from which EMG MPF were to be calculated. All EMG data processing was performed using a customized Matlab program (Mathworks, Inc., USA) and outlined in the following sections.

6.5.1.1 Amplitude

The sEMG data during the muscle specific maximum voluntary excitation (MVE) trials and the baseline static reference trials were processed. All raw sEMG data were digitally bandpass filtered using a dual pass 2^{th} order Butterworth filter (30-500 Hz) to remove heart rate artifact (Drake & Callaghan, 2006) and high frequency noise content from the signal. The bandpass filtered sEMG signals were full wave rectified and linear enveloped using a 2nd order Butterworth low pass filter (fc = 2Hz). The peak value of the sEMG signal for a given muscle across the 2 muscle specific MVE trials was extracted and assumed to represent the maximum voluntary excitation of the muscle of interest. The processed sEMG data from each muscle during the baseline static reference tasks were normalized to the muscles' specific maximum excitation value, giving the muscles' activation as a percentage of the maximum excitation (%MVE).

6.5.1.2 Mean Power Frequency (MPF)

The muscles selected for mean power frequency analysis of the sEMG data were determined on a participant by participant basis. Although all participants performed the same static reference task, differences in the muscular strategies used to perform the task exist between individuals. At low levels of muscular activation (<5-10% MVE), the mean power frequency (MPF) of the sEMG signal is influenced by muscle contraction level (Bartuzi & Roman-Liu, 2014; Roman-liu & Konarska, 2009). Thus, since the baseline MPF is used to represent the muscles 'non-fatigued' state, it is important that the value is not influenced by other factors such as differences in contraction level. To ensure an accurate representation of the baseline MPF frequency of the muscle, muscles that had an activation greater than or equal to 10% MVE across the three baseline static reference tasks were selected for further analyses.

The raw sEMG data collected during the static reference tasks underwent a series of processing steps to yield the sEMG MPF value during each task. All raw sEMG data were digitally bandpass filtered using a dual pass 2^{th} order Butterworth filter (30-500 Hz) to remove heart rate artifact (Drake & Callaghan, 2006) and high frequency noise content from the signal. For each static reference task the sEMG data recorded during the middle 3s of the task were divided into 0.5s intervals, resulting in a total of 6 intervals per static reference task. The sEMG data in each of the 0.5s intervals (750 data points) were padded with zeros to obtain a total of 1500 data points per interval that were then inputted into a discrete Fourier transform. The purpose of padding the sEMG data with 750 zeros was to create a 1Hz frequency resolution of the discrete Fourier transform. Padding the data with zeros increases the length of the input signal, thus increasing the frequency resolution of the a discrete Fourier transform, without changing the shape of the power spectrum (Smith, 1999). The output power spectrum obtained from the discrete Fourier transform was used to calculate the sEMG MPF as the sum of the spectral moment at each frequency, divided by the total spectral moment (Equation 1).

$$MPF = \frac{\left[\sum_{f=0}^{fc} f \text{ x } PSD(f)\right]}{\left[\sum_{f=0}^{fc} PSD(f)\right]} \qquad (1)$$

A spectral moment consists of the product of the power spectral density and the frequency that contains it. The sEMG MPF computed during each 0.5s interval (6 per static reference task) were averaged to obtain a single sEMG MPF value for the given reference task. The baseline sEMG MPF value for each muscle analyzed was computed as the average sEMG MPF during the three baseline static reference tasks. All sEMG MPF values obtained during subsequent static reference tasks were normalized to the baseline sEMG MPF for each muscle to allow for both within and between subject comparisons of the change in sEMG MPF with fatigue (Oberg et al., 1994a).

The normalized sEMG MPF data were used as an indicator of fatigue within a given muscle. Deviations in sEMG MPF less than 8.8% of the initial value can result from factors other than muscle fatigue (i.e. slight differences in joint position) (Oberg et al., 1991). Thus, the dependent variable termed “muscle fatigue onset” will be computed as the minute at which the MPF of the EMG from the infraspinatus muscle decreases by greater than 9%, expressed as a percentage of the participants’ total task duration.

To facilitate comparison of EMG MPF frequency data between individuals, given that the total task duration is participant specific, the EMG MPF data for each participant was rubber banded using linear interpolation (Winter, 2009). In repetitive tasks, EMG MPF exhibits a linear relationship with time (Nussbaum, 2001; Troiano et al., 2008). EMG MPF was calculated, using linear interpolation for each participant at 25%, 50%, 75%, and 100% of each participant's total task duration.

6.5.1.3 External Rotation Maximum Voluntary Force

All raw force data were digitally bandpass filtered using a dual pass 2^{th} order low pass Butterworth filter (2 Hz) to remove high frequency noise content from the signal. The maximum force level during the middle 3s of the 5s effort was obtained from the external rotation MVF effort performed by participants before and after the repetitive task. To allow comparison between individuals, the maximum external rotation MVF value obtained following the repetitive task was normalized to that before the repetitive task (% MVF). For each participant, the decline in ER MVF was expressed as the difference between individual's external rotation MVF (% MVF) value after the repetitive task and the initial value.

6.5.2 Kinematics

6.5.2.1 Partitioning of Kinematic Data

To facilitate comparison with the sEMG and RPF/RPD data, that were measured every two minutes during the repetitive task, upper extremity kinematic data measured during the last 20s of each 2-minute epoch (last 5 lift efforts) were analyzed. The last 5 efforts in each epoch were selected to obtain a stable estimate of an individual's movement characteristics based on the findings of Frost et al., (2010) that 5 trials of a task captures 95% of an individuals' 25 trial variability. This kinematic data reduction protocol is consistent with previous research on multi-joint kinematic changes with fatigue (Cantú et al., 2014; Fuller et al., 2009, 2011, 2013; Lomond & Côté, 2011).

The kinematic data were collected continuously during the repetitive task, and thus additional processing was required to partition the data into the four different actions performed by participants' in the 15 cycles completed each minute (lift-rest-lower-rest). First, all raw position data data were digitally bandpass filtered using a dual pass 2^{th} order low pass Butterworth filter (4 Hz) to remove high frequency noise content, such as digitization errors, from the data. The position of the P1 and P2 target locations, in addition to the Z position and velocity of the bottle, were used to partition the data into individual motions. The position variables used in this procedure to determine the start or end of a lift or lower motion was the Z position of the kinematic marker on the bottle relative to that of the kinematic markers on the P1 and P2 target locations. The lower threshold of the P1 target location was set to 20mm below the P1 position and the upper threshold was set to the height of the bottle (285 mm) plus the P1 target position plus 20mm. Only an upper threshold was set for the P2 target location (P2 position + 20mm) the bottle was never below the P2 target location during the repetitive task.

The Z velocity of the bottle was the variable used to determine when the bottle was at rest, and therefore at one of the target locations. When the Z velocity of the bottle was between +/- 10mm/s for at least 40ms (2 frames at the 50Hz sample rate) it was considered at rest (Burkitt et al., 2015). Although this does not mean that the bottle was not moving in the X or Y directions, the plane of motion that was most of interest was the Z plane. Requiring participants to place the bottle into holders at each target location constrained the X and Y motion, placing emphasis on that in the Z plane. Once the bottle was placed in the holder, the weight of the bottle was resting on the target locations resulting in minimal Z velocity.

An outline of the data partitioning procedure is below and complimented by Figure 4:

1. The start of a lift or lower motion was considered as the nearest frame (before or after) at which the Z velocity of the bottle was between +/- 10mm/s.

2. The Z position of the bottle at the potential start of the lift or lower motions were then compared with the P1 and P2 position thresholds.

    a. If the Z bottle position during this potential start of the motion was within the P1 or P2 position thresholds it was considered the start of the relevant motion.

3. The frame at which the Z velocity of the bottle was between +/- 10mm/s but not within this threshold the frame after was considered a potential end of the lift or lower motion.

    a. If the Z bottle position was greater than the P1 lower threshold it indicated the end of the lift motion

    b. If the Z bottle position was less than the P2 position threshold it indicated the end of the lower motion.

Lastly, to prevent false detection of the start or end of the lift or lower motions, additional constraints were placed on the frames identified as the potential start or end of the motions. The constraints were as follows:

1. Start of the motion always precedes the end of the motion.
2. At least 0.5s was required to elapse between the start and end of the motion
3. The start of the previous lift or lower motion was at least 2s prior.

Once the frame numbers of the final start and end points of the lift and lower motions were identified, the continuous 60s of kinematic data during each epoch were spliced and sorted into 4 different actions, as summarized above and outlined in Table 6. The kinematic data assigned to the lift and lower motions corresponded to the frames which lied between the start and end frame of the give motion. The 2 remaining actions were the two rest periods. Only the kinematics during the lift motions were analyzed in this thesis.

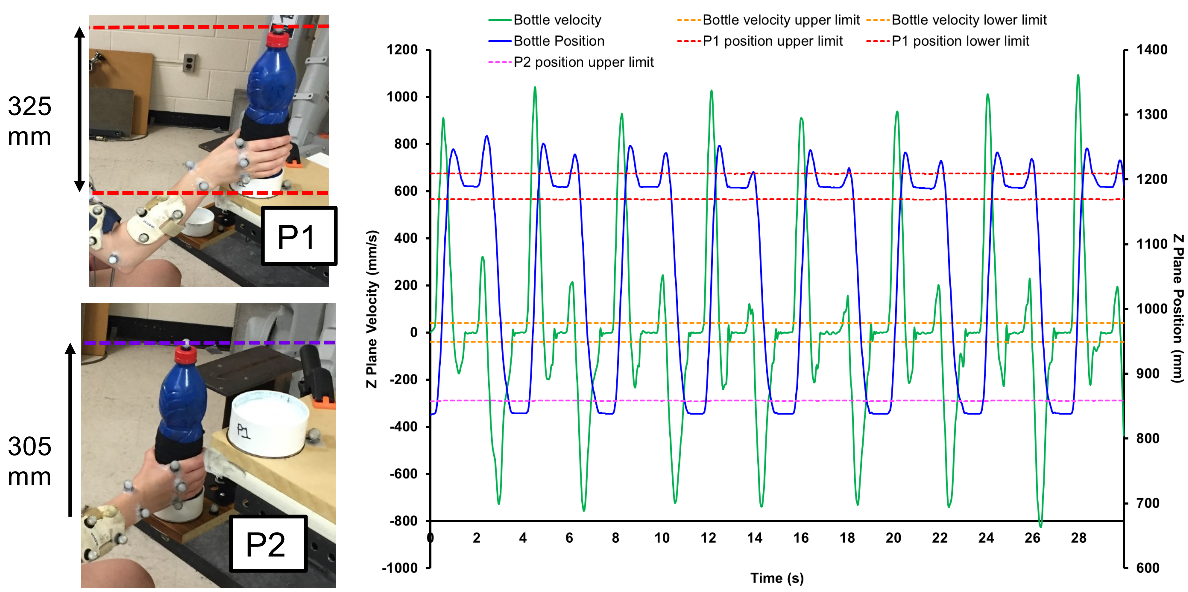


Figure 4: A time series graph of the Z positions and velocities used to partition the kinematic data into individual lift and lower motions. The data displayed are from one participant during the repetitive task. The images on the left provide a visual representation of the position thresholds, relative to the P1 and P2 target locations used to identify the start or end of a lift or lower motion. The upper and lower threshold of the P1 target location spanned a range of 325mm equivalent to 20mm below the P1 target location and 20mm above the P1 target location plus the height of the bottle (285mm). The P2 target location only had an upper threshold which was set at the bottle height (285mm) plus 20mm above the P2 target location.

Table 6: A description of the relationships between the bottle z position and velocity with the z position and velocities thresholds set to identify the start or end of the lift and lower motions. Further this table identifies how the data were spliced into the 4 different actions within the repetitive task Abbreviations – sr = sample rate, frame = frame number of the recorded sample.

	Start		End	
Action	Bottle Z Velocity	Bottle Z position	Bottle Z Velocity	Bottle Z position
Lift	t = frame-(1/2 sr) OR Velocity at t = frame+(1/2 sr) are within +/- 10mm/s	Not below P2 position threshold	t = frame+(1/2 sr) is not within +/- 10mm/s	Within P1 position threshold
Rest 1	End of Lift		Start of Lower	
Lower	t = frame-(1/2 sr) OR Velocity at t = frame+(1/2 sr) are within +/- 10mm/s	Not within P1 position threshold	t = frame+(1/2 sr) is not within +/- 10mm/s	Below P2 position threshold
Rest 2	End of Lower		Start of Lift	

6.5.2.2 Joint Angles

The static calibration trial was used to create rotation matrices between the anatomical axis systems and the cluster axis systems of the humerus and forearm. These rotation matrices enable the use of the position data from the cluster markers, which are less sensitive to skin motion artifact, when compared to the anatomical markers, to compute relevant joint angles. Thus, during the static calibration trial, local co-ordinate systems were constructed for humerus and forearm segments, as per ISB recommendations (Wu et al., 2005), using the position data of the reflective markers placed over top of the anatomical landmarks and for the marker clusters placed over the humerus and forearm segments. Note that the humerus rotation matrices between the anatomical axis systems and the cluster axis systems "[C to A] matrices" were computed as follows: 1) the humeral cluster relative to the humeral axis system, and 2) forearm cluster relative to the forearm axis system. The relationship between the cluster and anatomical axis systems were assumed to remain constant during the repetitive task.

To compute joint angles, rotation matrices describing the relative position of the local coordinate system of the distal segment with respect to that of the proximal segment were constructed and decomposed using a specific Euler/Cardan sequence corresponding to ISB recommendations (Wu et al., 2005). The following joint angles were computed: 1) thorax relative to global, 2) thoracohumeral (humerus to torso) 3) elbow (forearm relative to humerus), and 4) wrist (hand relative to forearm). A customized Matlab program (Mathworks, Inc., USA) was used to compute the joint angles from the position data collected during the experiment. The general process was as follows:

1. Construct time varying rotation matrices between the global coordinate system and the cluster coordinate system "[G to C] Matrix", using the position data of the clusters on the humerus and forearm segments.

2. Calculate the rotation matrix between the global coordinate system and the anatomical coordinate system, the "[G to A] matrices" for each body segment.

a. Humerus, Forearm: This consists of the product of time varying [G to C] matrix and the constant [C to A] matrix for the humeral cluster, forearm cluster, and acromion marker cluster.

b. Thorax, Hand: This consists of a matrix of the unit vectors representing the x, y, and z axes of the local coordinate system.

3. Calculate the rotation matrix between the local coordinate system of the distal segment, with respect to that of the proximal segment "[A-D to A-P] matrix". This consists of multiplying the transpose of the [G to A] matrix of the distal segment, the [A to G] matrix, by the [G to A] matrix of the proximal segment.

4. Decomposing the direction cosine matrix based on the Euler/Cardan sequence in the ISB recommendations, except for the thoracohumeral joint angle (Table 7). The torso, elbow and wrist Cardan sequence is ZXY (Equation 2). The ISB recommendations suggest a Y-X-Y decomposition sequence, however, with this sequence gimbal lock occurs at 0° and 180°. Thus, joint angles within 20° of these limits can be 'erratic' especially as approaching gimbal lock. Given the range of thoracohumeral elevation in this study includes postures in the range of 0-20° of thoracohumeral elevation, this rotation sequence was not suitable. Instead, an X-Z-Y rotation sequence was selected (Equation 3), which has gimbal lock at -90° and 90° of thoracohumeral plane of elevation (Phadke et al., 2011). The repetitive task was designed in a manner that does not require glenohumeral plane of elevation angles to fall within -70 to -90° and 70-90°.

$$\begin{bmatrix} \cos(\gamma)\cos(\alpha) - \sin(\gamma)\sin(\beta)\sin(\alpha) & \cos(\gamma)\sin(\alpha) + \sin(\gamma)\sin(\beta)\cos(\alpha) & -\sin(\gamma)\cos(\beta) \\ -\cos(\beta)\sin(\alpha) & \cos(\beta)\cos(\alpha) & \sin(\beta) \\ \sin(\gamma)\cos(\alpha) + \cos(\gamma)\sin(\beta)\sin(\alpha) & \sin(\gamma)\sin(\alpha) - \cos(\gamma)\sin(\beta)\cos(\alpha) & \cos(\gamma)\cos(\beta) \end{bmatrix} \quad (2)$$

$$\begin{bmatrix} \cos(\gamma)\cos(\alpha) & \cos(\gamma)\sin(\alpha)\cos(\beta) + \sin(\gamma)\sin(\beta) & \cos(\gamma)\sin(\alpha)\sin(\beta) - \sin(\gamma)\cos(\beta) \\ -\sin(\alpha) & \cos(\alpha)\cos(\beta) & \cos(\alpha)\sin(\beta) \\ \sin(\gamma)\cos(\alpha) & \sin(\gamma)\sin(\alpha)\cos(\beta) - \cos(\gamma)\sin(\beta) & \sin(\gamma)\sin(\alpha)\sin(\beta) + \cos(\gamma)\cos(\beta) \end{bmatrix} \quad (3)$$

Table 7: A list of the rotation sequences that will be used to calculate the joint angles studied in this experiment. The rotation sequences correspond to those suggested in the ISB recommendations (Wu et al., 2005). In bold is the name of the rotation referenced in this document, below indicates the names given to joint angles based on their direction. For example, in this document the joint angle called 'torso flexion' can referred to torso extension when the angle is positive. This will be specified throughout the document when it occurs, but for brevity when referring simply to the rotation the torso angle about the Z global axis will be termed torso flexion.

Joint	Rotation Sequence	α	β	γ
Torso to Global	Z-X-Y	**Flexion** Flexion (-) Extension (+)	**Lateral Flexion** Right Lateral Flexion (+) Left Lateral Flexion (-)	**Axial Rotation** Left Axial Rotation (+) Right Axial Rotation (-)
Thoraocohumeral	X-Z-Y	**Elevation** Elevation (+) Depression (-)	**Plane of Elevation** Horizontal Flexion (+) Horizontal Extension (-)	**Axial Rotation** External Rotation (-) Internal Rotation (+)
Elbow	Z-X-Y	**Flexion** Flexion (+) Hyperextension (-)	**Carrying Angle**	**Pronation** Pronation (+) Supination (-)
Wrist	Z-X-Y	**Flexion** Flexion (+) Extension (-)	**Pronation** Pronation (+) Supination (-)	**Deviation** Ulnar Deviation (+) Radial Deviation (-)

6.5.2.3 Symbolic Motion Structure Representation (SMSR) Strings

The SMSR algorithm was used to identify the basic spatial-temporal structure of the time series joint angle data during the last 5 lift motions in each epoch of the repetitive task. The SMSR algorithm was implemented into a customized program created in Matlab software (Mathworks, Inc., USA). The implementation of the SMSR algorithm followed the detailed steps outlined in Park et al., (2005), with modifications to the suggested threshold values used in the algorithm. A summary of the steps involved in the SMSR algorithm and the changes made to the threshold values used by Park et al., (2005) follow:

Step 1 - Landmark Identification: Examine each point in the time series data to determine if it can be considered a landmark. A landmark will have one of the following characteristics: 1) the first or last point in the time series data, 2) a local maxima or minima, 3) the start or end of a stationary segment; a point at time t in which the derivative at either t-1 or t+1 (not both) is greater than the user specified threshold "*elsope*". Park et al., (2005) suggest *eslope* corresponds to 1°/ min, which is slightly below the perception threshold of joint angular motion (Clark et al., 1985, 1986). The perception threshold of joint angular motion proposed by Clark et al., (1985, 1986) of 2°/ min was based on research with the ankle and the 2^{nd} MCP joint. Cordo et al., (2000) used an apparatus constraining the elbow and wrist joints to elicit rotation about the shoulder and found that to be consistent with Clark et al., (1985, 1986), in that the threshold of joint movement perception is 2°/min. Thus, in this thesis, the *eslope* threshold was increased from 1°/ min to 2°/ min as there is evidence that joint motion cannot be detected at 1°/ min.

Step 2 - Selection of Segment Boundary Points: Segment boundary points consist of landmarks that create elemental motion segments with a duration longer than a predetermined threshold "*etime*" to remove landmarks that represent noise in the time series data. Park et al., (2005) suggests *etime* to be set at 1/6s, which dictates the minimum duration of each motion segment. The authors proposed this value as they believed it would be sufficient to capture small changes in "normal-paced joint motion" with the understanding that no more than 2 movement corrections occur during a 1s movement (Wikens, 1986). The motivation behind the development of the SMSR algorithm was to identify the basic features of a motion that can be used to predict upper extremity movement in seated reaches, given the start and end positions of the hand. For movement prediction, the more segments there are in the motion, the easier it becomes to predict a similar motion simply by altering the duration and amplitude of each motion segment. However, the intended application of the SMSR in this thesis is to identify the basic structure of joint motion as a guide to inform visual detection of kinematic changes in repetitive work causing muscle fatigue. Thus, it is advantageous to have fewer motion segments in a 1s period to suit this purpose, as it is more likely visually detectable. Therefore, in this thesis, *etime* was set to 1/3s pertaining to that identified by Wikens (1986) in that a maximum of 2 movement corrections in a 1s period can occur. This translates into 2 maximum or minimums in the joint angle profile and therefore a total of 3 motion segments.

The first and last landmarks are selected as boundary points, then the other landmarks are examined consecutively in time to determine whether the landmark: 1) is located farther than *etime* from at least one other adjacent landmark, and 2) is located farther than *etime* from the nearest segment boundary point.

Step 3 Symbol Assignment: A user defined threshold "*e-angle*" of angular displacement is used to determine whether each segment, encompassed by a pair of boundary points, is stationary (***S***), increasing (***U***), or decreasing (***D***). Park et al., (2005) recommend an *e-angle* value of 1° with the intent to represent joint displacements that are large enough to be perceived by the individual. This decision was based on previous literature indicating that the minimum detection of joint angular displacement in dynamic tasks, termed dynamic position sense, ranges from 0.3-0.7° across joints within the body (Laidlaw & Hamilton, 1937; Griegg et al., 1973). Joint position sense is dependent on the speed of the movement, with increasing precision as joint velocity increases above 4°/min (Clark et al., 1985; Cordo et al., 2000). In this study, which consists of a repetitive task with rest breaks between each lift and lower motion, the threshold of detecting joint motion from rest seems most appropriate. In contrast to dynamic joint position sense, static joint position sense is less precise, ranging from 2-5°(Cordo et al., 2000). The higher end of this range was selected as the *e-angle* value used in this thesis because it is closer to minimum visually detectable changes in joint angle positions in workplace tasks, which are around 10° at the thoracohumeral and torso (Bao et al., 2009).

Step 4 Eliminate Redundancies: The SMSR string created in step 3 may contain redundancies. This step will remove any redundancies by merging consecutive segments with the same symbol (***S***, ***U*** or ***D***).

The SMSR string for a given joint angle time-series consists of the characters assigned to each segment, in sequential order. The SMSR algorithm was applied to the time-series joint angle data during the last 5 lift motions in each epoch (Section 6.5.2.1). Based on the assumption that 5 motions adequately captures an individual's trial to trial movement variability, for a given joint angle at a given epoch, most frequent SMSR across the 5 lift motions (at least 3/5 lift motions) was selected as the motion structure most frequently used during that epoch (Figure 5). In situations where there was not a single string meeting this criterion (less than 5% of all kinematic data), the string in the previous epoch was selected. This data reduction protocol enabled both within- and between-subject comparisons of joint angle SMSRs with time during the repetitive task, summarized by SMSR time histories created for each participant x joint angle combination (Figure 5).

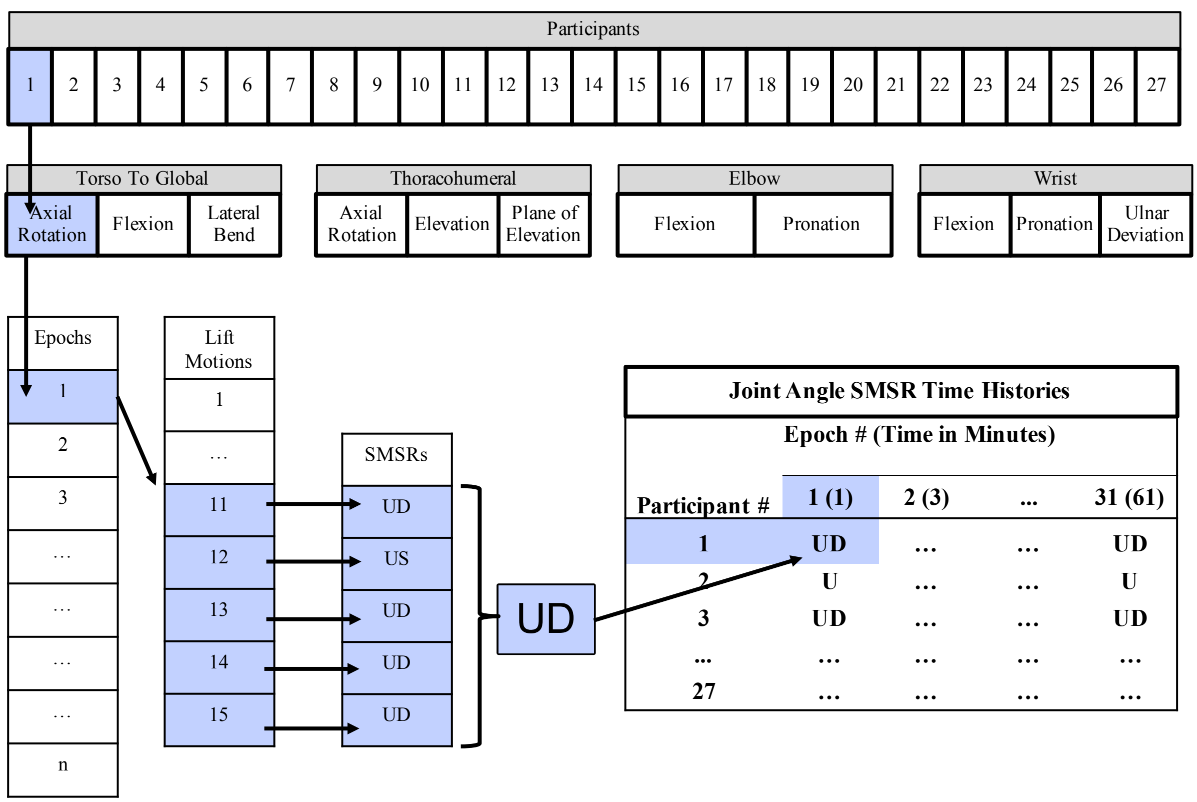


Figure 5: A schematic representation of the procedures followed to create joint angle SMSR time histories for each participant. The joint angles during the last 5 lift motions in an epoch were characterized by an SMSR. In this example 5 SMSRs were created to represent participant 1's torso axial rotation joint angles during the last 5 lift motion in the first epoch of the repetitive task. The most frequent SMSR across these 5 efforts (UD) was selected to represent the structure of the axial rotation motion during the given epoch, in this example epoch 1. Overall this procedure is a data reduction technique that facilitated the characterization of a participants' joint angles at a given epoch with a single SMSR.

6.5.2.4 Thoracohumeral Elevation SMSR Change Onset

Thoracohumeral SMSR change onset (Equation 4) was calculated as the time (minutes) in which the SMSR string corresponding to the thoracohumeral elevation angle differed from the SMSR at baseline, expressed as a percentage of the participants' total task duration (minutes).

$$\text{TH SMSR Change Onset (\% task duration)} = \frac{\text{TH SMSR string change (minutes)}}{\text{Total task duration (minutes)}} \quad (4)$$

6.5.2.5 Thoracohumeral Elevation SMSR Variability

Each participants' thoracohumeral elevation SMSR variability was determined as the number of times the participant switched SMSR strings between consecutive time points (epochs) during the repetitive task. A participant who maintained a ***U*** string throughout the whole repetitive task would have a total of 0 switches and thus indicate no thoracohumeral elevation SMSR variability. A participant that switched from ***U*** to ***UD*** to ***U*** would have a total of 2 switches during the repetitive task and thus indicate variation of their thoracohumeral elevation SMSR. Participants thoracohumeral elevation SMSR variability was calculated and used to identify two groups of participants, as outlined below (Section 6.6.3).

6.5.3 Rating of Perceived Fatigue and Discomfort

To facilitate comparison of the RPF and RPD time series data between individuals, given that the total task duration is participant specific, the RPF and RPD data for each participant were rubber banded using linear interpolation (Winter, 2009). In repetitive tasks RPF and RPD exhibit a linear relationship with time (Frey Law et al., 2010b; Iridiastadi & Nussbaum, 2006;

Rose et al., 2014). RPF and RPD were calculated, using linear interpolation for each participant at 25%, 50%, 75%, and 100% of participants' total task duration.

6.6 Statistical Analysis

6.6.1 SMSR Strings

At the participant level, a difference in a single character of the SMSR of a given joint angle between any two points in time was considered significant. As explained above (Section 6.5.2.3, Figure 5), the SMSR string with the highest frequency at each epoch (at least 3/5 efforts) was selected to represent the basic structure of the joint angle motion at the given epoch. Since the SMSR string at each epoch reflected the majority of the 5 lift motions analyzed in the epoch, a difference in the SMSR string between epochs was considered significant and assumed not to be a result of sampling error.

6.6.2 Thoracohumeral Elevation SMSR Change Onset

A linear regression equation between the thoracohumeral elevation SMSR change onset (independent variable) and the infraspinatus muscle fatigue onset (dependent variable) was created using a least squares approach. The goodness of fit was determined by calculating the coefficient of determination (r^2).

6.6.3 Thoracohumeral Elevation SMSR String Variability

Participants were divided into two groups, based on whether they varied their thoracohumeral elevation SMSR during the repetitive task. The first group, termed "No SMSR variability" consisted of participants which changed SMSRs 0 or 1 times during the repetitive task. Thus, the second group termed "SMSR string variability" changed their SMSRs at least twice during the repetitive task. Although not the explicit focus of this thesis, sex was included as a potential factor that may contribute to differences in the examined fatigue responses. In low to moderate intensity intermittent isometric efforts, women exhibit longer task endurance times and a slower rate of strength decline than males (Hunter, 2009; Hunter et al., 2004). The statistical tests outlined below were designed to identify whether there were main effects or interactions between the variability group and sex of participants on fatigue measures during the repetitive task.

6.6.3.1 EMG MPF

The time series rubber banded EMG MPF data from each muscle with greater than 10% activation during the static reference task at baseline were input into separate general linear models (i.e. one per muscle). Each generalized linear model had two between-subject factors: 1) the sex of the participants (male or female), and 2) group (no thoracohumeral elevation SMSR variability or thoracohumeral elevation SMSR variability). The within-subject factor (repeated measure) consisted of the 4 time points during the repetitive task: 25%, 50%, 75%, 100%. Significance was set at $p<0.05$ and Tukey HSD comparisons with a significance of $p<0.05$ were used to test significant main effects and interactions.

6.6.3.2 Rating of Perceived Fatigue and Discomfort

The time series rubber banded RPF and RPD data were input into separate general linear models. The two between-subject factors were: 1) the sex of the participants (male or female), and 2) group (no thoracohumeral elevation SMSR variability or thoracohumeral elevation SMSR variability). The within subject factor (repeated measure) consisted of the 4 time points during the repetitive task: 25%, 50%, 75%, 100%. Significance was set at $p<0.05$ and Tukey HSD comparisons with a significance of $p<0.05$ were used to test significant main effects and interactions.

6.6.3.3 ER MVF

The ER MVF data (% baseline following the repetitive task) were inputted into a generalized linear model with two between-subject factors. The two between-subject factors were: 1) the sex of the participants (male or female), and 2) group (no thoracohumeral elevation SMSR variability or thoracohumeral elevation SMSR variability). Significance was set at $p<0.05$ and Tukey HSD comparisons with a significance of $p<0.05$ were used to test significant main effects and interactions.

7 RESULTS

7.1 Change in SMSR String

7.1.1 Global Level

All participants exhibited a change in the SMSR string across several of the examined joint angles during the repetitive task. Participants exhibited a change in movement strategy at an average of 7.30 +/- 1.61 of the 11 joint angles measured (Appendix B; Table 1). All but one participant changed the SMSR string representation of their wrist flexion angles during the repetitive task (Appendix B; Table 13). The number of participants exhibiting a change in SMSR of the other measured joint angles in this thesis ranged between 15-22, except for wrist ulnar deviation in which only 4/27 participants exhibited a change (Figure 6). All participants changed

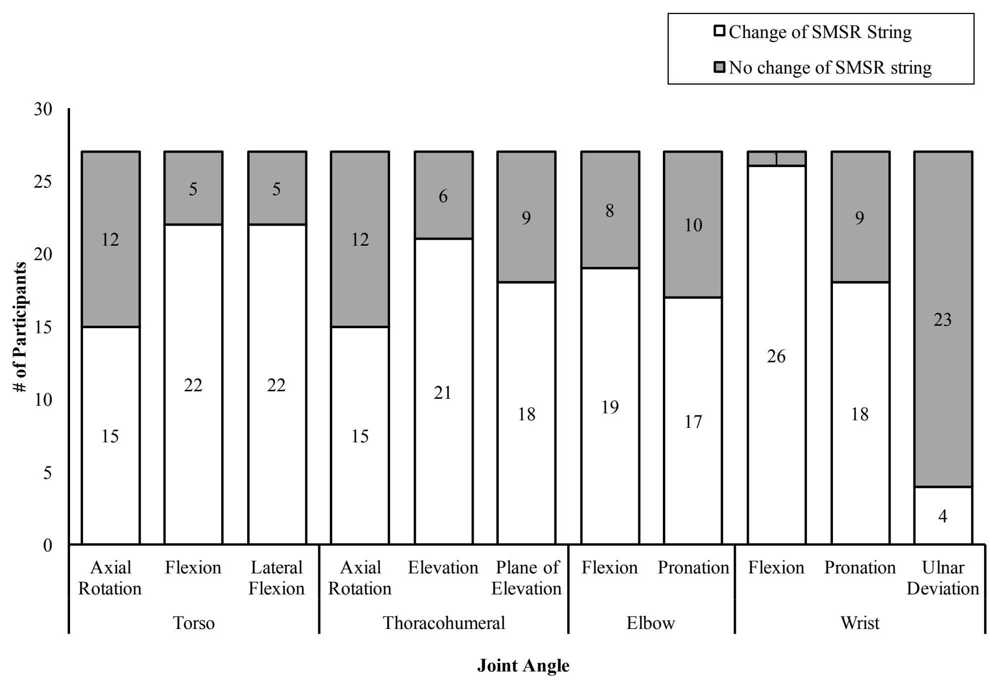


Figure 6: The number of participants that changed the SMSR string representation of a given joint angle during the repetitive task. A total of 27 participants completed the study, and 11 joint angles were analyzed. These data are presented above in a stacked bar graph to show how many participants, of the 27 that completed the study, did or did not change the SMSR by joint angle.

the SMSR string representation of at least 1/3 angles at the torso (27/27), followed in descending order by the thoracohumeral (26/27), wrist (26/27), and elbow (24/27) joints (Figure 7).

7.1.2 Joint Angle Level

Across joint angles, participants changed the SMSR string representation of their joint angles in similar ways, using a small subset of different SMSR strings. The primary SMSR strings representing each joint angle are discussed in the following sections. A subset of the joint angle vs. time data from 2 different participants during the repetitive task, and the corresponding SMSRs are also included. To present these results at the participant level, a table showing the 'SMSR string time history' of each participant during the repetitive task was created for each joint angle. For simplicity, only one SMSR string time history table per joint is included in the results section, with the remaining tables reported in Appendix B.

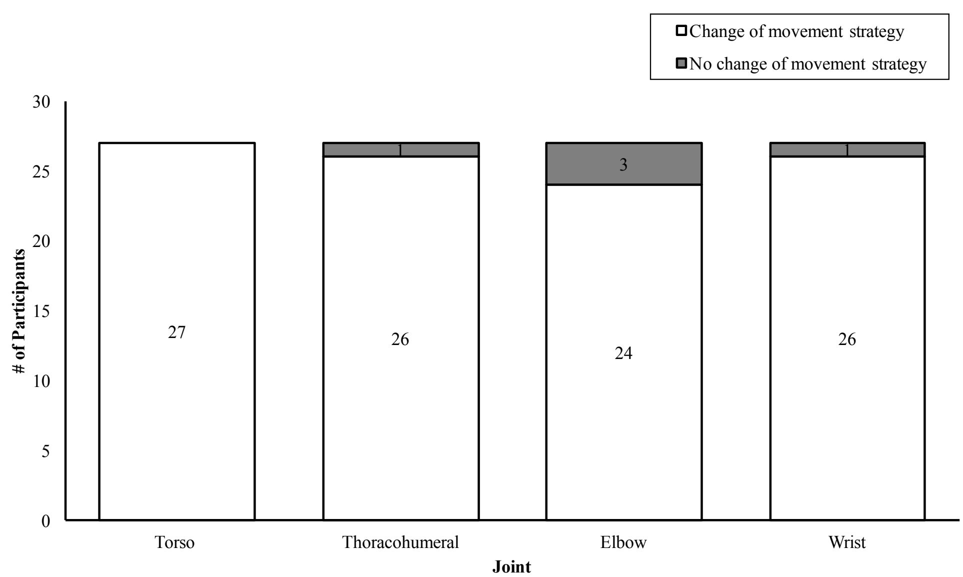


Figure 7: The number of participants that changed the SMSR string representation of at least one joint angle at a given joint during the repetitive task. A total of 27 participants completed the study, and 4 joints were analyzed. These data are presented above in a stacked bar graph to show how many participants, of the 27 that completed the study, did or did not change the SMSR string representation of a given joint angle at least one joint angle at a given joint during the repetitive task.

7.1.2.1 Torso Axial Rotation

Participants' torso axial rotation joint angles were characterized by either a D or DS SMSR string (Appendix B, Table 14). All participants who did not change movement strategy during the repetitive task had a D string character (Figure 8). A D string character indicates torso axial rotation to the right. In contrast, participants who elicited a change in movement strategy transitioned between D and DS strings (Figure 9). A DS string character also indicates torso axial rotation to the right, with a period of little axial rotation motion at the end of the effort.

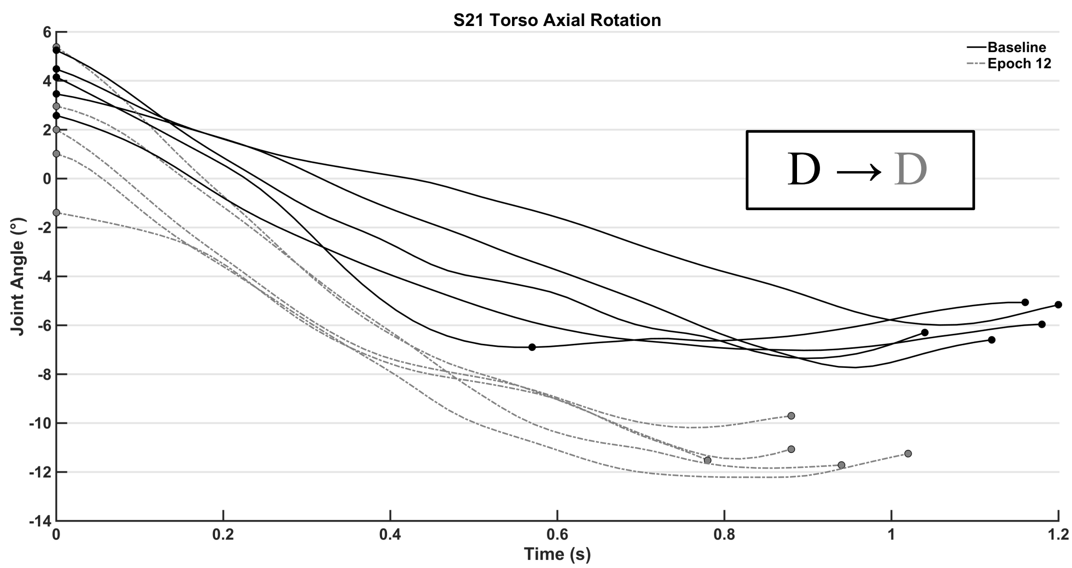


Figure 8: Torso axial rotation joint angle data from participant 21 as a function of time. Positive values indicate right lateral flexion and negative indicate left lateral flexion. A total of 5 lift motions at baseline (dark solid lines) and another time point (dotted lines) during the repetitive task are displayed. This participant maintained a D string throughout the repetitive task. The SMSR string representation of each epoch is shown on the graph to the right hand side, in font matching the color of the lines displayed. Note, the string selected to represent the 5 efforts at a given point in time (epoch) was that which represented atleast 3/5 efforts examined. In this example, at baseline 4/5 lifts were characterized by a D string and one with a DS string, thus the D string was selected to represent the participants torso axial rotation SMSR at baseline.

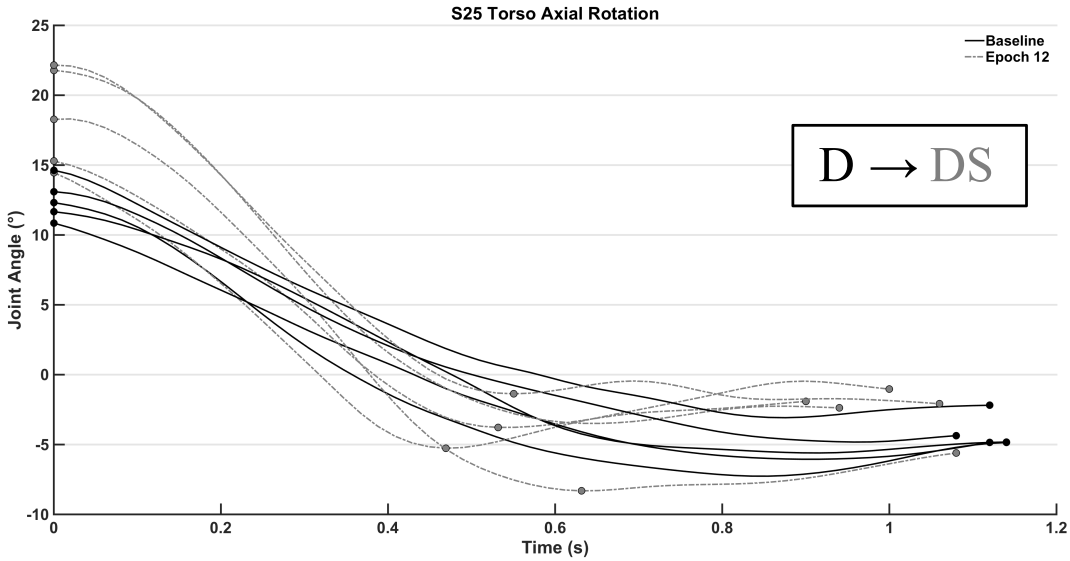


Figure 9: Torso axial rotation joint angle data from participant 25 as a function of time. Positive values indicate right lateral flexion and negative indicate left lateral flexion. A total of 5 lift motions at baseline (dark solid lines) and another time point (dotted lines) during the repetitive task are displayed. This participant switched between D and DS string throughout the repetitive task. The SMSR string representation of each epoch is shown on the graph to the right hand side, in font matching the color of the lines displayed.

7.1.2.2 Torso Flexion

Participants' torso flexion joint angles were characterized by ***U***, ***S*** or ***US*** SMSR strings (Appendix B, Table 15). A ***U*** SMSR string indicates torso extension, given that flexion angles are negative per ISB convention. Thus, participants varied between either torso extension (***U***), minimal torso extension (***S***), or torso extension followed by a period of minimal change in joint angle (***US***) (Figure 10, Figure 11). Most participants (17/27) exhibited a change in SMSR string during the repetitive task intermittently, by switching between strategies at least twice during the repetitive task from ***U*** to ***US*** or ***S***.

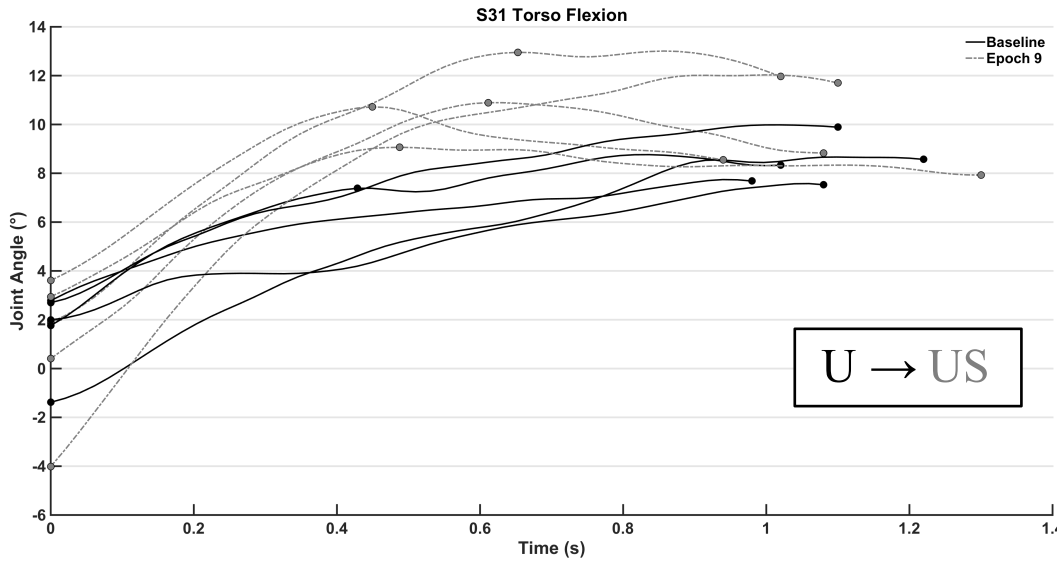


Figure 11 Torso flexion joint angle data from participant 31 as a function of time. Positive values indicate extension and negative indicate flexion. A total of 5 lift motions at baseline (dark solid lines) and another time point (dotted lines) are displayed. This participant switched between a ***U*** and ***US*** strings during the repetitive task. The SMSR string representation of each epoch is shown on the graph to the right hand side, in font matching the color of the lines displayed. Note, the string selected to represent the 5 efforts at a given point in time (epoch) was that which represented at least 3 of 5 efforts examined. In this example, at baseline, 4 of 5 lifts were characterized by a ***U*** string and only 1 of 5 with a US string, thus the ***U*** string was selected to represent the participants torso flexion SMSR at baseline.

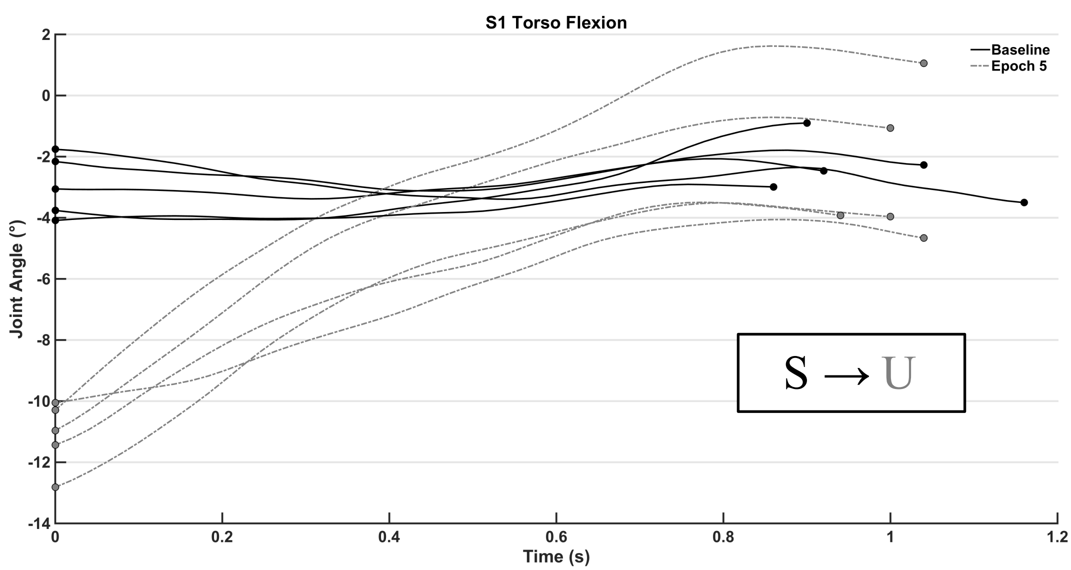


Figure 10: Torso flexion joint angle data from participant 1 as a function of time. Positive values indicate extension and negative indicate flexion A total of 5 lift motions at baseline (dark solid lines) and another time point (dotted lines) during the repetitive task are displayed. This participant switched between a ***S*** and ***U*** strings during the repetitive task. The SMSR string representation of each epoch is shown on the graph to the right hand side, in font matching the color of the lines displayed.

7.1.2.3 Torso Lateral Flexion

Participants' torso lateral flexion joint angles were characterized by ***D***, ***S*** or ***DS*** SMSR strings (Table 8). A ***D*** SMSR string indicates torso lateral flexion to the left. Thus, participants varied between either left torso lateral flexion (***D***), minimal torso lateral flexion (***S***), or left torso lateral flexion followed by a period of minimal change in joint angle (***US***) (Figure 12, Figure 13). Most participants (20/27) exhibited a change in SMSR string during the repetitive task intermittently, by switching between strategies at least twice during the repetitive task (Table 8). The few participants who did not change SMSR string during the repetitive task (5/27) had an ***S*** SMSR string and therefore did not use torso lateral flexion during the repetitive task (Table 8).

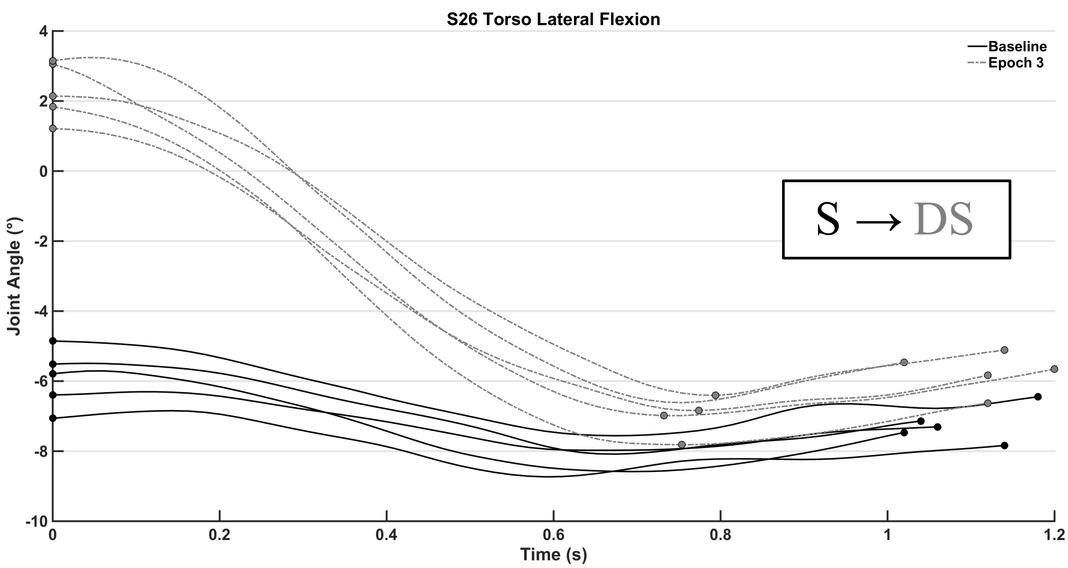


Figure 12: Torso lateral flexion joint angle data from participant 26 as a function of time. Positive values indicate right lateral flexion and negative indicate left lateral flexion. A total of 5 lift motions at baseline (dark solid lines) and another time point (dotted lines) during the repetitive task are displayed. This participant switched between ***S*** and ***DS*** strings throughout the repetitive task. The SMSR string representation of each epoch is shown on the graph to the right hand side, in font matching the color of the lines displayed.

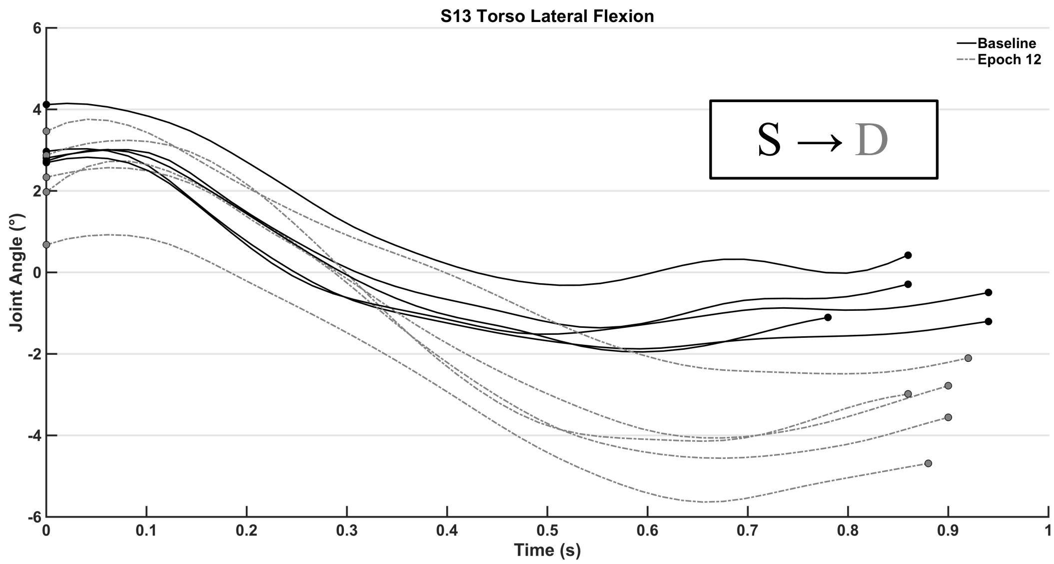


Figure 13: Torso lateral flexion joint angle data from participant 13 as a function of time. Positive values indicate right lateral flexion and negative indicate left lateral flexion. A total of 5 lift motions at baseline (dark solid lines) and another time point (dotted lines) during the repetitive task are displayed. This participant switched between ***S*** and ***D*** strings throughout the repetitive task. The SMSR string representation of each epoch is shown on the graph to the right hand side, in font matching the color of the lines displayed.

Table 8: A time history of the SMSR strings representing participants' torso lateral flexion joint angles during the repetitive task. Participants' have been grouped by the frequency of changes in the SMSR string during the repetitive task.

Torso Lateral Flexion		Time (min)																														
SMSR String	Participant #	1 (Baseline)	3	5	7	9	11	13	15	17	19	21	23	25	27	29	31	33	35	37	39	41	43	45	47	49	51	53	55	57	59	61
No Change	4	S	S	S	S	S	S	S	S																							
	5	S	S	S	S	S	S	S	S	S	S																					
	15	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S
	16	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S															
	19	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S															
Change (1 epoch only)	2	DS	DS	D	DS	DS	DS																									
	29	DS	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D									
Change (>1 epoch)	18	S	D	S	S	S	S	S	S	S	S	D	S	S	S	S																
	24	D	D	D	S	S	D	S	D	D	D	D	D	D	S	D	D	D	D	D	S	D	D	D	D	D	D	D				
	22	S	S	S	DS	S	S	S	DS	S	S	S	S	S	DS	S	S	S	DS	S	S											
	28	S	D	D	D	S	S	S	S	S	S	S	S	S	S																	
	25	D	D	DS	D	D	D	D	D	S	DS	D	D	DS	DS	D	D															
	13	S	D	D	S	S	S	D	D	DS	S	S	D	D	S	S	D	S	S	S	S	S	S									
	20	D	DS	DS	D	D																										
	30	DS	DS	DS	DS	DS	DS	DS	DS	S	S	S	S	S	DS	S	S															
	23	S	D	D	D	D	D	D	D	D	D	D	S	S	D	D	D	S	S	S	D	S	D	S	D	S	S	S	S	S	S	S
	7	S	D	D	S	D																										
	8	S	DS	DS	DS	DS	DS	S	DS	DS	DS	DS	DS	DS	DS	S	S	DS	S	DS												
	9	S	S	DS	S	S	D	S	D	S	DS	DS	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	S	D	D	D	D
	31	DS	D	D	D	DS	D	D	D	D	D	D	D	D	D	D	D	DS	DS													
	11	DS	D	D	D	S	S	D	S	DS	D	S																				
	27	DS	D	D	DS	D	D	D	D	D	D	D																				
	17	DS	DS	D	D	D	D	D	D	D	D	D	D																			
	21	S	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	S	D	S	D	D	D	D	D	D	D	S	D	D
	26	S	DS	DS	D	DS	D	D	D	D	D	D	S	D	D	D	D	D	D	D	D	D	D	D	D	S						
	1	S	D	DS	D	DS	D	D	D	D	D																					
	14	DS	D	D	D	D	S	S	S	S	D	D	S	S	D	S	S	S	D	S												

7.1.2.4 Thoracohumeral Axial Rotation

Participants' thoracohumeral axial rotation joint angles were characterized by ***U***, ***UD*** or ***US*** SMSR strings (Appendix B, Table 16). A ***U*** SMSR string indicates thoracohumeral internal rotation, whereas a ***UD*** SMSR string indicates internal rotation followed by external rotation. Most participants did not vary the SMSR string at all (12/27), or only changed once (7/27) during the repetitive task. The most common SMSR string amongst these participants was the ***U*** string, with few using a ***UD*** strategy and only one participant changing from a ***U*** to ***US*** strategy once. The other 7/27 participants varied the SMSR string intermittently during the repetitive task, switching between the ***U*** and ***UD*** strategies. One participant (16) varied the SMSR string intermittently between a variety of strings (***U***, ***DU***, ***US***, ***S***, ***SU***).

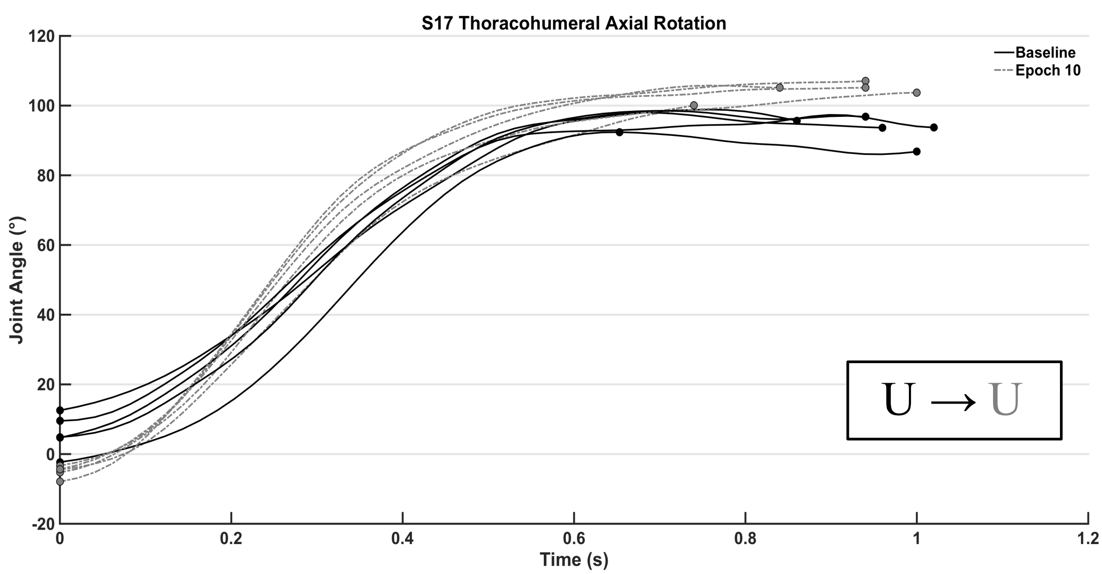


Figure 14: Thoracohumeral axial rotation joint angle data from participant 17 as a function of time. Positive values indicate internal rotation and negative indicate external rotation. A total of 5 lift motions at baseline (dark solid lines) and another time point (dotted lines) are. This participant maintained a ***U*** string throughout the repetitive task. The SMSR string representation of each epoch is shown on the graph to the right hand side, in font matching the color of the lines displayed.

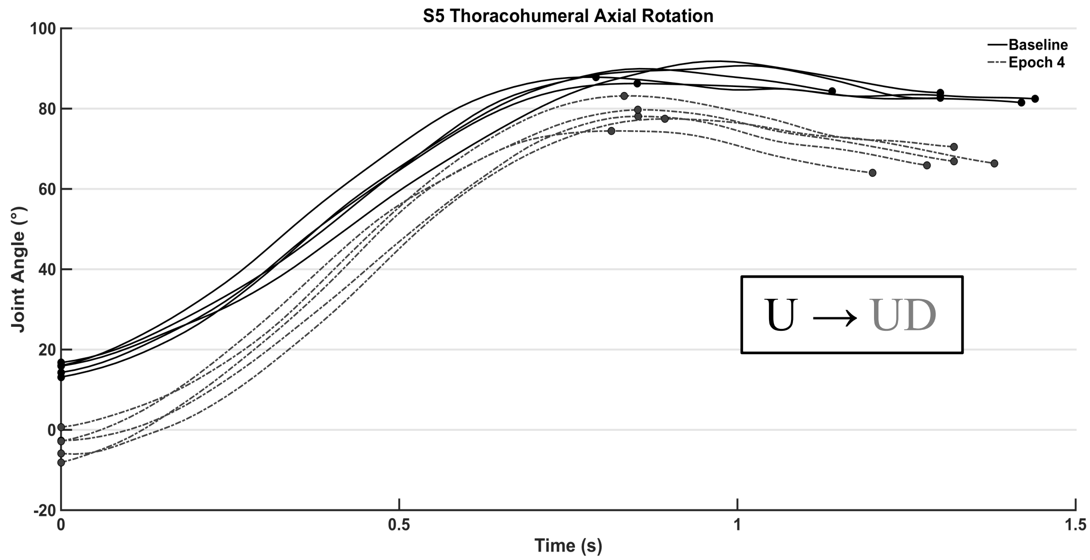


Figure 15: Thoracohumeral axial rotation joint angle data from participant 5 as a function of time. Positive values indicate internal rotation and negative indicate external rotation. A total of 5 lift motions at baseline (dark solid lines) and another time point (dotted lines) during the repetitive task are displayed.This participant switched between a ***U*** and ***UD*** string throughout the repetitive task. The SMSR string representation of each epoch is shown on the graph to the right hand side, in font matching the color of the lines displayed. Note, the string selected to represent the 5 efforts during an epoch was that which represented atleast 3 of 5 efforts examined. In this example, at baseline 3 of 5 lifts were characterized by a ***U*** string and 2 of 5 with a ***US*** string, thus the ***U*** string was selected to represent the participant's thoracohumeral axial rotation SMSR at baseline.

7.1.2.5 Thoracohumeral Elevation

Participants' thoracohumeral elevation joint angles were characterized by ***U***, ***UD*** or ***US*** SMSR strings (Table 9). A ***U*** SMSR string indicates thoracohumeral elevation, whereas a ***UD*** SMSR string indicates elevation followed by depression (Figure 16). A ***US*** string indicates elevation (***U***) followed by a period of little change in joint angle (***S***) (Figure 17). Over half of participants (15/27) changed their elevation SMSR strings more than twice during the repetitive task typically switching between a ***U*** and ***US*** or ***UD*** string. Most participants that did not change SMSR string or did so only once had a ***U*** strategy, with fewer maintaining the ***UD*** strategy.

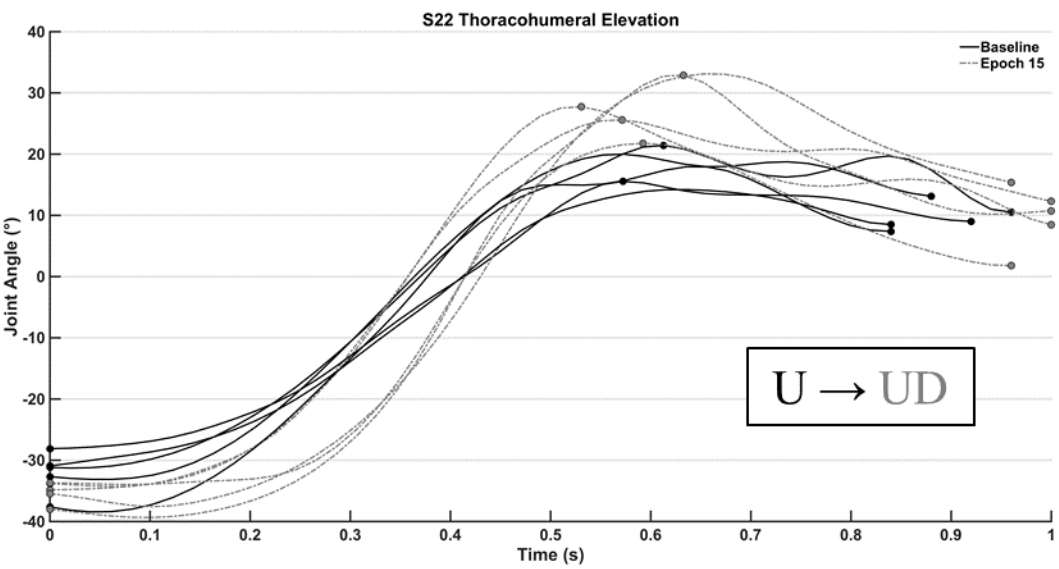


Figure 16: Thoracohumeral elevation joint angle data from participant 22 as a function of time. Positive values indicate elevation and negative indicate depression A total of 5 lift motions at baseline (dark solid lines) and another time point (dotted lines) during the repetitive are displayed. This participant switched between a ***U*** and ***UD*** string throughout the repetitive task. The SMSR string representation of each epoch is shown on the graph to the right hand side, in font matching the color of the lines displayed. Note, the string selected to represent the 5 efforts during an epoch was that which represented at least 3 of 5 efforts examined. In this example, at baseline, 4 of 5 lifts were characterized by a ***U*** string and 1 of 5 with a ***US*** string, thus the ***U*** string was selected to represent the participant's thoracohumeral elevation SMSR at baseline.

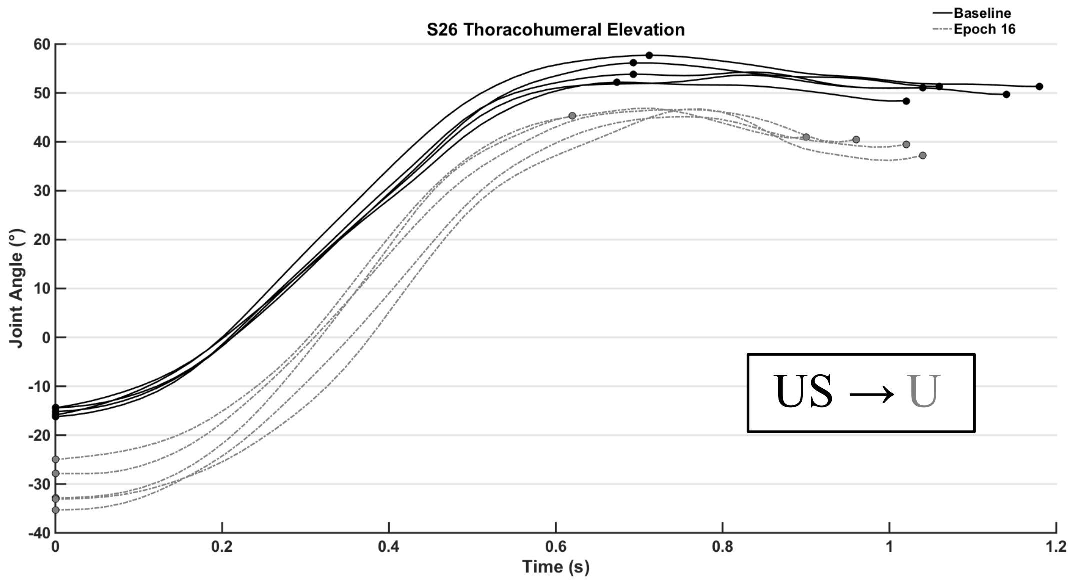


Figure 17: Thoracohumeral elevation joint angle data from participant 26 as a function of time. Positive values indicate elevation and negative indicate depression A total of 5 lift motions at baseline (dark solid lines) and another time point (dotted lines) during the repetitive are displayed. This participant switched between a ***U*** and ***US*** string throughout the repetitive task. The SMSR string representation of each epoch is shown on the graph to the right hand side, in font matching the color of the lines displayed. Note, the string selected to represent the 5 efforts during an epoch was that which represented atleast 3 of 5 efforts examined. In this example, at epoch 16, 4 of 5lifts were characterized by a ***U*** string and 1 of 5 with a ***US*** string, thus the ***U*** string was selected to represent the participant's thoracohumeral elevation SMSR at epoch 16.

Table 9: A time history of the SMSR strings representing participants' thoracohumeral elevation joint angles during the repetitive task. Participants' have been grouped by the frequency of changes in the SMSR string during the repetitive task.

Thoraochumeral Elevation		Time (min)																														
SMSR String	Participant #	1 (Baseline)	3	5	7	9	11	13	15	17	19	21	23	25	27	29	31	33	35	37	39	41	43	45	47	49	51	53	55	57	59	61
No Change	8	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD												
	23	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
	25	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD															
	28	U	U	U	U	U	U	U	U	U	U	U	U	U	U																	
	2	UD	UD	UD	UD	UD	UD																									
Change (1 epoch only)	21	U	UD	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
	24	U	U	US	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U				
	19	U	U	U	U	U	U	U	U	UD	U	U	U	U	U	U	U															
	16	U	U	U	U	U	U	U	US	U	U	U	U	U	U	U	U															
	18	U	U	U	U	U	U	U	UD	U	U	U	U	U	U	U																
	20	U	U	UD	U	U																										
	5	U	UD	UD	UD	UD	UD	UD	UD	UD	UD																					
Change (>1 epoch)	31	UD	UD	UD	UD	UD	U	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	U													
	17	U	UD	U	U	U	UD	U	U	U	U	U	U																			
	30	U	U	U	US	U	U	UD	UD	U	U	U	U	US	U	U	U															
	1	U	U	UD	UD	UD	U	U	U	U	U																					
	14	UD	U	U	U	U	U	UD	UD	UD	U	UD	UD	UD	UD	UD	UD	UD	UD	UD												
	15	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	U	U	U	U	U	U	U	UD	UD	U	U	U	UD	U	U
	29	UD	UD	U	UD	UD	U	UD	U	U	U	U	UD	UD	UD	UD	UD	UD	UD	UD	U	U	U									
	7	UD	U	UD	U	U																										
	4	US	UD	US	U	U	U	US	U																							
	22	U	U	U	UD	U	UD	UD	UD	U	UD	UD	U	UD	UD	UD	UD	UD	U	UD	UD											
	13	UD	U	U	U	U	U	UD	U	UD	U	U	U	U	U		UD	U	U	U	U	UD	U									
	9	UD	UD	UD	U	U	U	U	U	U	U	UD	UD	U	U	U	U	U	U	U	U	U	UD	U	U	U	U	U	U	U	U	U
	11	US	U	U	US	U	U	U	U	U	U	U																				
	27	UD	U	US	U	US	U	U	U	U	U	U																				
	26	US	UD	UD	UD	UD	UD	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U						

7.1.2.6 Thoracohumeral Plane of Elevation

Participants' thoracohumeral plane of elevation joint angles were characterized primarily by ***U***, ***US*** or ***UD*** SMSR strings (Appendix B, Table 17). A ***U*** SMSR string indicates thoracohumeral horizontal flexion, whereas a ***UD*** SMSR string indicates horizontal flexion followed by horizontal extension. A ***US*** string indicates horizontal flexion (***U***) followed by a period of little change in joint angle (***S***). Over half of participants (16/27) changed their plane of elevation SMSR strings more than twice during the repetitive task. Most commonly, participants varied between ***U*** and ***US*** strings or ***U*** and ***UD*** strings. Participant 30 varied between an SU and ***U*** strategy. Participant 17 switched between ***U***, ***US***, ***S*** and ***D*** strings. Participants that did not change SMSR string or did so only once had a ***U*** strategy.

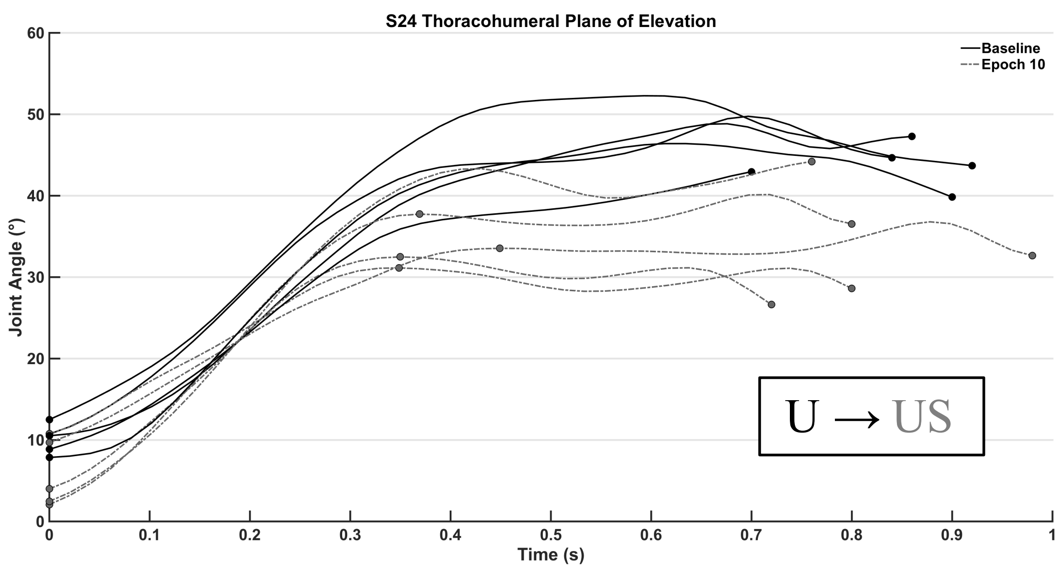


Figure 18: Thoracohumeral plane of elevation joint angle data from participant 24 as a function of time. Positive values horizontal flexion and negative indicate horizontal extension. A total of 5 lift motions at baseline (dark solid lines) and another time point (dotted lines) during the repetitive are displayed. This participant switched between a ***U*** and ***US*** string throughout the repetitive task. The SMSR string representation of each epoch is shown on the graph to the right hand side, in font matching the color of the lines displayed.

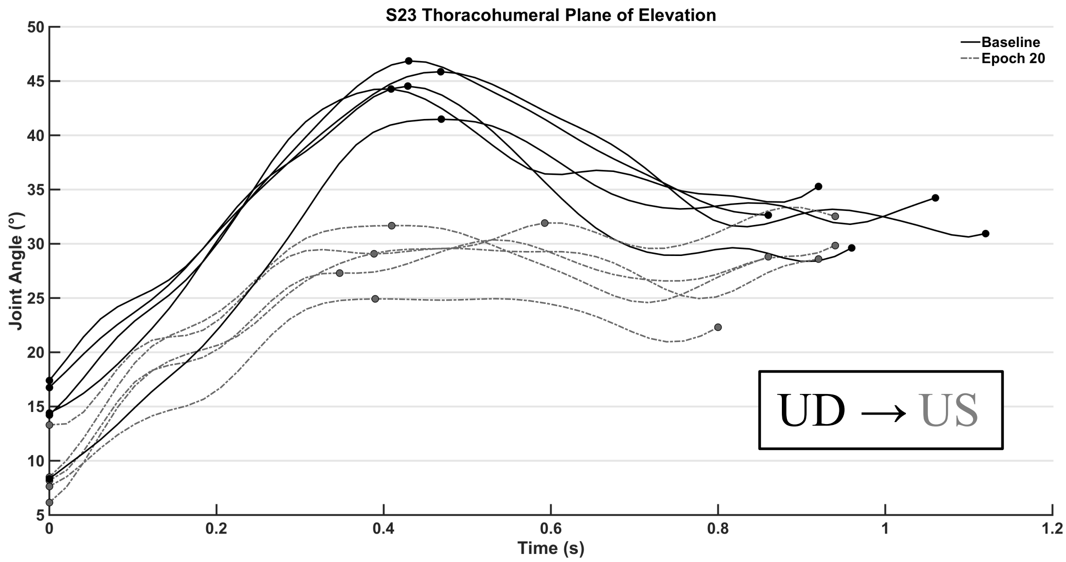


Figure 19: Thoracohumeral plane of elevation joint angle data from participant 23 as a function of time. Positive values horizontal flexion and negative indicate horizontal extension. A total of 5 lift motions at baseline (dark solid lines) and another time point (dotted lines) during the repetitive are displayed. This participant switched between a UD and US string throughout the repetitive task. The SMSR string representation of each epoch is shown on the graph to the right hand side, in font matching the color of the lines displayed.

7.1.2.7 Elbow Flexion

Participants' elbow flexion joint angles were characterized primarily by ***U***, ***UD***, or ***US*** SMSR strings (Table 10). A ***U*** SMSR string indicates elbow flexion, whereas a ***UD*** SMSR string indicates flexion followed by extension. A ***US*** string indicates flexion (***U***) followed by a period of little change in joint angle (***S***). Over half of participants (15/27) changed their elbow flexion SMSR strings more than twice during the repetitive task. Most participants varied between ***U*** and ***UD*** strings, with only a few switching between ***U*** and ***US*** strings (Figure 21). Both ***U*** and ***UD*** strings were observed in participants who did not change strings during the repetitive task (Figure 20).

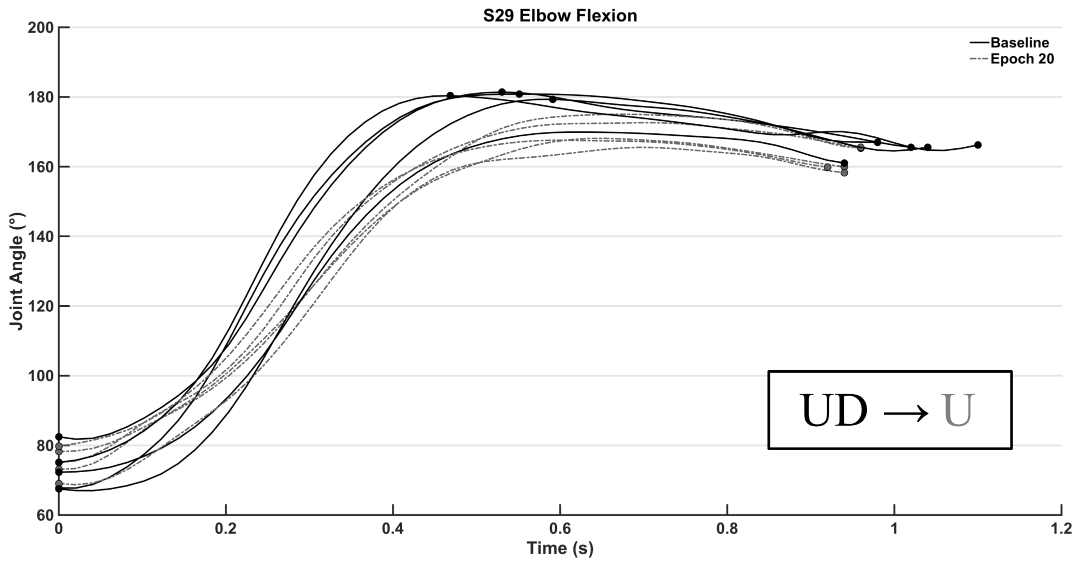


Figure 21: Elbow flexion joint angle data from one participant as a function of time. Positive values indicate flexion. A total of 5 lift motions at baseline (dark solid lines) and another time point (dotted lines) during the repetitive are displayed. This participant switched between a ***UD*** and ***U*** string throughout the repetitive task. The SMSR string representation of each epoch is shown on the graph to the right hand side, in font matching the color of the lines displayed.

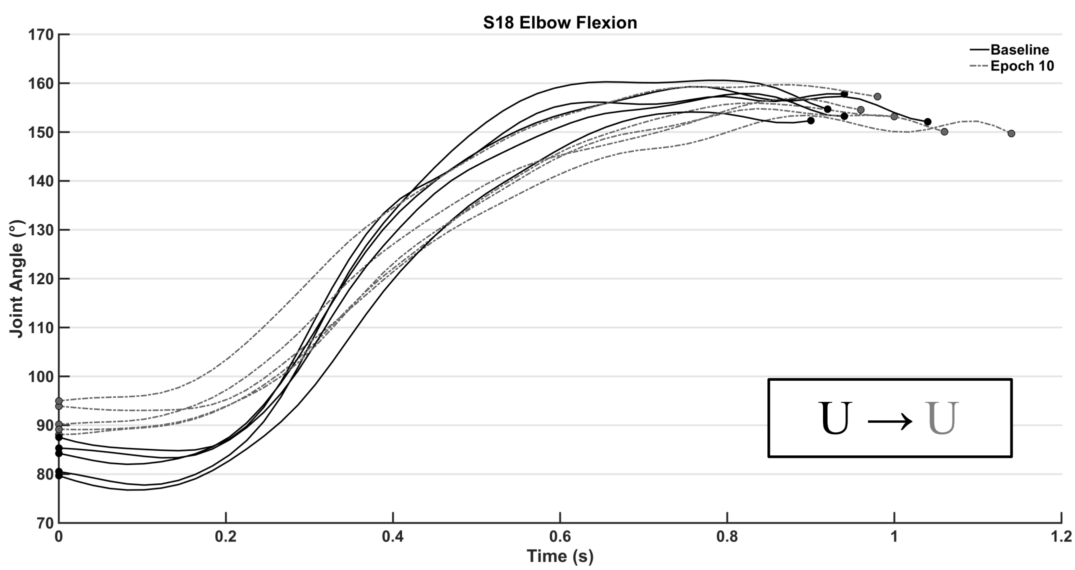


Figure 20: Elbow flexion joint angle data from participant 18 as a function of time. Positive values indicate flexion. A total of 5 lift motions at baseline (dark solid lines) and another time point (dotted lines) during the repetitive are displayed. This participant maintained a ***U*** string throughout the repetitive task. The SMSR string representation of each epoch is shown on the graph to the right hand side, in font matching the color of the lines displayed.

Table 10: A time history of the SMSR strings representing participants' elbow flexion joint angles during the repetitive task. Participants have been grouped by the frequency of changes in the SMSR string during the repetitive task.

Elbow Flexion		Time (min)																														
SMSR String	Participant #	1 (Baseline)	3	5	7	9	11	13	15	17	19	21	23	25	27	29	31	33	35	37	39	41	43	45	47	49	51	53	55	57	59	61
No Change	1	U	U	U	U	U	U	U	U	U	U																					
	15	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
	18	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U																
	19	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U															
	16	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U															
	5	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD																					
	8	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD												
	20	UD	UD	UD	UD	UD																										
Change (1 epoch only)	21	U	U	U	U	U	U	U	U	U	U	UD	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
	2	UD	UD	U	UD	UD	UD																									
	28	US	U	U	U	U	U	U	U	U	U	U	U	U	U																	
	25	U	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD															
Change (>1 epoch)	23	U	U	U	US	U	U	U	U	US	U	U	U	U	U	U	U	US	U	US	U	U	U	U	U	U	U	U	U	U	US	U
	24	U	U	UD	U	U	U	U	UD	U	U	U	U	U	U	UD	U	U	UD	U	U	U	UD	U	U	U	U	U				
	31	U	U	U	U	U	U	U	U	UD	U	U	U	U	U	UD	U	UD	UD													
	4	UD	UD	UD	UD	U	U	UD	U																							
	29	UD	UD	U	UD	U	U	U	UD	UD	UD	U	UD	UD	U	UD	UD	U	UD	UD	U	U	UD									
	13	U	U	U	U	U	UD	UD	U	UD	UD	U	U	U	UD		UD	U	U	U	UD	UD	UD									
	30	U	U	U	UD	UD	U	UD	UD	U	U	U	U	UD	UD	UD	U															
	14	UD	UD	U	U	U	U	US	UD	UD	U	U	UD	U	UD	UD	UD	U	UD	UD												
	7	UD	U	U	U	UD																										
	9	UD	UD	UD	U	U	UD	UD	UD	UD	UD	UD	UD	UD	U	U	U	U	U	U	U	U	UD	U	U	U	U	U	U	U	U	U
	27	US	U	US	US	US	U	U	U	U	U	U																				
	26	UD	UD	UD	UD	UD	UD	U	U	U	UD	U	U	U	U	UD	U	U	U	U	U	U	U	U	U	UD						
	11	UD	U	U	UD	U	U	UD	U	U	U	U																				
	17	UD	UD	U	U	U	UD	U	U	U	U	U	U																			
	22	U	U	U	UD	UD	UD	UD	UD	U	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD											

7.1.2.8 Elbow Pronation

Participants' elbow pronation joint angles were characterized primarily by ***U***, ***UD***, ***D***, ***U***, ***S***, or ***US*** SMSR strings (Appendix B, Table 18). A ***U*** SMSR string indicates pronation, whereas a ***D*** SMSR string indicates supination. Thus, a ***UD*** string indicates pronation (***U***) followed by supination (***D***). Only one of the participants that changed the SMSR once or not at all, had a ***D*** string whereas the other 11 participants maintained a ***UD*** string (Figure 23). Most participants that changed SMSR string intermittently throughout the repetitive task (15/27) alternated between ***U*** and ***UD*** strategies (Figure 22), with a few switching between ***U*** and ***US*** or ***UD***. Participant 30 switched between ***UD***, ***SD***, ***D*** and ***S*** strings.

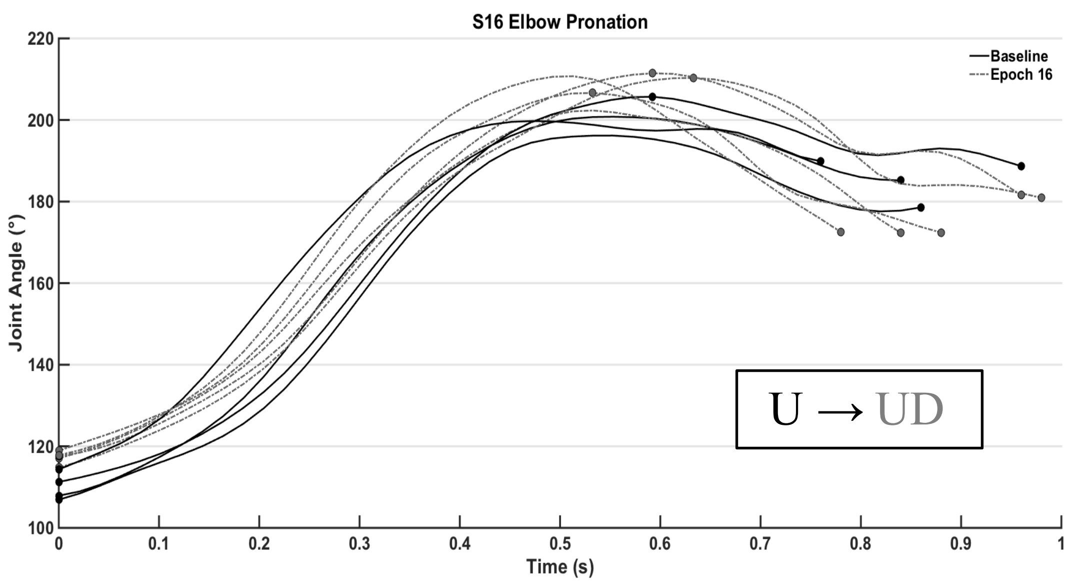


Figure 22: Elbow pronation joint angle data from participant 16 as a function of time. Positive values indicate pronation and negative values indicate supination. A total of 5 lift motions at baseline (dark solid lines) and another time point (dotted lines) during the repetitive are displayed. This participant switched between a ***U*** and ***UD*** string throughout the repetitive task. The SMSR string representation of each epoch is shown on the graph to the right hand side, in font matching the color of the lines displayed.

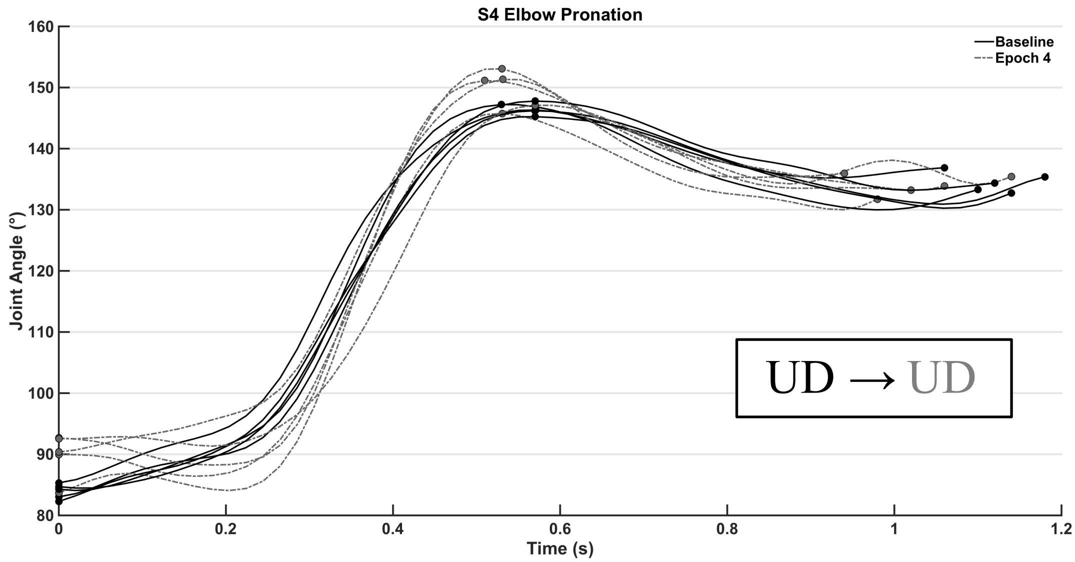


Figure 23: Elbow pronation joint angle data from participant 4 as a function of time. Positive values indicate pronation and negative values indicate supination. A total of 5 lift motions at baseline (dark solid lines) and another time point (dotted lines) during the repetitive are displayed. This participant maintained a ***UD*** string throughout the repetitive task. The SMSR string representation of each epoch is shown on the graph to the right hand side, in font matching the color of the lines displayed.

7.1.2.9 Wrist Flexion

There was a lot of variability in participants' wrist flexion SMSR strings, with a total of 8 different string representations used across participants (Table 11; Figure 25). Listed in order of those used most to least frequency amongst participants, the 8 SMSR string representations of wrist flexion angles are as follows: ***D***, ***DU***, ***DS***, ***U***, ***UD***, ***SD***, ***S*** and ***US***. A ***D*** string indicates wrist extension and thus a ***U*** string indicates wrist flexion. Only 3/27 participants did not change the SMSR string more than once throughout the repetitive task and maintained a ***D*** string. Most of the participants that did change strings during the repetitive task switched between ***D*** and ***DU*** or ***DS*** (Figure 24; Figure 26).

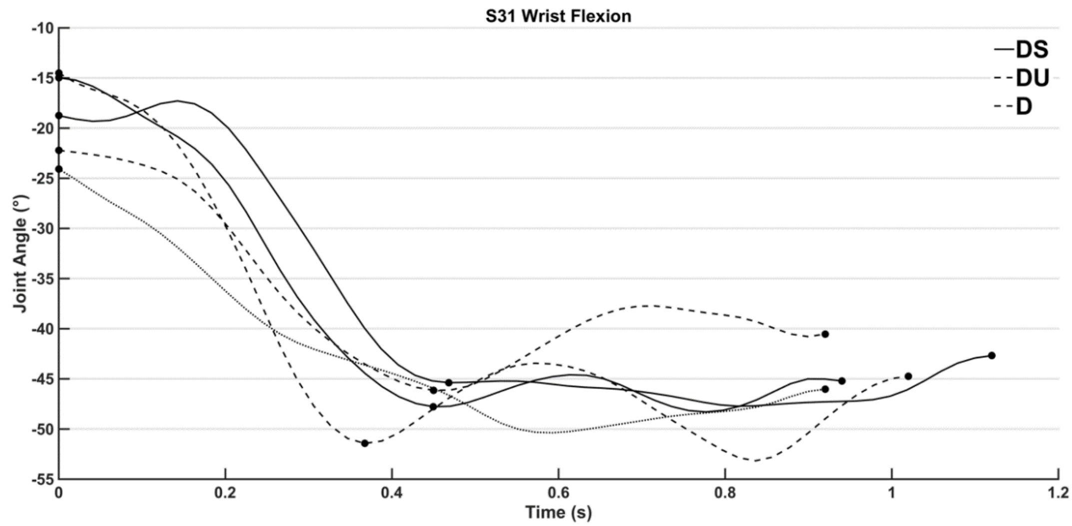


Figure 25: Wrist flexion joint angle data from participant 31 as a function of time. Positive values indicate flexion and negative indicate extension. Five consecutive lift motions at one point in time during the repetitive task (epoch 8) are displayed. The legend on the top right of the graph indicates the SMSR of each lift motion. The purpose of this graph is to show the large variability in participants wrist flexion joint angle data, using this participant as an example. Note: This participant is an extreme case, with 3 different SMSRs characterizing wrist flexion within an epoch. Most participants had 2 or less SMSRs in a given epoch but still had considerable varitation in the joint angle time series data between epochs.

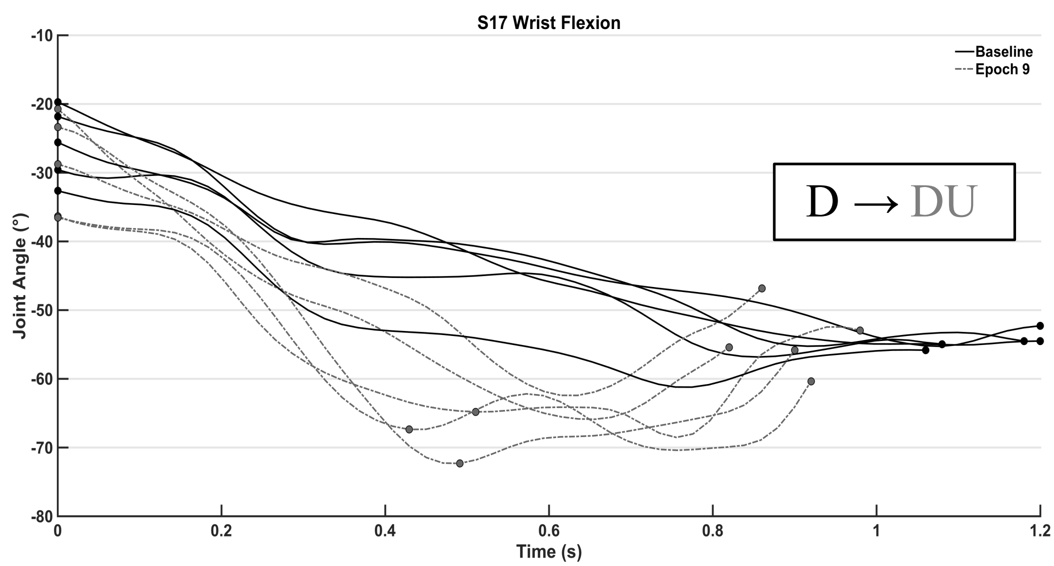


Figure 24: Wrist flexion joint angle data from participant 17 as a function of time. Positive values indicate flexion and negative indicate extension. A total of 5 lift motions at baseline (dark solid lines) and another time point (dotted lines) during the repetitive are displayed. This participant switched between a ***D*** and ***DU*** string throughout the repetitive task. The SMSR string representation of each epoch is shown on the graph to the right hand side, in font matching the color of the lines displayed. Note, the string selected to represent the 5 efforts during an epoch was that which represented at least 3 of 5 efforts examined. In this example, at epoch 9, 3 of 5 lifts were characterized by a ***DU*** string and 1 of 5 with a ***D*** string, thus the ***D*** string was selected to represent the participant's wrist flexion SMSR at epoch 9.

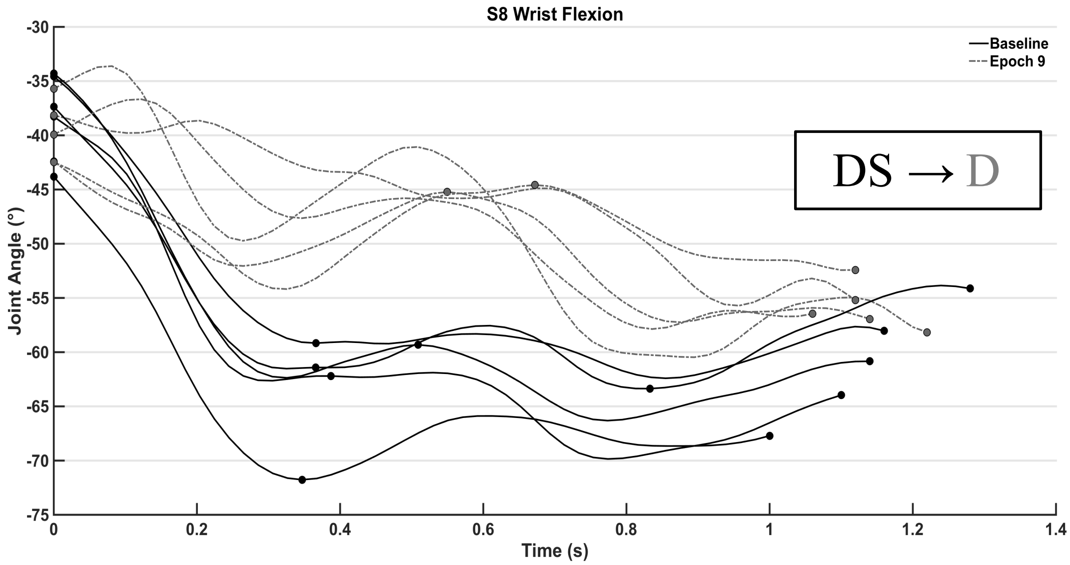


Figure 26: Wrist flexion joint angle data from participant 8 as a function of time. Positive values indicate flexion and negative indicate extension. A total of 5 lift motions at baseline (dark solid lines) and another time point (dotted lines) during the repetitive are displayed. This participant switched between a ***DS*** and ***D*** string throughout the repetitive task. The SMSR string representation of each epoch is shown on the graph to the right hand side, in font matching the color of the lines displayed. Note, the string selected to represent the 5 efforts during an epoch was that which represented at least 3 of 5 efforts examined. In this example, at epoch 9, 3 of 5 lifts were characterized by a ***D*** string and 2 of 5 with a ***SD*** string, thus the ***D*** string was selected to represent the participant's wrist flexion SMSR at epoch 9.

Table 11: A time history of the SMSR strings representing participants' wrist flexion joint angles during the repetitive task. Participants' have been grouped by the frequency of changes in the SMSR string during the repetitive task.

Wrist Flexion		Time (min)																														
SMSR String	Participant #	1 (Baseline)	3	5	7	9	11	13	15	17	19	21	23	25	27	29	31	33	35	37	39	41	43	45	47	49	51	53	55	57	59	61
No Change	7	D	D	D	D	D																										
Change (1 epoch only)	21	D	D	D	D	D	D	D	D	D	D	D	D	DS	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
	11	SD	D	D	D	D	D	D	D	D	D	D																				
Change (>1 epoch)	13	U	U	U	U	U	U	U	U	US	U	U	U	S	U		U	SU	U	U	U	U	U									
	15	D	D	D	D	D	D	D	D	D	DU	DU	D	D	D	D	D	D	UD	D	D	D	D	D	D	D	D	DS	DS	D	D	D
	23	DU	DU	DU	DU	DU	DU	DU	DU	DU	D	DU	DU	D	DU	DU	DU	DU	DU	DU	DU	DU	DU	DU	DU	D	DU	D	DU	D	D	DU
	28	DS	D	D	DS	DS	DS	DS	DS	DS	DS	DS	DS	DS	DU																	
	4	DU	D	D	DU	DU	DU	DU	DU																							
	16	DU	DU	DU	DU	DU	DU	DU	DU	D	DU	D	D	DU	D	DU	DU															
	17	D	DU	D	D	D	DU	D	D	DU	D	D	D																			
	22	D	D	D	DS	D	UD	SD	UD	D	D	D	D	DS	D	D	D	D	D	D	D											
	2	SD	D	SD	D	SD	SD																									
	8	DS	DS	D	D	DS	DS	DS	DS	D	DS	SD	DS	DS	S	DS	DS	D	DS	D												
	1	DU	DU	DU	DU	DU	D	DU	D	D	D																					
	20	DS	DS	DU	DS	DU																										
	19	DU	DU	U	D	D	U	U	U	DU	U	DU	DU	DU	DU	DU	DU															
	29	D	D	SD	SD	SD	D	D	D	D	D	D	D	SD	DU	D	SD	D	DS	SD	SD	D	UD									
	18	DU	DS	DS	D	DU	U	DS	D	DU	DU	DU	DU	DS	DU	DS																
	24	DU	D	D	DU	DU	DU	DU	DU	D	D	D	D	DU	D	D	D	DU	D	D	D	D	D	DU	D	DU	DU	DU				
	5	SD	SD	UD	SD	D	UD	UD	UD	D	SD																					
	27	DS	D	DS	DS	DS	DU	DU	DU	DU	DU	DU																				
	31	D	US	DU	D	DU	D	DS	DS	DS	DU	DU	DU	DU	D	DU	D	DS	D													
	26	DS	DS	D	DS	D	DS	DU	DU	DS	D	DU	DU	D	DS	DS	D	DU	DU	D	DU	DU	DU	DU	DU	DU						
	9	DU	DS	DS	DS	DS	DU	D	D	D	S	D	SU	DU	S	D	D	D	D	D	D	D	DU	D	D	D	D	D	D	D	D	D
	25	DS	DS	US	S	D	S	SD	S	S	S	UD	SD	S	U	SD	S															
	30	SD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	U	UD	UD	UD															
	14	DS	D	D	D	D	D	DU	DU	DU	DU	DU	DU	DU	DU	DU	DU	DU	DU	DU												

7.1.2.10 Wrist Pronation

Participants' wrist pronation joint angles were also variable and characterized primarily by ***D***, ***DU***, ***U***, or ***S*** SMSR strings (Appendix B Table 19; Figure 27). A ***U*** SMSR string indicates pronation, whereas a ***D*** SMSR string indicates supination. Thus, a ***DU*** string indicates supination (***D***) followed by pronation (***U***). Participants that did not vary SMSR string more than once during the repetitive task maintained ***DU*** or ***U*** strings (Figure 28). Most participants that did vary strings during the repetitive task did so between ***DU*** and ***D*** or ***S***. Two participants varied between ***DU*** and ***U***.

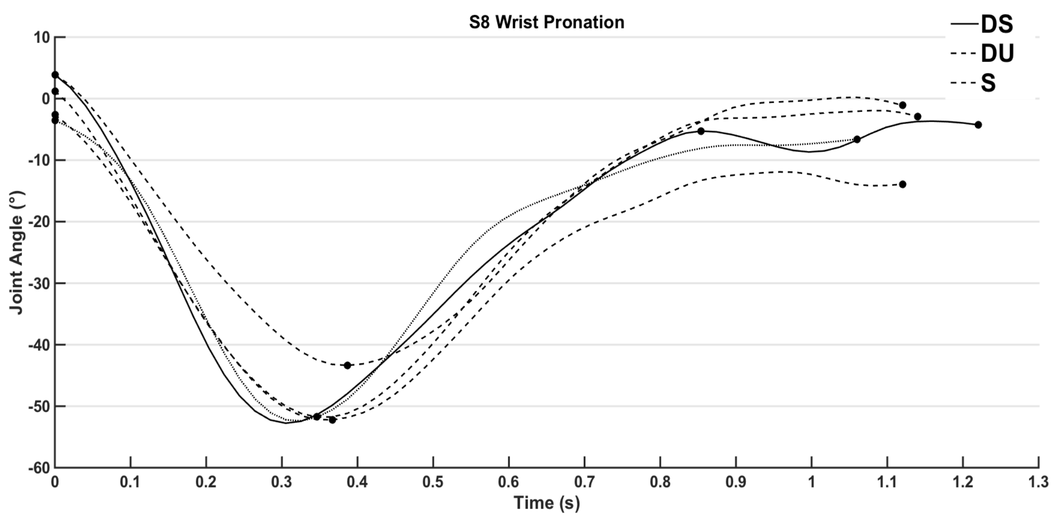


Figure 27: Wrist pronation joint angle data from participant 8 as a function of time. Positive values indicate pronation and negative indicate supination. Five consecutive lift motions at one point in time during the repetitive task (epoch 8) are displayed. The legend on the top right of the graph indicates the SMSR of each lift motion. The purpose of this graph is to show the large variability in participants wrist pronation joint angle data, using this participant as an example. Note: This participant is an extreme case, with 3 different SMSRs characterizing wrist pronation within an epoch. Most participants had 2 or less SMSRs in a given epoch but still had considerable varitation in the joint angle time series data between epochs.

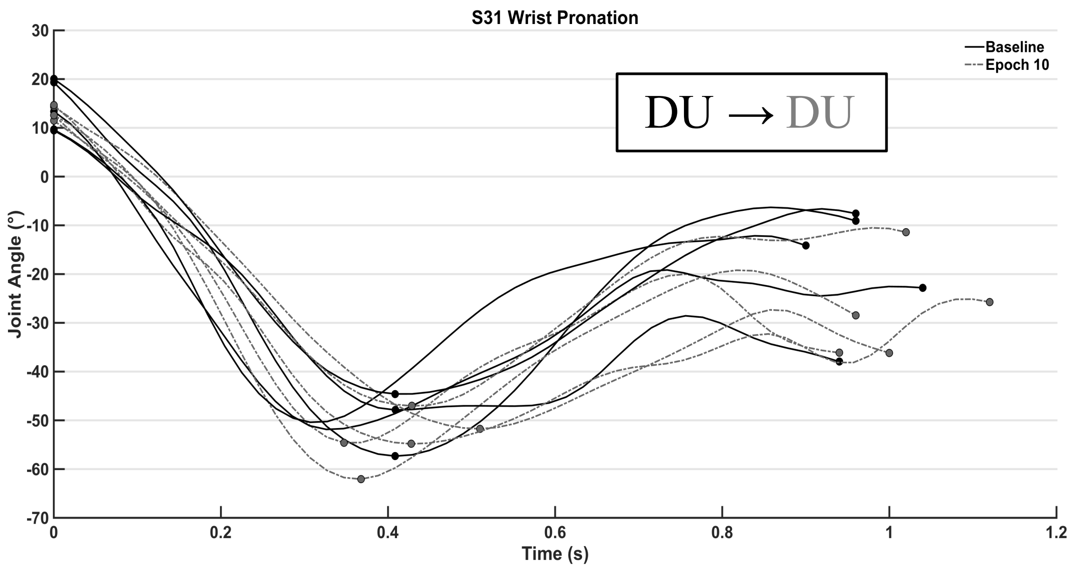


Figure 28: Wrist pronation joint angle data from participant 31 as a function of time. Positive values indicate pronation and negative values indicate supination. . A total of 5 lift motions at baseline (dark solid lines) and another time point (dotted lines) during the repetitive are displayed.This participant maintained a ***DU*** string throughout the repetitive task. The SMSR string representation of each epoch is shown on the graph to the right hand side, in font matching the color of the lines displayed.

7.1.2.11 Wrist Ulnar Deviation

There was very little variability in wrist ulnar deviation SMSR string with only the ***U*** and ***US*** strings observed (Appendix B, Table 20). A ***U*** string indicates ulnar deviation, whereas the ***US*** indicates ulnar deviation followed by a period of little change in joint angle. The ***U*** string was maintained throughout the repetitive task by 23/27 participants (Appendix B, Figure 30). The other participants switched between ***U*** and ***US*** strings (Figure 29).

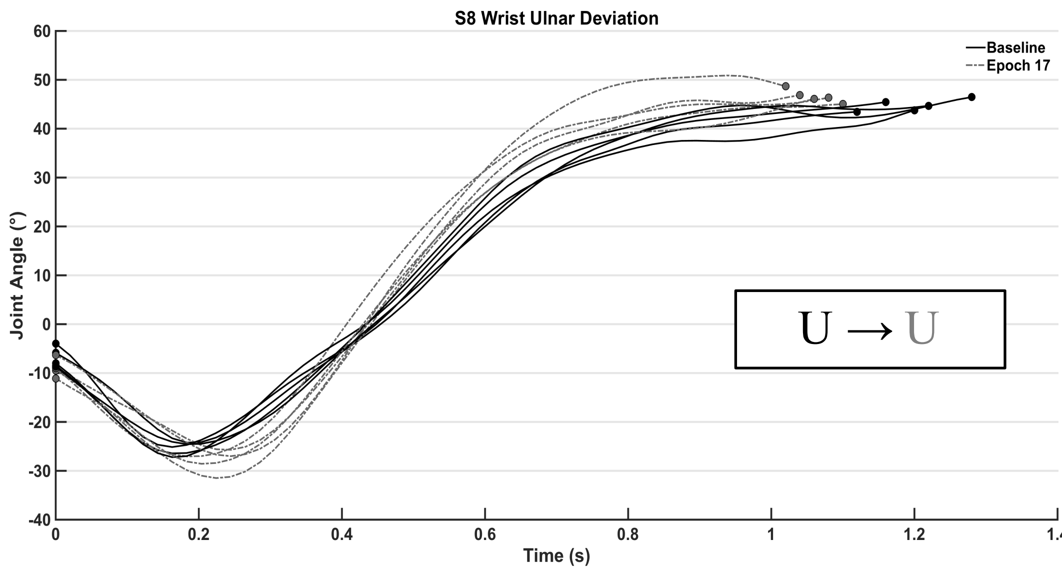


Figure 30: Wrist ulnar deviation joint angle data from participant 8 as a function of time. Positive values indicate ulnar deviation and negative indicate radial deviation. A total of 5 lift motions at baseline (dark solid lines) and another time point (dotted lines) during the repetitive are displayed. This participant maintained a ***DU*** string throughout the repetitive task. The SMSR string representation of each epoch is shown on the graph to the right hand side, in font matching the color of the lines displayed.

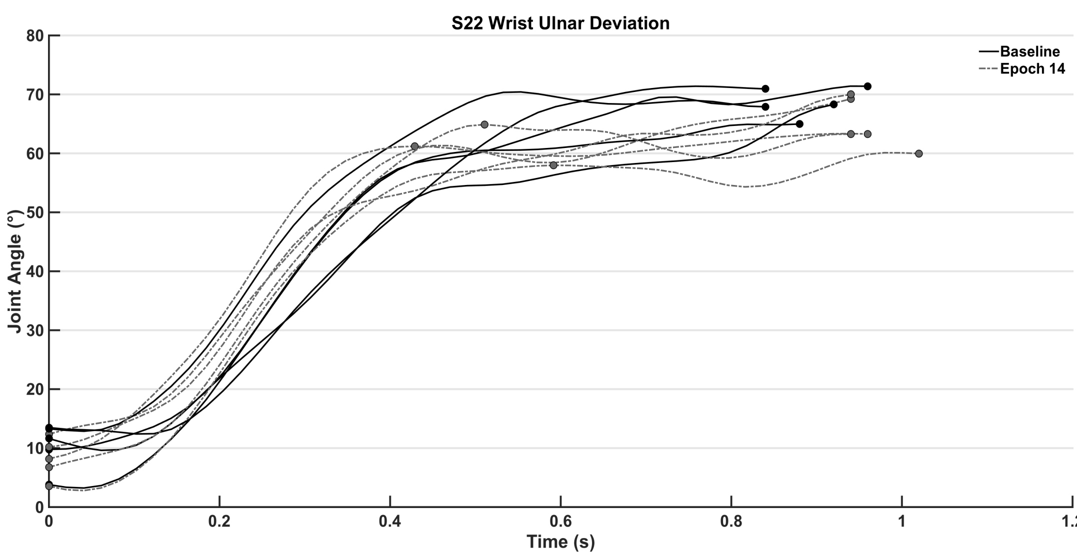


Figure 29: Wrist ulnar deviation joint angle data from participant 8 as a function of time. Positive values indicate ulnar deviation and negative indicate radial deviation. A total of 5 lift motions at baseline (dark solid lines) and another time point (dotted lines) during the repetitive are displayed. This participant switched between a ***U*** and ***US*** string throughout the repetitive task. The SMSR string representation of each epoch is shown on the graph to the right hand side, in font matching the color of the lines displayed. Note, the string selected to represent the 5 efforts during an epoch was that which represented at least 3 of 5 efforts examined. In this example, at epoch 14, 3 of 5 lifts were characterized by a ***US*** string and 2 of 5 with a ***U*** string, thus the ***US*** string was selected to represent the participant's wrist ulnar deviation SMSR at epoch 14.

7.2 SMSR Change and Infraspinatus Muscle Fatigue Onset

A weak linear relationship between thoracohumeral elevation SMSR change onset and infraspinatus muscle fatigue onset exists ($R^2 = 0.275$, $F(1,18) = 6.42$, $p = 0.02$) (Figure 31).

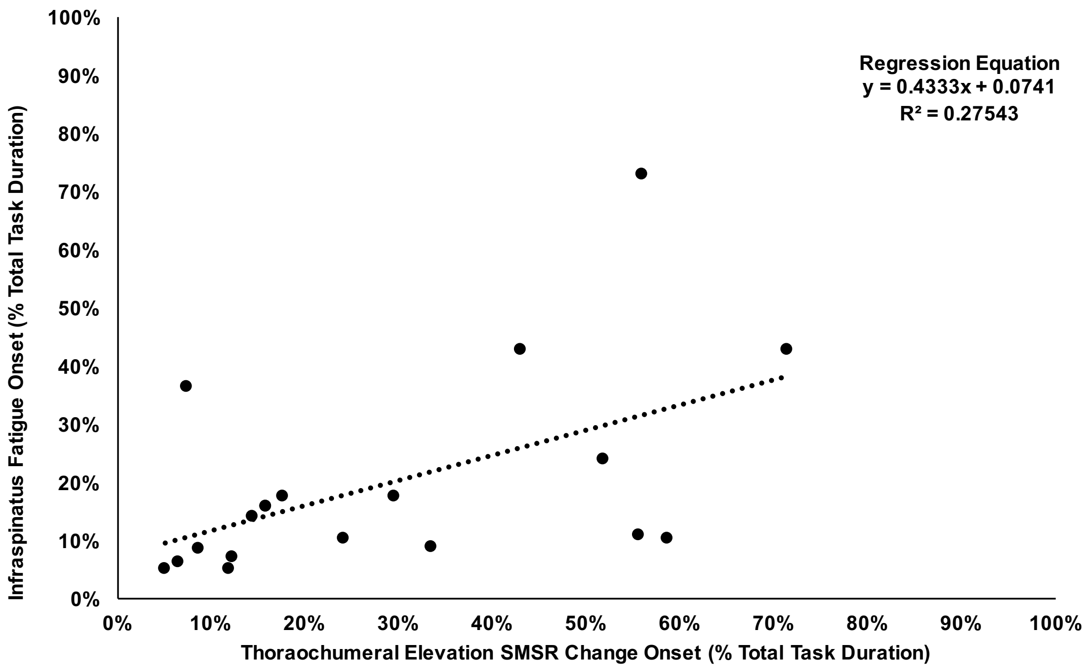


Figure 31: Infraspinatus muscle fatigue onset as a function of the onset of a change in thoracohumeral elevation SMSR across participants. The regression equations and R^2 values of the linear relationship between thoracohumeral elevation SMSR change onset and infraspinatus muscle fatigue onset are displayed on the right side of the graph.

7.3 Thoracohumeral SMSR String Variability and Muscle Fatigue

A total of 7/12 muscles met the baseline activation criterion (>10% MVE) across the three baseline efforts (Table 12). Thus, MPF of the EMG signal recorded from these muscles were analyzed. The potential effects of TH SMSR variability group, sex and time on the EMG MPF of all 7 muscles were tested.

Table 12: Descriptive data of the activation of each muscle across participants during the 3 baseline efforts prior to the start of the repetitive task. The average, and standard deviation of the activation of each muscle across participants is shown. The total number of participants with an activation greater than 10% at baseline is also displayed. The muscles that underwent mean power frequency analysis were those with at least 25 participants meeting the 10% MVE activation at baseline criterion; indicated with an asterisk (*) in the table below.

Muscle	Average (%MVE)	Standard Deviation (%MVE)	Total # Participants > 10% MVE
Anterior Deltoid*	22.0	8.9	**27**
Middle Deltoid*	18.9	4.3	**27**
Posterior Deltoid	12.1	4.3	19
Infraspinatus*	29.1	9.1	**27**
Supraspinatus*	21.4	6.2	**27**
Upper Trapezius*	20.7	8.0	**25**
Middle Trapezius*	24.5	6.8	**27**
Lower Trapezius*	37.5	12.2	**27**
Latissimus Dorsi	23.1	11.4	20
Serratus Anterior	23.0	11.9	22
Pectoralis Major (Sternal)	11.1	7.2	11
Pectoralis Major (Clavicular)	9.8	8.4	9

There were no significant main effects of group, sex, time, or an interaction of these variables on the following dependent variables: 1) Infraspinatus EMG MPF, 2) Middle Trapezius MPF, 3) Lower Trapezius MPF, and 4) Middle deltoid EMG MPF (Figure 33).

There was a main effect of group on Anterior deltoid EMG MPF ($F(1,25) = 5.01$, $p = 0.304$, $\eta^2 = 0.2$). The group with no thoracohumeral elevation SMSR string variability had significantly higher anterior deltoid EMG MPF (7.45%) collapsed across time and sex in comparison to the group with thoracohumeral elevation SMSR string variability (Figure 32).

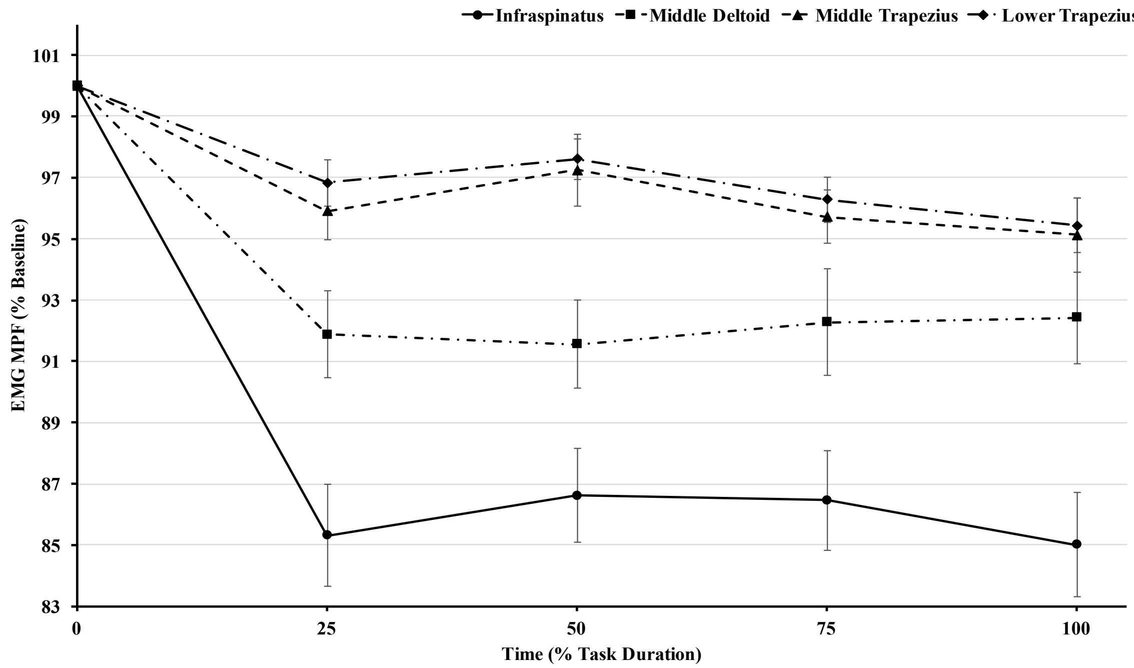


Figure 33: Average EMG MPF across participants as a function of time during the repetitive task for four muscles of the shoulder complex. Standard error bars are displayed for each muscle (n = 27).

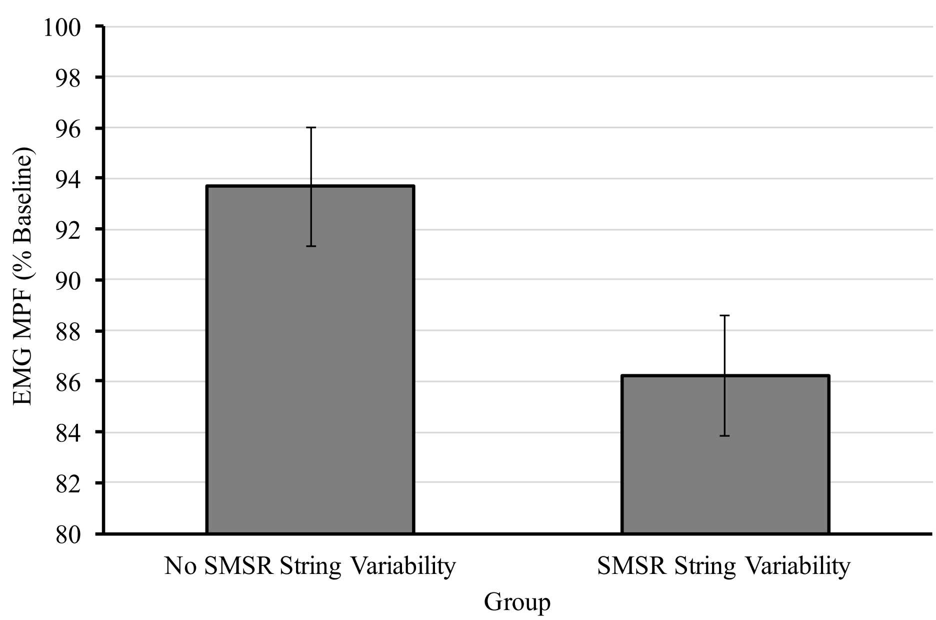


Figure 32: Main effect of group on anterior deltoid EMG MPF as a percentage of baseline. Standard error bars are included (No SMSR string variability n = 14, SMSR string variability n = 13). Collapsed across sex and time, the average anterior deltoid EMG MPF for the no SMSR string variability was significantly higher than that of the SMSR string variability group ($p<0.05$).

There was an interaction effect between sex and time on both the upper trapezius muscle EMG MPF ($F(3,60) = 3.781$, $p = 0.015$, $\eta^2 = 0.19$) and supraspinatus muscle EMG MPFs ($F(3,66) = 3.706$, $p = 0.016$, $\eta^2 = 0.17$). Males had significantly higher upper trapezius EMG MPF at 75% (3.9%) and 100% (6.6%) of total task duration, in comparison to females ($p<0.05$) (Figure 34). Males also had significantly higher supraspinatus EMG MPF at 50% (2.5%), 75% (2.7%) and 100% (3.4%) of total task duration, in comparison to females ($p<0.05$) (Figure 35).

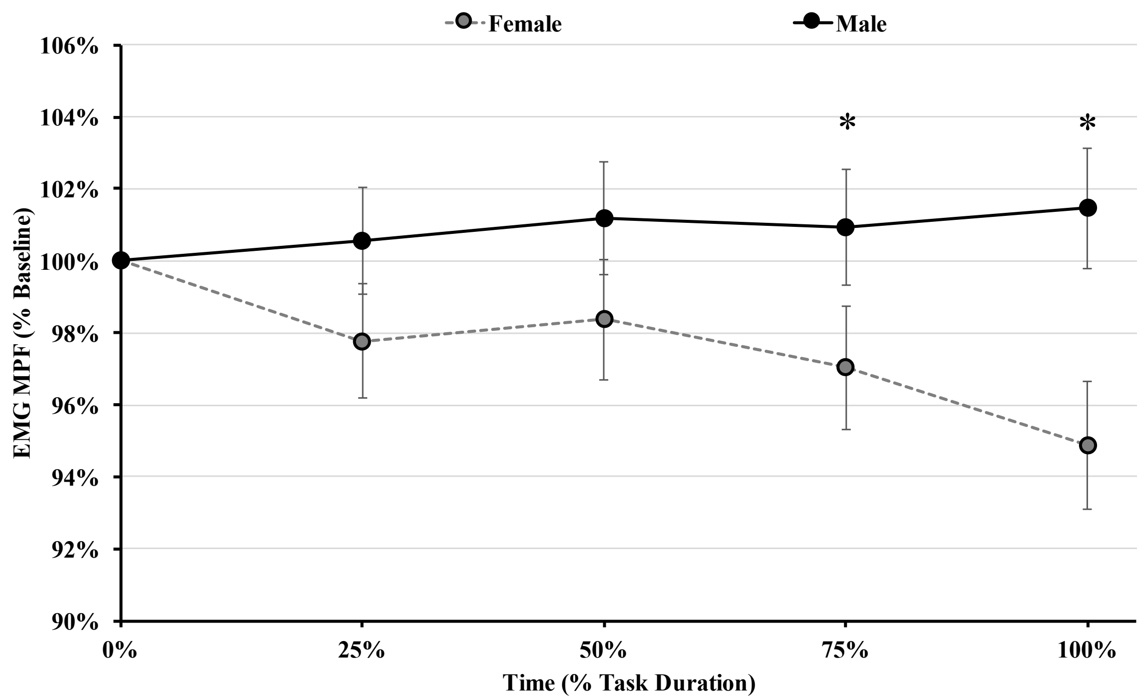


Figure 34: Interaction effect of sex and time on the EMG MPF of the upper trapezius muscle. males had significantly higher upper trapezius EMG MPF in comparison to females at 75% and 100% of total task duration (p<0.05) indicated on the graph with an asterisk. Standard error bars are displayed (males n = 13, females n = 11).

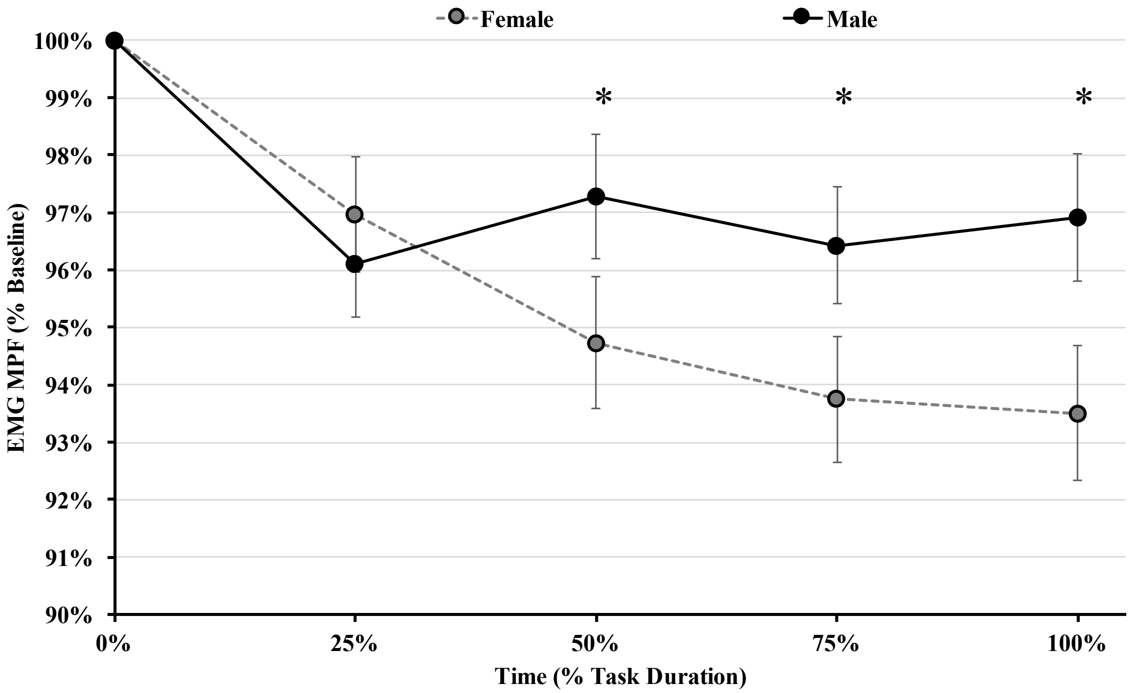


Figure 35: Interaction effect of sex and time on the EMG MPF of the supraspinatus muscle. males had significantly higher supraspinatus EMG MPF in comparison to females at 50%, 75% and 100% of total task duration ($p<0.05$) indicated on the graph with an asterisk. Standard error bars are displayed (males n = 14, females n = 12).

There was a main effect of time on both the rating of perceived fatigue ($F(3,63) = 119.1$, $p < 0.01$, $\eta^2 = 5.67$) and discomfort ($F(3,66) = 33.4$, $p < 0.01$, $\eta^2 = 1.52$). All comparisons of mean RPF or mean RPD between time points during the repetitive task were significant except the difference in RPF or RPD between 50% and 75% of total task duration ($p<0.05$) (Figure 36).

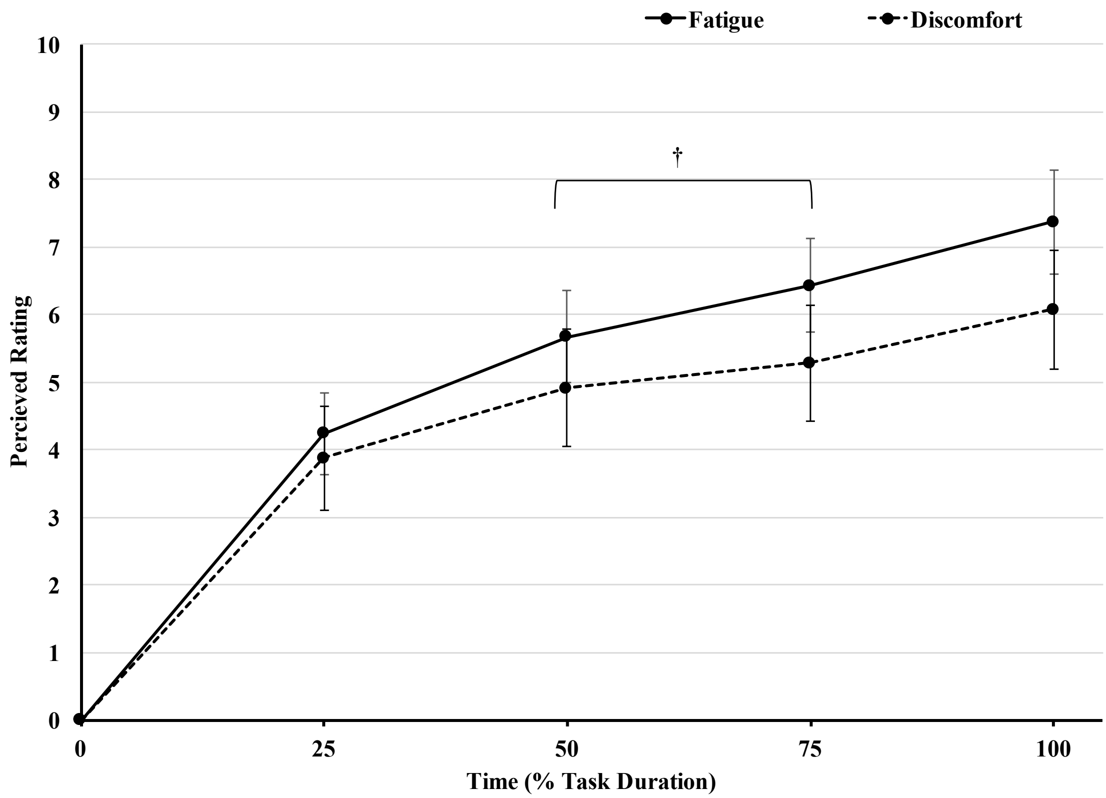


Figure 36: The main effect of time on ratings of perceived fatigue and discomfort during the repetitive task. For both RPF and RPD, the only non-significant differences between time points during the repetitive task were between 50% and 75% of total task duration; indicated on the graph with a † symbol($p<0.05$). Standard error bars are shown on the graph (RPF n = 25, RPD n = 26).

There was an interaction between group and sex on the decline in external rotation MVF following the repetitive task ($F(2,23) = 776.$, $p = 0.011$, $\eta^2 = 0.34$). Females in the SMSR string variability group had a significantly larger decline in external rotation MVF (16.7%) following the repetitive task in comparison to females in the no SMSR string variability group.

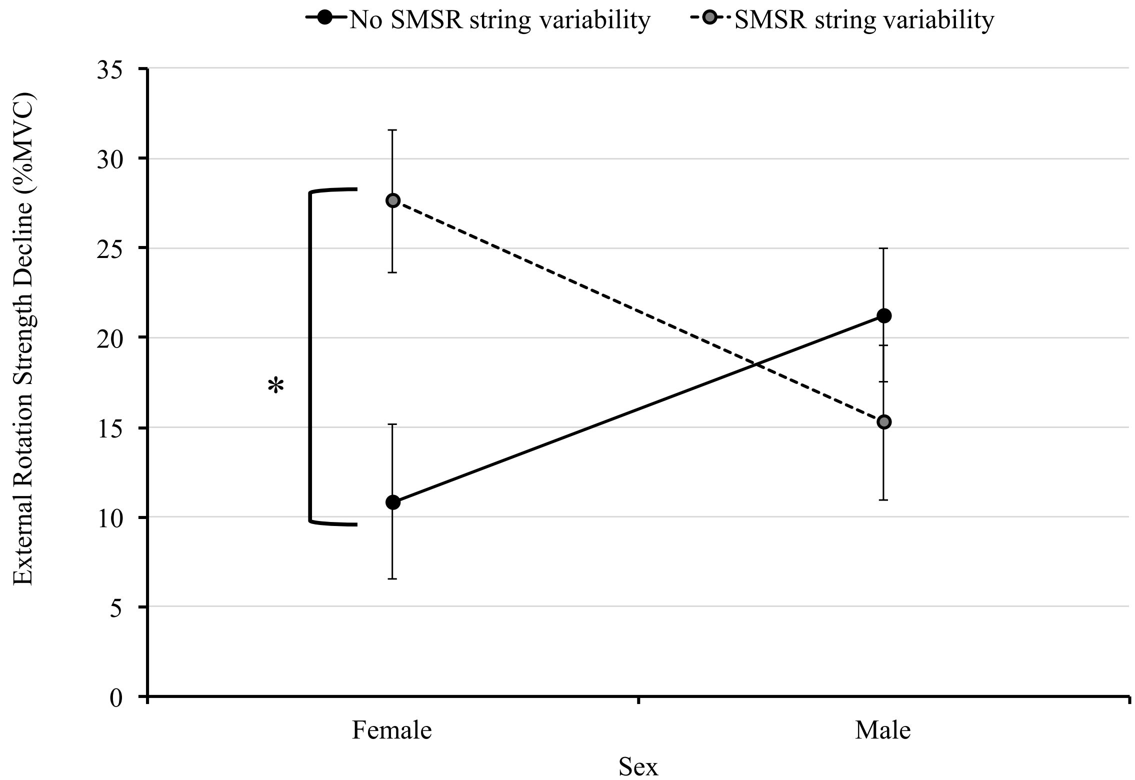


Figure 37: The interaction between group and sex on participants' external rotation strength decline following the termination of the repetitive task. A significant difference between groups existed for females as indicated by an asterisk. Standard error bars are displayed; no SMSR string variability males (n = 8) and females (n = 6), SMSR string variability males (n = 6) and females (n = 7).

8 DISCUSSION

This thesis was one of the first to explore potentially visually identifiable changes of upper extremity joint kinematics with relation to shoulder muscle fatigue accumulation in a workplace emulative repetitive task. In principle, the results of this thesis indicate that upper extremity kinematic changes occurring in a repetitive task may be visually identifiable, as directional changes in joint motion were identified by the SMSR algorithm. The similarity of joint angle SMSRs between participants during the repetitive task encourages the further study of task specific heuristics, and eventual development of guidelines to facilitate visual detection of upper extremity kinematic changes with shoulder muscle fatigue across a healthy, young population of individuals. This study also showed that future guidelines might benefit from focus on the variability of an individuals' thoracohumeral elevation SMSRs as an indicator of local muscle fatigue, rather than the onset of a change in thoracohumeral elevation SMSR.

8.1 Objective 1: Potentially visually identifiable upper extremity kinematic changes

This thesis was one of the first to define changes in upper extremity joint kinematics during a repetitive task by characterizing the structure of the joint angle time histories at the participant level. As identified in previous work, individuals change upper extremity kinematics in repetitive tasks known to cause muscle fatigue (Côté et al., 2005; Fuller et al., 2011; Gates & Dingwell, 2008; Lomond & Côté, 2011). Using a modified version of the SMSR algorithm (Park et al., 2005a), it was possible to identify changes in the basic structure of upper extremity joint angle data in the majority of participants during this repetitive task, confirming the first hypothesis.

8.1.1 Ergonomic Relevance

This thesis characterized kinematic changes in repetitive tasks that is more likely to be visually identifiable in comparison to changes in joint angle magnitudes reported in literature on upper extremity kinematics in repetitive tasks. Current observation-based analyses of upper extremity kinematics (i.e. postures) in workplace tasks rely on ergonomists' ability to accurately classify working postures into correct predefined posture categories. Posture category widths of approximately 30° appear to be the best suited for most upper extremity joints (Bao et al., 2009; Lowe, 2004; Van Wyk et al., 2009). However, the magnitudes of changes in upper extremity joint angles during repetitive tasks, with muscle fatigue, tend to be smaller than 30° (Fuller et al., 2009; McDonald et al., 2016; Tse et al., 2016). This questions the utility of implementing an observation based approach to identify changes in joint angles that are smaller than what can be accurately identified by an observer. Instead of magnitude based observational analyses, a focus on identifying directional changes in joint motion (i.e. flexion/extension) may provide a viable alternative that facilitates visual detection of upper extremity kinematic changes with muscle fatigue in repetitive tasks. Individuals can reliably identify directional changes in joint angles as an indicator of job severity in repetitive tasks (Lowe & Krieg, 2009). In this thesis, the detected changes in participants' joint angle SMSRs corresponded to directional changes in joint motion that may be visually identifiable**.**

To identify kinematic changes during the task performed in this thesis, observers could focus on directional changes in thoracohumeral elevation. Although joint angle SMSRs changed across upper extremity joints in the repetitive task, this example will focus on changes in thoracohumeral elevation SMSRs. Throughout the repetitive task individuals varied between ***U*** and ***UD*** SMSRs. In the context of this repetitive task observers could be asked to identify whether a worker varies between continuous thoracohumeral elevation from the bottom to top target (***U***) or a combination of thoracohumeral elevation and depression (***UD***) to complete a lift. An advantage of this approach is that observers would be required to simply identify changes in the direction of joint motion with no reference to an "angular cut point boundary". Lowe et al., (2009) and Spielholz et al., (2001) had observers count the number of wrist and forearm motions that "passed beyond a pre-defined neutral boundary and back within the neutral boundary". For example, at the wrist this would consist of identifying when an individual flex or extend the wrist beyond 30° degrees from a neutral wrist posture. Observer errors in counting the number of directional movements at a joint, using these criteria, are attributed to the misperception of a predefined "angular cut point boundary" (Lowe & Krieg, 2009; Spielholz et al., 2001). Therefore, it is reasonable to suggest observers may more accurately estimate the number of changes in directional motion at a joint when angular cut point boundaries are removed. Although this thesis did not explicitly determine if individuals could visually identify the directional changes in joint motion identified by a change in SMSRs during repetitive work, video recordings were taken during this study and can be used in future research to explore the potential validity and reliability of visually detecting changes in upper extremity joint motion as identified by joint angle SMSRs.

A limitation of an observational based analysis of directional changes in upper extremity kinematics is that it does not enable estimated joint loads. The advantage of an observational approach that focuses on directional changes in joint motion is that it may provide a method enabling visual detection of kinematic changes that would be difficult to identify based on categorizing changes in absolute joint angles. However, body segment posture classifications are required inputs into biomechanical models, such as 3D match, that can estimate loads at the joint of interest (Callaghan et al., 2001; Sutherland et al., 2008). Thus, this approach does not have the intent of replacing existing methods used to analyze injury risk of occupational tasks based on joint loads, but instead provide a visual cue of muscle fatigue. Visual detection of kinematic changes in repetitive tasks may provide an accessible, reliable and non-invasive method to detect shoulder muscle fatigue in the workplace, enabling ergonomic intervention focused on mitigating the associated deleterious effects that lead to chronic injury.

8.1.2 Multi-joint response to shoulder muscle fatigue

Kinematic changes, as indicated by a change in joint angle SMSRs, occurred across upper extremity joints in this repetitive task, supporting a multi-joint approach to upper extremity movement reorganization with muscle fatigue. These data suggest that in this repetitive task, participants changed upper extremity movement strategy by exploiting the abundant degrees of freedom across joints within the upper extremity (Latash, 2012). This may explain why the EMG MPF from the infraspinatus and middle deltoid muscles first exhibited a large decline within the first 25% of the task, indicative of muscle fatigue, but then plateaued throughout the remainder of the task. Without a change in the demands placed on these muscles, a continued decrease in EMG MPF is expected with time during the repetitive task (Iridiastadi & Nussbaum, 2006; Troiano et al., 2008). Thus, consistent with others' hypotheses, the multi-joint changes in upper extremity movement strategy may serve to redistribute loads away from fatiguing tissues and enable task performance (Emery & Côté, 2012; Fuller et al., 2009; Lomond & Côté, 2011).

8.2 Objective 2: Between subject variability of upper extremity joint angle SMSRs

Joint angle SMSRs exhibited little variation (i.e. three strings or less) between subjects at the torso, thoracohumeral and elbow joints, partially confirming the second hypothesis. This contrasts with the high between-subject variability of descriptive values of joint angle data (i.e. maximum angle, range of motion, etc.) that is often greater than the within-subject kinematic variability of these data (Frost et al., 2015). Given that the intent of the SMSR is to identify invariant features of motion, analogous to the generalized motor programs used by the central nervous system to plan motions, it is likely that the SMSR is preferentially sensitive to movement changes *along* the goal equivalent manifold of the task (Cusumano & Cesari, 2006; Gates & Dingwell, 2008; Latash et al., 2002). Recent work has identified that, in fatiguing tasks, individuals' movement variability *perpendicular* to the goal equivalent manifold does not change and they maintain task performance (Gates & Dingwell, 2008). To combat deleterious effects of muscle fatigue, individuals change movement strategies in ways that *align* with the goal equivalent manifold. Time series joint angle data are the sum of movement features that are both *along* and *perpendicular* to the goal equivalent manifold. Thus, if the SMSR is sensitive to movement changes *along* the goal equivalent manifold, this kinematic analysis may 'filter out' movement variability that does not *align* with the goal equivalent manifold, and thus exhibit little between-subject variability.

8.2.1 Ergonomic Relevance

Little between-participant variation in joint angle SMSRs facilitates generalization of kinematic changes among individuals in repetitive tasks, increasing the potential application of this approach as a facilitator of visual detection of kinematic changes in repetitive work. The ability to generalize upper extremity kinematic changes, indicative of local muscle fatigue, across a population is necessary to reflect diverse occupational populations. For example, in this thesis, participants changed between ***U*** and ***UD*** thoracohumeral elevation SMSRs. Heuristic guidelines could instruct an observer to identify whether individuals switch between thoracohumeral elevation (***U***) and a combination of thoracohumeral elevation and depression (***UD***) as a change in movement strategy, associated with shoulder muscle fatigue, during the repetitive task. Applied to the torso, an observer could identify whether individuals switch between "little movement" (***S***) and torso extension (***U***) as a change in movement strategy, associated with shoulder muscle fatigue, during the repetitive task. These guidelines would apply to individuals within a sample population regardless of the large potential differences in peak or average joint angles across individuals during the repetitive task (Frost et al., 2015).

8.3 Objective 3: Temporal relationship between a change in thoracohumeral elevation SMSR and infraspinatus muscle fatigue

This thesis identified a weak linear relationship between the onset of infraspinatus muscle fatigue and the onset of a change in thoracohumeral elevation SMSRs. The onset of changes in thoracohumeral elevation SMSRs preceded the onset of infraspinatus muscle fatigue, contrary to the hypothesis that infraspinatus muscle fatigue would occur before a change in thoracohumeral elevation SMSRs. The hypothesis was based on the theory that in repetitive upper extremity tasks, muscle fatigue drives the transition to a different movement strategy to redistribute the load away from fatiguing tissues and enable task completion (Cantú et al., 2014; Côté et al., 2002, 2005; Emery & Côté, 2012; Lomond & Côté, 2011). Fuller et al. (2011) also found that in a repetitive reaching task, changes in upper extremity kinematics occurred prior to the onset of increasing upper trapezius EMG amplitude, which is a metric indicative of muscle fatigue. The authors suggest that physiological changes that occur with muscle fatigue are processed by the central nervous system and facilitate a change in movement strategy before EMG manifestations of muscle fatigue are detectable. This theory suggests that muscle fatigue is a driving mechanism behind kinematic changes in repetitive tasks, despite our findings and those of Fuller et al., (2011) that show kinematic changes tend to occur prior to the onset of EMG measures of muscle fatigue.

8.3.1 Potential confounding factors in establishing a temporal relationship

Several confounding factors may have confounded the linear relationship between the onset of infraspinatus muscle fatigue and the onset of a change in torso or thoracohumeral SMSRs. Although participants were provided with practice (25 trials) before beginning the task, it is possible that the first change in movement strategy at the beginning of the task was a result of learning. Typically, when learning a novel task, individuals constrain the available degrees of freedom as a method to simplify the motor control required to complete the task (Bernstein, 1967). Then, after practice, an individual begins to exploit different movement strategies involving different relative contributions of the available degrees of freedom (Bernstein, 1967; Jaric & Latash, 1999). Changes in the relative contribution of joints to task completion should be reflected by a change in SMSR string, meaning that the onset of the first change in SMSR string may not reflect considerable muscle fatigue and instead a learning effect.

The criterion used to identify infraspinatus muscle fatigue onset (i.e. > 9% decline in the EMG MPF relative to baseline) may not have been an appropriate indicator of fatigue onset. A decline in EMG MPF greater than 9% of baseline is often used in the literature to identify muscle fatigue (Oberg et al., 1990, 1991). This threshold is derived from research on the upper trapezius muscle, identifying that deviations in EMG MPF less than 8.8% of the initial value can result from factors other than muscle fatigue (i.e. slight differences in joint position or load) (Bartuzi & Roman-Liu, 2014; Oberg et al., 1991; Roman-Liu & Konarska, 2009). Muscle fatigue is a continuous process that begins immediately after the onset of activity (Enoka & Duchateau, 2008). Therefore, although the 9% decline threshold may be useful in determining changes in EMG MPF that can be attributed to muscle fatigue, it does not mean that there is no muscle fatigue below this threshold. Recent work has identified a linear relationship between the rate of change of the EMG MPF and endurance time in a fatiguing task (Troiano et al., 2008), which suggests that differences in the rate of change in EMG MPF may provide information about muscle fatigue accumulation among individuals. Another approach consists of determining subject-specific variability in the EMG MPF signal at baseline and using it to determine when a significant change has occurred; i.e. similar to performing a one sided t-test (Nussbaum, 2001). Both methods are based on a negative linear relationship between EMG MPF and endurance time. Thus, with the continuum of total task duration amongst participants in this study, variability in the onset of EMG MPF between individuals should exist. Only 3 participants had an onset of infraspinatus fatigue that did not occur within the first 3 minutes of the repetitive task. Overall, it is likely the criterion used to identify infraspinatus muscle fatigue, yielding a fatigue onset that exhibited little variability amongst participants, made it difficult to identify a linear relationship with the onset of a change in torso or thoracohumeral SMSRs.

8.3.2 Ergonomic Relevance

The results of this thesis do not encourage the use of the onset of potentially visually identifiable kinematic changes in thoracohumeral elevation as an indicator of the onset of shoulder muscle fatigue. In this repetitive task, the infraspinatus muscle was the first to fatigue across participants and thus used to indicate the onset of shoulder muscle fatigue. Although the confounding factors discussed above may have masked a potential relationship between these variables, it is also quite possible that a strong relationship does not exist. As a continuous, time varying process, it may not be possible to empirically define muscle fatigue "onset" as a discreet point in time, because the process of fatigue begins immediately after the onset of physical activity (Enoka & Duchateau, 2008). Instead, it is likely more informative to relate upper extremity kinematic changes to the level of muscle fatigue accumulation during a repetitive task. Second, upper extremity movement variability has been shown to increase over time with muscle fatigue accumulation in repetitive tasks (Fuller et al., 2009, 2011; Gates & Dingwell, 2011). Variability of thoracohumeral elevation movement strategy instead of the first onset of a change may more accurately reflect a kinematic response to muscle fatigue in repetitive tasks. The time varying nature of both muscle fatigue accumulation and upper extremity kinematic variability in repetitive tasks motivated the fourth research question in this thesis, discussed below.

8.4 Objective 4: Thoracohumeral elevation SMSR variability & shoulder muscle fatigue

This thesis detected differences in shoulder muscle fatigue accumulation between two groups of individuals identified by whether they varied their thoracohumeral elevation SMSRs during the repetitive task. The most cogent finding was that those who varied their thoracohumeral elevation SMSRs during the repetitive task had significantly greater anterior deltoid muscle fatigue than those who did not. Secondarily, females who varied their thoracohumeral elevation SMSRs during the repetitive task had significantly greater decline in external rotation MVF relative to baseline, than those who did not.

8.4.1 Ergonomic Relevance

Although the intent of this research was to identify a link between rotator cuff muscle fatigue and potentially visually identifiable upper extremity kinematic changes in a repetitive task, the identified relationship between thoracohumeral elevation SMSR variability and anterior deltoid muscle fatigue may still provide an indication of local muscle fatigue accumulation at the glenohumeral joint that is associated with chronic injury progression. The involvement of both the deltoid and rotator cuff muscles in humeral head translation, with muscle fatigue in repetitive tasks, suggests a coupling of deltoid and rotator cuff muscle fatigue. In repetitive tasks, especially those involving thoracohumeral elevation, humeral head translation results from a force imbalance between the deltoid and rotator cuff muscles (Chopp et al., 2010b, 2011). For this to occur, both muscle groups must be active; the deltoids contribute as a prime mover in thoracohumeral elevation and the rotator cuff works to maintain glenohumeral joint stability. Although humeral head translation implies a considerable level of fatigue in the rotator cuff muscles, impairing their ability to resist the upward pull of the deltoid muscles on the humeral head, it does not mean that only the rotator cuff muscles are fatigued. In fact, both deltoid and rotator cuff muscle fatigue occur from repetitive tasks that induce kinematic changes, such as humeral head translation, that reduce the size of the subacromial space (Chopp et al., 2010b, 2011; Ebaugh et al., 2006a; Mc Quade et al., 1998).

A relationship between anterior deltoid muscle fatigue and problematic kinematic changes at the glenohumeral joint gives purpose to the finding that it may be possible to identify anterior deltoid muscle fatigue through visual detection of thoracohumeral elevation SMSRs. For example, those who varied between thoracohumeral elevation (***U***) and a combination of thoracohumeral elevation and depression (***UD***) movement strategies during the repetitive task had significantly greater anterior deltoid muscle fatigue accumulation. Thus, observers could be instructed to identify whether individuals vary between continuous thoracohumeral elevation (***U***) and a combination of thoracohumeral elevation and depression (***UD***) to complete a lift motion during this repetitive task. Visual identification of these kinematic changes could cue ergonomic intervention to mitigate shoulder muscle fatigue accumulation in repetitive tasks which is associated with the development of shoulder MSDs in the workplace.

8.4.2 Thoracohumeral elevation SMSR variability & anterior deltoid muscle fatigue

Variability in thoracohumeral elevation angle SMSRs was associated with local muscle fatigue at the shoulder, specifically that of the anterior deltoid, confirming the forth hypothesis. Anterior deltoid is a prime mover at the glenohumeral joint, contributing largely to elevation moments, particularly in movements in front of the body (Ackland et al., 2008; Kuechle et al., 1997; Veeger & van der Helm, 2007). Thus, variations in thoracohumeral elevation movement strategy can certainly influence the demands on the anterior deltoid muscle that drives this motion; for example, anterior deltoid activation varies with changes in elevation angles (Brookham et al., 2010b). It is likely that the observed variability in thoracohumeral elevation SMSRs reflect a change in movement strategy to enable task performance versus one with the intent of facilitating anterior deltoid muscle fatigue recovery. In fatiguing tasks targeting a specific group of muscles, such as the elbow extensors or muscle of the hand, variability in muscular demand throughout the task (standard deviation of force levels) exhibits a curvilinear decrease with muscle fatigue accumulation rates (Sonne & Potvin, 2015; Yung & Wells, 2012). If the goal of the change in movement strategy was to mitigate fatigue accumulation by varying muscular demands, less anterior deltoid muscle fatigue in the group with greater variation in thoracohumeral elevation SMSRs would be expected. Instead, our results indicate the opposite, suggesting the change in upper extremity kinematics in this repetitive task are performance focused. This is consistent with several studies identifying changes in upper extremity joint kinematics in repetitive tasks without decrements in task performance (Côté et al., 2002; Fuller et al., 2009; Gates & Dingwell, 2008, 2011; Lomond & Côté, 2011). It is therefore likely that the neuromuscular system exploits the abundant degrees of freedom in the upper extremity to compensate for deleterious effects of muscle fatigue, such as increased force variability (Hunter et al., 2004) and a reduction in joint position sense (Emery & Côté, 2012), to enable task performance.

8.4.3 Thoracohumeral elevation SMSR variability & external rotation MVF decline

The finding that a relationship between thoracohumeral elevation SMSR variability and external rotation MVF decline following the repetitive task was exclusive to females may be attributed to methodological factors. The external rotation MVF effort was designed to preferentially identify the force generating capacity of the infraspinatus muscle (Brookham et al., 2010a). Thus, a relationship should exist between the magnitude of a change in infraspinatus EMG MPF and external rotation MVF following the repetitive task, as both are indicators of muscle fatigue (Bartuzi & Roman-Liu, 2014; Vøllestad et al., 1997). There is no evidence to suggest that the strength of the relationship between infraspinatus EMG MPF and external rotation MVF is sex dependent, however in this thesis females exhibited a stronger relationship between infraspinatus EMG MPF and external rotation MVF than males. Therefore, during the external rotation MVF males may have abducted the humerus or involved the torso to generate force, despite the instructions to focus on force generation by externally rotating at the shoulder.

Nonetheless, future research should include a more constrained external rotation MVF effort that enables only external rotation moment generation about the shoulder to estimate infraspinatus strength. This is needed to determine whether there is a biological basis for the sex effect between thoracohumeral elevation SMSR variability and external rotation MVF exhibited in this study.

8.5 Challenges in measuring distal upper extremity kinematics

8.5.1 Elbow joint angle magnitudes

The elbow joint angles computed across participants in this repetitive task were higher than expected, which can be attributed to the method used to compute them. Using an anatomical based approach to identify the elbow axis of rotation, as outlined in the ISB recommendations, results in considerable 'cross talk' between joint angles (Chin et al., 2010; Fraysse & Thewlis, 2014a). In this context, cross talk refers to artificial magnification of joint angle magnitudes about a given axis of rotation, due to the improper identification of the true anatomical axes. At the elbow, evidence of cross talk has been shown in constrained flexion/extension tasks that when using anatomical based approaches to derive joint angles, produce pronation and carrying angles despite the fact that little rotation is occurring about these axis (Chin et al., 2010). Difficulty in identifying the true forearm axes of rotation using anatomical landmarks is a widely accepted explanation for the considerable cross talk observed in elbow joint angle calculations when using ISB convention (Chin et al., 2010; Fraysse & Thewlis, 2014b). Relevant to this thesis, however, cross talk serves to increase or decrease the absolute magnitude of joint angle profiles with little effect on the shape of the time series joint angle data (Chin et al., 2010; Fraysse & Thewlis, 2014b). Thus, given that the kinematic analysis of the elbow joint angle data were based on the shape of the time series data, the anatomical axes method outlined in the ISB recommendations was deemed suitable for this purpose.

8.5.2 Wrist joint angle SMSRs

The high level of variability in the wrist joint angle SMSRs, particularly those representing the flexion and pronation joint angles, is likely a result of the methods used to compute the joint angles. A very simplistic, global model of the wrist was used to compute wrist joint motion during the repetitive task. The validity of joint angle data are largely influenced by appropriate alignment of joint coordinate systems and the anatomical axes of rotation (Schmidt et al., 1999). In activities where motion at the wrist is minimal, or consists primarily of flexion or extension movements, a ball and socket model of the wrist (used in this thesis) may be suitable (Schmidt et al., 1999). However, this task required considerable ulnar deviation at the wrist induced by the 'holder' in which participants had to place the bottle in at each target location. Thus, in deviated wrist postures, which require both rotation and translation about the carpal joints of the wrist, it is difficult to accurately represent joint motion by assuming a simple ball in socket model (Coburn & Crisco, 2005; Kobayashi et al., 1997). Further, the primary purpose of wrist joint motion in this type of goal directed task was likely to ensure the bottle aligned with the holder at each target location. With this role, reversals in joint motion (i.e. corrections) are expected to maintain the desired hand path amidst the typical variability of joint motion at proximal upper extremity joints (Cluff et al., 2012; Haggard et al., 1995). Reversals in joint motion would present as directional changes at the joint and should be identified by the SMSR algorithm. Overall, although there is evidence that would explain why there is larger between-subject variability in wrist joint angle SMSRs, as compared to the other upper extremity joints, a more sophisticated analysis of wrist joint motion is required to identify whether the variability in joint angle SMSRs exists or is attributed to errors associated with the simplistic wrist model used.

8.6 Secondary Findings

8.6.1 Sex differences in supraspinatus and upper trapezius EMG MPF

The interaction of sex and time on the EMG MPF of the supraspinatus and upper trapezius muscles may be due to differences in neuromuscular activation strategies between the sexes. In a similar, repetitive upper extremity task requiring individuals to point between two locations, females had greater EMG variability in the upper trapezius muscle (Srinivasan et al., 2016). The author suggest that females may use a different neuromuscular control strategy then males, focused on mitigating upper trapezius muscle fatigue, as there were no differences between sexes in task endurance time. The current results however, suggest the opposite. In comparison to males, females had more upper trapezius and supraspinatus muscle fatigue, indicated by significantly lower EMG MPF, in the latter portion of the repetitive task. Other factors, such as a proportionally different change in muscle lengths between males and females facilitated by small deviations in posture during the submaximal effort could have contributed to differences in EMG MPF. Perhaps females adopted a posture that lengthened the upper trapezius and supraspinatus muscles relative to that at baseline, or males adopted a posture that shortened these muscles relative to baseline. Muscle lengthening decreases power spectrum parameters of the EMG signal (Roman-liu, 2016).

8.6.2 Ratings of perceived fatigue and discomfort

Ratings of perceived fatigue and discomfort increased with time, but did not differ between individuals based on whether they varied their thoracohumeral elevation SMSR. The linear relationship identified between these measures and time in a repetitive task is consistent with previous findings (Oberg et al., 1994b; Rose et al., 2000, 2014). One potential reason differences between groups were not identified could be because the RPF and RPD measures were not site specific (Dickerson et al., 2006). Therefore, consistent with increased anterior deltoid muscle fatigue, greater RPF and RPD of the shoulder region would be expected. Body region specific RPF and RPD measures may be useful to potential identifying whether the group with little thoracohumeral elevation SMSR variability developed fatigue at other upper extremity joints, thus guiding a focus on differences in SMSR strategies at those joints.

8.7 Limitations & Future Directions

8.7.1 Discretization of thoracohumeral elevation SMSR variability

An important limitation of this thesis is the division of participants into two groups based on whether they varied their thoracohumeral elevation SMSR without further quantification of the observed variability. Given that both muscle fatigue accumulation and upper extremity kinematic variability increase with time in repetitive tasks, a continuous model of the relationship between these variables may be more suited. Quantification of this potential relationship would help to establish heuristic guidelines that indicate the number of variations in thoracohumeral elevation movement strategy (SMSRs) during a repetitive task that correspond to a problematic level of shoulder muscle fatigue, requiring ergonomic intervention, in repetitive tasks. Future research should focus on determining whether a relationship between the number of transitions in thoracohumeral joint angle SMSRs during a repetitive task is related to the magnitude of local muscle fatigue at the shoulder joint.

8.7.2 Single joint angle relationship with muscle fatigue

This study only investigated the relationship between thoracohumeral elevation SMSRs changes and shoulder muscle fatigue. The fact that joint angle SMSRs across upper extremity joints changed during the repetitive task suggests potential relationships between these kinematic variables and shoulder muscle fatigue. Thoracohumeral elevation angles were chosen for subsequent analyses as they were the rotation at the thoracohumeral joint which covered the largest range of motion, indicating a considerable contribution to task completion. However, given that all participants had considerable increases in RPF and RPD throughout the repetitive task, it may have been that those who did not vary thoracohumeral elevation SMSRs developed muscle fatigue at other upper extremity joints or even in different glenohumeral muscles. This thesis suggests a lack of thoracohumeral elevation SMSR variation may indicate marginal fatigue in the anterior deltoid muscle, but should not be interpreted as the absence of muscle fatigue within the upper extremity. For example, perhaps individuals who did not vary their thoracohumeral elevation SMSR instead had a greater contribution of the torso to task completion. Thus, a lack of variability in thoracohumeral elevation SMSR could, for example, represent localized muscle fatigue in the back. Future research should include electromyographic analysis of prime mover muscles across upper extremity joints to identify a potential relationship between SMSR variability and fatigue across upper extremity joints.

8.7.3 Data Reduction

The kinematic data reduction protocol used in this thesis could be influenced by sampling error, however this is not likely. Participants' kinematics were represented by 5 lift efforts every 2 minutes, corresponding to the frequency at which other fatigue measures (EMG MPF and RPF/RPD) were recorded. The collection of numerus trials of a given task are suggested to achieve a stable estimate of an individual's movement characteristics. Although a range of the minimum number of trials exists in the literature, Frost et al., (2010) identified that the measurement of 3 and 5 trials of a task captured 88% and 95% of an individuals' variability measured across 25 trials of the task, respectively. Thus, it is likely that examining 5 efforts adequately captured individuals' within subject variability at a given point in time. The frequency of the fatigue measures (once every 2 minutes) was consistent with that used in other studies examining upper extremity fatigue in repetitive tasks (Cantú et al., 2014; Fuller et al., 2011, 2013; Lomond & Côté, 2011; McDonald et al., 2014). Studies have reported moderate to strong linear relationships between EMG MPF and perceived ratings with time in repetitive tasks (Nussbaum, 2001; Troiano et al., 2008). This means that sampling these measures at equally spaced intervals should be appropriate. However, given the novelty of this research, the relationship between time and joint angle SMSRs was assumed to be linear. Future research needs to confirm the validity of this assumption, or respond by adjusting the sampling frequency if instead this relationship is of a higher order (i.e. polynomial, exponential).

8.7.4 SMSR Algorithm Parameters

The values chosen for the required SMSR algorithm parameters (*eslope, etime, and e-angle*) that are used to identify the basic structure of joint motion certainly influence the SMSR characterization of a given joint angle profile. In this thesis, the SMSR algorithm *eslope* and *etime* parameter values were modified from those recommended by Park et al., (2005) in the development of the SMSR algorithm to reflect current research on the thresholds of both static and dynamic joint position sense (Clark et al., 1985; Cordo et al., 2000). Unfortunately, little research, aside from that by Wikens et al., (1986), has studied the number of movement corrections that can be made in a 1s reaching motion which corresponds to the *etime* parameter. The *etime* value used in the SMSR algorithm in this thesis remains the same as that suggested by Wikens et al., (1986) at 1/3s corresponding to 2 movement corrections in a 1s motion. Given that this determines the number of motion segments identified by the SMSR, varying this parameter will influence the maximum number of characters in the SMSR of joint motion. The results of this thesis indicate that the selected SMSR parameters were sufficient in characterizing thoracohumeral elevation motion (i.e. SMSR variability or not) during the repetitive task that was related to anterior deltoid muscle fatigue. Future research should investigate the extent to which variations in the SMSR algorithm parameters (*eslope, etime, and e-angle*) influence the SMSR of joint angle data during repetitive upper extremity goal directed tasks and whether these potential differences influence the relationship between SMSR thoracohumeral elevation variability and anterior deltoid muscle fatigue.

8.7.5 Task specificity

Although this thesis identified the generalizability of changes in joint angle SMSRs across the sample population, these findings are task specific and may lack generalizability across workplace tasks or require modifications based on population subsets. The sample participant population consisted of university aged adults free of upper extremity disorders. Differences in fatigue responses exist between young and older populations, with older individuals exhibiting a decrease in the rate of fatigue accumulation in submaximal tasks (Hunter et al., 2005; Qin et al., 2014). Thus, future research should investigate whether age related differences in muscle fatigue accumulation rates influence the relationship between shoulder muscle fatigue and kinematic adaptations during repetitive tasks. The repetitive task in this thesis was scaled to each individual's reach length and strength capacity. It was also constrained temporally, requiring participants to stay on pace with a metronome. Although some repetitive tasks in the workplace can be adjusted to accommodate differences in workers' anthropometrics and may require workers to perform tasks at a set cadence (i.e. assembly line work), this is generally not the case across workplaces. Further, it is highly unlikely the required demands of the task are scaled relative to an individual's capacity, but instead involve the same absolute demand across individuals. Thus, it is important to investigate the relationship between variability of thoracohumeral elevation SMSRs and local muscle fatigue in less constrained tasks (i.e. not scaled to participants reach length, no set pace) as well as within individuals across a given task with different levels of relative demand (i.e. lift a bottle at 20% MVF, 30% MVF, 40% MVF etc.).

8.7.6 Visual detection of directional changes in joint motion

An important next step in this line of research is to identify the potential validity and reliability of observers' visual detection of directional changes in upper extremity joint motion, as identified by joint angle SMSRs. Research on visual detection of wrist flexion/extension and elbow pronation/supination motions suggests observers can reliably identify directional changes in joint angles as an indicator of job severity in repetitive tasks (Lowe & Krieg, 2009). Absolute errors in observers' counts of wrist or elbow motions in repetitive tasks are attributed to assigning a range of joint angle motion that is considered neutral and thus not to be considered as a movement (i.e. <30° wrist flexion) rather than individuals abilities to identify directional changes in joint motion (Lowe & Krieg, 2009; Spielholz et al., 2001). Future research focused on establishing the validity and reliability of visual detection of directional changes in repetitive tasks is required to drive further development of an observational based tool to detect shoulder muscle fatigue in repetitive work.

9 CONCLUSION

The overall purpose of this thesis was to determine if, during a workplace emulative repetitive task, the basic structure of upper extremity joint angle data, characterized by the SMSR algorithm (Park et al., 2005), changes across individuals and to characterize the relationship between changes in thoracohumeral elevation SMSRs, and traditional indicators of shoulder muscle fatigue. Joint angle SMSRs characterize motion as a sequence of directional changes in joint angle time series data (Park et al., 2005), which can be visually identified by ergonomists (Lowe & Krieg, 2009). In principle, the results of this thesis indicate that upper extremity kinematic changes in a repetitive task may be visually identifiable, as directional changes in joint motion were identified across upper extremity joints by the SMSR algorithm. The similarity of joint angle SMSRs between participants during the repetitive task encourages the further study of task specific heuristics, and eventual development of guidelines to facilitate visual detection of upper extremity kinematic changes with shoulder muscle fatigue across a healthy, young population of individuals. Variability in thoracohumeral elevation SMSRs throughout the repetitive task was related to greater anterior deltoid muscle fatigue accumulation, providing a link between directional changes in thoracohumeral elevation joint motion and shoulder muscle fatigue accumulation.

This thesis has established a foundation for future research focused on potentially visually identifiable upper extremity joint kinematic changes indicators of shoulder muscle fatigue in repetitive tasks. First, the potential validity and reliability of observers' visual detection of directional changes in upper extremity joint motion, with emphasis on thoracohumeral motion, needs to be quantified. The strength of this observational approach to identifying shoulder muscle fatigue relies heavily on the ability of an individual to visually detect relevant directional changes in joint motion. This study also showed that future guidelines might benefit from focus on the variability of an individuals' joint angle SMSRs as an indicator of local muscle fatigue, rather than the onset of a change in a joint angle's SMSR. Research is needed to determine whether a relationship between the number of transitions in thoracohumeral joint angle SMSRs during a repetitive task is related to the magnitude of local muscle fatigue at the joint and whether the absence of thoracohumeral elevation SMSR variability is related to fatigue accumulation at other upper extremity joints. This information is fundamental in developing heuristic guidelines that incorporate the number of variations in thoracohumeral joint angle SMSRs corresponding to a level of local muscle fatigue requiring ergonomic intervention.

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Appendix A – Perceived Rating Scales

Rating of Perceived Fatigue

Fatigue should be identified as the sense of a decline in strength, feelings of exhaustion, or a reduction in the ability to continue to perform the task.

RPF Scale		
Completely Rested	0	No fatigue at all
	0.5	Very light fatigue
	1	Light fatigue
	2	Fairly fatigued
	3	Moderately fatigued
	4	Fatigued
50% Rested	5	Very fatigued
	6	
	7	Nearly exhausted
	8	
	9	
Completely Fatigued	10	Absolutely exhausted

Rating of Perceived Discomfort

Discomfort consists of sensations of pain which can be sharp, dull or throbbing in nature, and/or the presence of aches, cramping, soreness or localized heat.

RPF Scale		
No Discomfort	0	No discomfort at all
	0.5	
	1	Light discomfort
	2	
	3	Mild Discomfort
	4	
Moderate Discomfort	5	Moderate Discomfort
	6	
	7	Great Discomfort
	8	
	9	
Worst Discomfort Imaginable	10	Extreme Discomfort

Appendix B –Supplementary Data

Table 13: A visual representation of the joints angles which exhibited a change in SMSR string during the lift motion of the repetitive task for each participant.

	Joint	Torso to Global			Thoraochumeral			Elbow		Wrist			
Participant #	Rotation	Axial Rotation	Flexion	Lateral Flexion	Axial Rotation	Elevation	Plane of Elevation	Flexion	Pronation	Flexion	Pronation	Ulnar Deviation	Total # of Joint Angles
1			✓	✓	✓	✓			✓	✓	✓		7
2		✓	✓	✓			✓	✓		✓			6
4			✓			✓	✓	✓		✓			5
5		✓	✓		✓	✓				✓			5
7		✓	✓	✓	✓	✓		✓	✓				7
8		✓	✓	✓	✓		✓		✓	✓	✓	✓	9
9				✓	✓	✓		✓	✓	✓	✓		7
11			✓	✓	✓	✓		✓	✓	✓	✓		8
13				✓		✓		✓	✓	✓	✓		6
14		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	11
15		✓			✓	✓			✓	✓	✓	✓	7
16		✓	✓		✓	✓	✓		✓	✓	✓		8
17		✓	✓	✓		✓	✓	✓	✓	✓	✓		9
18			✓	✓		✓	✓		✓	✓	✓		7
19		✓	✓			✓	✓			✓	✓		6
20			✓	✓	✓	✓	✓			✓			6
21			✓	✓		✓		✓	✓	✓	✓		7
22		✓	✓	✓	✓		✓	✓		✓		✓	8
23		✓	✓	✓	✓		✓	✓	✓	✓	✓		9
24			✓	✓		✓	✓	✓	✓	✓	✓		8
25		✓		✓	✓		✓	✓		✓	✓		7
26		✓	✓	✓		✓	✓	✓		✓	✓		8
27			✓	✓		✓	✓	✓	✓	✓	✓		8
28				✓				✓		✓			3
29		✓	✓	✓	✓	✓	✓	✓		✓	✓		9
30			✓	✓		✓	✓	✓	✓	✓			7
31		✓	✓	✓	✓	✓	✓	✓	✓	✓			9
Total # of Participants		15	22	22	15	21	18	19	17	26	18	4	

Table 14: A time history of the SMSR strings representing participants' torso axial rotation joint angles during the repetitive task. Participants have been grouped by the frequency of changes in the SMSR string during the repetitive task.

Torso Axial Rotation		Time (min)																														
SMSR String	Participant #	1 (Baseline)	3	5	7	9	11	13	15	17	19	21	23	25	27	29	31	33	35	37	39	41	43	45	47	49	51	53	55	57	59	61
No Change	28	D	D	D	D	D	D	D	D	D	D	D	D	D	D																	
	30	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D															
	27	D	D	D	D	D	D	D	D	D	D	D																				
	4	D	D	D	D	D	D	D	D																							
	24	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D				
	1	D	D	D	D	D	D	D	D	D	D																					
	21	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
	11	D	D	D	D	D	D	D	D	D	D	D																				
	13	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D									
	9	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
	20	D	D	D	D	D																										
	18	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D																
Change (1 epoch only)	26	D	D	DS	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D						
	19	D	D	D	D	D	D	D	DS	D	D	D	D	D	D	D	D															
	16	D	D	D	D	D	D	D	DS	D	D	D	D	D	D	D	D															
	7	DS	D	D	D	D																										
	14	DS	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D												
	15	DS	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
Change (>1 epoch)	5	D	D	D	D	DS	DS	D	D	D	D																					
	23	D	DS	DS	D	D	D	D	D	D	DS	D	D	DS	D	DS	D	D	D	D	D	D	DS	D	D	DS	D	D	D	D	D	D
	22	D	D	D	DS	DS	D	D	DS	D	D	DS	D	DS	DS	D	DS	D	D	D	DS											
	31	D	D	DS	D	D	D	DS	D	DS	D	DS	DS	D	DS	DS	DS	D	DS													
	2	DS	D	D	D	D	DS																									
	25	D	DS	DS	DS	DS	DS	D	DS	D	D	DS	DS	DS	DS	D	DS															
	8	DS	DS	D	D	D	D	D	D	D	D	D	D	DS	D	DS	D	D	D	D												
	17	DS	D	DS	D	D	D	D	D	D	D	D	D																			
	29	DS	D	D	D	D	D	D	D	D	D	D	DS	D	D	D	DS	D	D	D	D	D	D									

Table 15: A time history of the SMSR strings representing participants' torso flexion joint angles during the repetitive task. Participants have been grouped by the frequency of changes in the SMSR string during the repetitive task.

Torso Flexion		Time (min)																														
SMSR String	Participant #	1 (Baseline)	3	5	7	9	11	13	15	17	19	21	23	25	27	29	31	33	35	37	39	41	43	45	47	49	51	53	55	57	59	61
No Change	9	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
	15	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S
	13	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S									
	25	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U															
	28	S	S	S	S	S	S	S	S	S	S	S	S	S	S																	
Change (1 epoch only)	26	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	S						
	29	U	U	US	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U									
	7	US	U	U	U	U																										
	5	S	U	U	U	U	U	U	U	U	U																					
	19	S	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U															
Change (>1 epoch)	16	U	U	U	S	U	U	U	U	S	U	U	U	U	U	U	U															
	11	U	U	U	US	U	U	US	U	U	U	U																				
	18	U	U	U	S	U	U	S	S	U	U	U	U	U	U	U																
	8	US	U	U	U	US	US	US	U	US	US	U	US	U	US	US	US	US	US	US												
	14	U	U	U	U	S	U	U	S	S	S	S	U	U	U	U	U	S	U	U												
	4	U	U	S	U	S	S	S	U																							
	22	U	U	U	U	U	S	S	S	S	S	U	S	S	S	U	S	S	U	S	U											
	31	U	US	U	U	US	U	U	U	US	US	U	US	S	US	S	S	U	S													
	20	S	S	US	U	U																										
	27	US	U	U	U	U	U	U	U	US	US	US																				
	1	S	S	S	U	U	U	U	U	U	U																					
	30	US	US	U	U	U	S	U	U	US	S	S	US	S	S	S	S															
	2	S	US	U	U	U	U																									
	17	U	S	U	S	S	S	S	S	S	S	S	S																			
	24	U	S	S	S	S	U	S	S	U	S	S	S	U	S	S	S	S	S	S	S	S	S	S	S	S	S	S				
	21	US	U	U	U	U	U	U	U	U	U	U	U	U	S	S	S	U	S	S	S	S	S	S	S	S	S	S	S	S	S	S
	23	US	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	S	S	U	U	S	S	S	U	S	S	U	U	U	U	U

Table 16: A time history of the SMSR strings representing participants' thoracohumeral axial rotation joint angles during the repetitive task. Participants have been grouped by the frequency of changes in the SMSR string during the repetitive task.

Thoracohumeral Axial Rotation		Time (min)																														
SMSR String	Participant #	1 (Baseline)	3	5	7	9	11	13	15	17	19	21	23	25	27	29	31	33	35	37	39	41	43	45	47	49	51	53	55	57	59	61
No Change	2	UD	UD	UD	UD	UD	UD																									
	4	U	U	U	U	U	U	U	U																							
	13	U	U	U	U	U	U	U	U	U	U	U	U	U	U		U	U	U	U	U	U	U									
	17	U	U	U	U	U	U	U	U	U	U	U	U																			
	18	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U																
	19	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U															
	21	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
	24	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U				
	26	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U						
	27	U	U	U	U	U	U	U	U	U	U	U																				
	28	U	U	U	U	U	U	U	U	U	U	U	U	U	U																	
	30	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U															
Change (1 epoch only)	23	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	US	U
	8	UD	UD	UD	U	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD												
	20	U	U	UD	U	U																										
	7	US	U	U	U	U																										
	5	U	UD	UD	UD	UD	UD	UD	UD	UD	UD																					
	11	UD	U	U	U	U	U	U	U	U	U	U																				
	29	UD	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U									
Change (>1 epoch)	31	U	U	U	U	U	U	U	U	UD	U	U	U	U	U	U	U	UD	UD													
	1	U	U	UD	U	UD	U	U	U	U	U																					
	16	U	U	DU	U	U	U	U	US	S	U	SU	U	DU	U	U	U															
	22	U	U	U	UD	U	UD	UD	UD	U	U	U	U	UD	UD	UD	UD	UD	U	UD	UD											
	9	UD	UD	UD	U	U	U	UD	U	U	UD	UD	UD	U	U	U	U	U	U	U	U	U	UD	U	U	U	U	U	U	U	U	U
	15	UD	UD	UD	UD	UD	U	U	U	U	U	UD	U	U	U	UD	U	U	U	U	U	U	U	U	UD	U	U	U	U	U	U	U
	14	UD	U	U	U	U	U	U	UD	UD	U	U	U	U	U	U	U	U	UD	U												
	25	U	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	U	UD	UD															

Table 17: A time history of the SMSR strings representing participants' thoracohumeral plane of elevation joint angles during the repetitive task. Participants have been grouped by the frequency of changes in the SMSR string during the repetitive task.

Thoracohumeral Plane of Elevation		Time (min)																														
SMSR String	Participant #	1 (Baseline)	3	5	7	9	11	13	15	17	19	21	23	25	27	29	31	33	35	37	39	41	43	45	47	49	51	53	55	57	59	61
No Change	1	U	U	U	U	U	U	U	U	U	U																					
	5	U	U	U	U	U	U	U	U	U	U																					
	7	U	U	U	U	U																										
	9	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
	11	U	U	U	U	U	U	U	U	U	U	U																				
	13	U	U	U	U	U	U	U	U	U	U	U	U	U	U		U	U	U	U	U	U	U									
	15	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
	21	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
	28	U	U	U	U	U	U	U	U	U	U	U	U	U	U																	
Change (1 epoch only)	8	U	U	U	U	US	U	U	U	U	U	U	U	U	U	U	U	U	U	U												
	20	U	U	U	U	US																										
Change (>1 epoch)	29	US	US	U	US	US	US	U	US	US	US	US	US	US	US	US	US	US	US	US	US	US	US									
	24	U	U	U	U	US	U	U	U	U	US	U	U	U	U	U	U	U	U	U	US	U	U	U	U	U	U	U				
	26	US	US	US	US	US	US	US	UD	US	US	US	US	US	US	US	US	UD	US	US	US	US	UD	UD	US	US						
	2	U	U	U	U	US	UD																									
	27	US	U	US	U	U	US	US	US	US	US	U																				
	31	U	U	U	U	US	U	U	U	US	US	U	U	U	US	US	US	US	U													
	18	US	U	U	US	U	US	U	U	U	US	US	US	US	US	US																
	30	SU	SU	U	SU	SU	SU	SU	SU	U	U	U	U	SU	SU	U	U															
	17	U	U	U	US	U	U	U	S	S	D	D	D																			
	22	U	U	U	US	U	U	US	U	US	US	US	US	US	U	US	US	U	U	US	US											
	19	U	U	U	UD	U	UD	UD	UD	UD	UD	UD	U	UD	UD	U	UD															
	16	US	U	US	U	US	U	U	US	U	U	U	U	U	US	U	U															
	14	U	US	U	UD	U	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD												
	4	SU	U	U	U	US	U	U	US																							
	25	U	US	US	US	US	US	U	US	US	US	US	US	US	US	US	US															
	23	U	UD	UD	US	UD	UD	UD	US	UD	US	US	US	UD	UD	US	US	US	US	US	US	US	US	US	US	UD	UD	U	UD	U	UD	UD

Table 18: A time history of the SMSR strings representing participants' elbow pronation joint angles during the repetitive task. Participants have been grouped by the frequency of changes in the SMSR string during the repetitive task.

Elbow Pronation		Time (min)																														
SMSR String	Participant #	1 (Baseline)	3	5	7	9	11	13	15	17	19	21	23	25	27	29	31	33	35	37	39	41	43	45	47	49	51	53	55	57	59	61
No Change	29	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD									
	2	UD	UD	UD	UD	UD	UD																									
	4	UD	UD	UD	UD	UD	UD	UD	UD																							
	5	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD																					
	19	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD															
	20	UD	UD	UD	UD	UD																										
	22	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D											
	25	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD															
	26	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD						
	28	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD																	
Change (1 epoch only)	8	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	US												
	27	UD	U	UD	UD	UD	UD	UD	UD	UD	UD	UD																				
Change (>1 epoch)	7	UD	UD	UD	U	UD																										
	23	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	U	UD	UD	UD	UD	UD	UD	U	UD	U	UD	UD
	31	UD	UD	UD	UD	US	U	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD													
	18	UD	U	U	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD																
	15	UD	UD	U	UD	UD	UD	U	U	U	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	UD	U	UD	UD	UD	UD	UD
	17	UD	UD	UD	UD	UD	UD	UD	UD	UD	S	S	UD																			
	13	UD	S	U	US	UD	UD	UD	UD	US	UD	UD	UD	U	UD		UD	UD	UD	UD	UD	UD	US									
	14	UD	UD	U	UD	U	UD	UD	U	U	U	U	UD	UD	UD	UD	UD	UD	UD	UD												
	24	U	U	UD	UD	U	U	U	UD	U	U	U	U	UD	U	UD	UD	U	UD	U	UD	U	U	U	U	U	U	UD				
	16	U	U	UD	U	UD	U	U	U	U	U	U	U	UD	UD	UD	UD															
	21	UD	UD	U	UD	UD	UD	U	UD	U	UD	UD	UD	UD	UD	U	U	U	U	UD	UD	U	UD	UD	U	UD	U	UD	U	UD	UD	U
	11	UD	U	U	UD	U	U	UD	U	UD	UD	UD																				
	1	UD	UD	UD	UD	US	U	UD	U	U	U																					
	9	US	US	US	U	US	US	US	US	U	US	U	US	U	U	U	U	U	U	U	U	U	US	U	U	U	U	U	U	U	U	U
	30	UD	UD	UD	SD	D	S	D	D	UD	UD	D	D	D	D	D	D															

Table 19: A time history of the SMSR strings representing participants' wrist pronation joint angles during the repetitive task. Participants have been grouped by the frequency of changes in the SMSR string during the repetitive task.

Wrist Pronation		Time (min)																														
SMSR String	Participant #	1 (Baseline)	3	5	7	9	11	13	15	17	19	21	23	25	27	29	31	33	35	37	39	41	43	45	47	49	51	53	55	57	59	61
No Change	2	U	U	U	U	U	U																									
	4	DU	DU	DU	DU	DU	DU	DU	DU																							
	5	DU	DU	DU	DU	DU	DU	DU	DU	DU	DU																					
	7	DU	DU	DU	DU	DU																										
	20	DU	DU	DU	DU	DU																										
	22	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U											
	28	DU	DU	DU	DU	DU	DU	DU	DU	DU	DU	DU	DU	DU	DU																	
	30	DU	DU	DU	DU	DU	DU	DU	DU	DU	DU	DU	DU	DU	DU	DU	DU															
	31	DU	DU	DU	DU	DU	DU	DU	DU	DU	DU	DU	DU	DU	DU	DU	DU	DU	DU													
Change (1 epoch only)	18	DU	D	DU	DU	DU	DU	DU	DU	DU	DU	DU	DU	DU	DU	DU																
	27	DU	D	DU	DU	DU	DU	DU	DU	DU	DU	DU																				
	11	DU	U	U	U	U	U	U	U	U	U	U																				
	29	DU	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U									
Change (>1 epoch)	23	DU	DU	DU	DU	DU	DU	DU	DU	DU	DU	DU	DU	DU	DU	DU	DU	DU	DU	DU	DU	DU	DU	DU	DU	DU	DU	DU	DU	D	DU	DU
	26	DU	DU	U	DU	DU	S	DU	DU	DU	DU	DU	DU	DU	DU	DU	DU	DU	DU	DU	DU	DU	DU	DU	DU	DU						
	24	DU	D	DU	DU	D	DU	DU	D	D	DU	DU	DU	DU	DU	DU	DU	DU	DU	D	DU	DU	D	D	DU	DU	D	DU				
	25	DU	DU	DU	DU	D	DU	DU	D	D	DU	DU	D	DU	DU	S	S															
	1	DU	DU	DU	DU	DU	D	DU	D	D	D																					
	8	D	D	DU	S	S	S	D	S	DU	D	S	D	D	D	D	D	D	D	DU												
	16	DU	DU	DU	D	DU	D	D	DU	D	D	DU	DU	DU	DU	D	D															
	19	DU	D	D	DU	D	DU	DU	DU	DU	DU	DU	D	D	D	U	DU															
	17	DU	D	D	DU	S	D	DU	DU	DU	D	D	DU																			
	13	D	D	D	DU	DU	DU	DU	DU	DU	DU	D	DU	DU	DU		DU	DU	DU	DU	DU	DU	DU									
	15	DU	U	U	U	U	DU	U	U	U	U	U	U	U	U	U	U	U	U	U	U	DU	U	U	U	U	U	U	U	U	U	U
	21	DU	DU	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	S	DU	U	U	U	U
	14	DU	D	S	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D												
	9	DUS	DU	DU	DU	DU	DU	DU	DU	D	DU	DU	DU	DU	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D

Table 20: A time history of the SMSR strings representing participants' wrist ulnar deviation joint angles during the repetitive task. Participants have been grouped by the frequency of changes in the SMSR string during the repetitive task.

Wrist Ulnar Deviation		Time (min)																														
SMSR String	Participant #	1 (Baseline)	3	5	7	9	11	13	15	17	19	21	23	25	27	29	31	33	35	37	39	41	43	45	47	49	51	53	55	57	59	61
No Change	24	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U				
	1	U	U	U	U	U	U	U	U	U	U																					
	2	U	U	U	U	U	U																									
	4	U	U	U	U	U	U	U	U																							
	5	U	U	U	U	U	U	U	U	U	U																					
	7	U	U	U	U	U																										
	9	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
	11	U	U	U	U	U	U	U	U	U	U	U																				
	13	U	U	U	U	U	U	U	U	U	U	U	U	U	U		U	U	U	U	U	U	U									
	16	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U															
	17	U	U	U	U	U	U	U	U	U	U	U	U																			
	18	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U																
	19	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U															
	20	U	U	U	U	U																										
	21	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
	23	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
	25	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U															
	26	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U						
	27	U	U	U	U	U	U	U	U	U	U	U																				
	28	U	U	U	U	U	U	U	U	U	U	U	U	U	U																	
	29	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U									
	30	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U															
	31	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U													
Change (1 epoch only)	8	U	U	U	U	US	U	U	U	U	U	U	U	U	U	U	U	U	U	U												
	15	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	US	U	U	U	U	U	U	U	U	U
Change (>1 epoch)	22	U	U	U	U	U	U	U	U	U	US	U	U	U	US	U	U	U	U	U	US											
	14	U	U	U	U	U	U	US	U	U	U	U	U	U	U	U	US	US	US	US												