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Variability in musculoskeletal fatigue responses associated with repeated exposure to an occupational overhead drilling task completed on successive days

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A R T I C L E I N F O

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A B S T R A C T

Emerging research suggests that muscular and kinematic responses to overhead work display a high degree of variability in fatigue-related muscular and kinematics changes, both between and within individuals when evaluated across separate days. This study examined whether electromyographic (EMG), kinematic, and kinetic responses to an overhead drilling task performed until volitional fatigue were comparable to those of a repeated identical exposure of the task completed 1 week later. Surface EMG and intramuscular EMG, sampled from 7 shoulder muscles, and right upper limb kinematics and kinetics were analyzed from 15 male and 14 female participants. No significant day-to-day changes in EMG mean power frequency (MPF) were observed, though serratus anterior displayed significantly less fatigue-related increase in EMG root-mean-squared (RMS) signal amplitude on day 2. Unfatigued upper kinematics on day 2 featured an increase in thoracohumeral elevation, elbow flexion, and decrease in wrist ulnar deviation compared to unfatigued state on day 1. Fatigue-related changes in shoulder joint flexion moment that were present on day 1 were reduced on day 2, suggesting that a more efficient overhead work strategy was learned and preserved across successive days. Day-to-day changes in upper limb joint angle variability, quantified by median absolute deviation (MdAD), were joint dependent. Despite yielding a variable fatigue-related kinetic strategy on both days, kinematic and kinetic fatigue-related changes on a second day of completing an overhead drilling task suggested a potential kinematic learning effect.

1. Introduction

The effects of muscle fatigue on kinematic changes are well documented and understood yet remain difficult to predict. Muscle fatigue produces a transient and fluctuating state of sensorimotor feedback and reductions in muscle force generating capacity [Enoka & Stuart, 1992]. Evidence suggests that as a muscle fatigues, individuals employ alternate muscular strategies in effort to maintain task performance, such that accuracy and other task parameters can be maintained [Enoka & Stuart, 1992; Forestier & Nougier, 1998; Monjo, Terrier, & Forestier, 2015; McDonald, Tse, & Keir, 2016; Tse, McDonald, & Keir, 2016]. As a result of these adaptation strategies, kinematics are also affected, altering the moment arms and orientation of the body segments [Madeleine, 2010; Bouillard,

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Jubeau, Nordez, & Hug, 2014; Duchateau & Baudry, 2014]. On the topic of fatigue-related kinematic and muscular adaptations, the shoulder is of particular interest from a movement and motor variability perspective, as biomechanical characterizations of the shoulder are often challenged by its many degrees of freedom [Madeleine, 2010; Bouillard et al., 2014; Mulla, McDonald, & Keir, 2018].

Muscle fatigue has implications for several musculoskeletal parameters. With respect to shoulder musculature, fatigue has demonstrably led to reductions in joint position sense and accuracy [Carpenter, Blasier, & Pellizzon, 1998], decrements in force generating capacity of local muscles [Vollestad, 1997; Pethick & Tallent, 2022], changes in muscle activity and co-activity [Szucz, Navalgund, & Borstad, 2009; De Looze, Bosch, & Dieen, 2009], and kinematics changes [McQuade, Dawson, & Smidt, 1998; Chopp-Hurley, O'Neill, McDonald, Maciukiewicz, & Dickerson, 2016]. However, attempts to characterize scapulothoracic and thoracohumeral shoulder motion changes due to fatigue have been challenging due to the high degree of variability reported, which has suggested both task and joint dependency [Oomen, Graham, & Fischer, 2023; Gates & Dingwell, 2011; Ebaugh, McClure, & Karduna, 2006; Chopp-Hurley et al., 2016; Mulla et al., 2018; McDonald, Mulla, & Keir, 2019]. This high upper limb kinematic variability demonstrated with fatigue is likely consequent of redundant motor control solutions available during shoulder and arm tasks [Scholz & Schöner, 1999; Hirashima & Oya, 2016; Sohn & Ting, 2018].

Apart from inter-participant variability, researchers have similarly demonstrated considerable intra-participant muscular and kinematic variability during overhead work, where intra-participant variability is defined as the variation in within participant responses to an identical stimulus. There are currently few studies concerned with intra-participant changes in muscular and kinematic responses. Previous work investigating shoulder kinematics changes associated with a repeated performance of a shoulder fatigue task have reported increases [Ebata, 2012] and decreases [Qin, Lin, Faber, Buchholz, & Xu, 2014] in thoracohumeral elevation, along with a high degree of variability in scapulothoracic posture in particular [Mulla et al., 2018]. The authors reported that scapular kinematics revealed standard deviations in joint position of up to 14.5° between participants completing planar shoulder motions, and within-subject changes in scapulothoracic joint position ranging from a 10° to −15° difference between days [Mulla et al., 2018]. These findings are supported by Qin and colleagues who showed that participants exhibited increased variability at the shoulder, and decreased variability at the elbow and wrist [Qin et al., 2014]. Electromyographic (EMG) measures of fatigue across repeated identical exposures have been explored minimally. Mulla and colleagues [2018] found that for the same rotator cuff fatigue task and planar shoulder motions, participants displayed varying profiles of muscle activity across days. Overall, the high degree of intrapersonal variability in muscular and kinematic responses in these studies highlight the redundancy of available muscle synergies that can conceivably achieve an end effector target position when task effort is inflated due to fatigue [Madeleine, 2010; Ebata, 2012; Mulla et al., 2018].

Overhead arm postures represent common workplace exposures and activities of daily living that may provide a useful model for exploring kinematics changes associated with arm fatigue. Tasks which are oriented above head level may often require elevation of the arm at or above 90° [Wiker, Chaffin, & Langolf, 1989; Punnett, Fine, Keyserling, Herrin, & Chaffin, 2000; Chopp, Fischer, & Dickerson, 2010], however ergonomics literature often accepts a threshold of arm elevation greater than 60°, or work oriented above the shoulder to define overhead work [Grieve & Dickerson, 2008]. Overhead arm postures have been shown to elicit elevated muscular activity from the rotator cuff [Grieve & Dickerson, 2008; Maciukiewicz, Cudlip, Chopp-Hurley, & Dickerson, 2016], scapular stabilizer [Dickerson, Meszaros, Cudlip, Chopp-Hurley, & Langenderfer, 2015; Maciukiewicz et al., 2016], and humeral abductor and adductor musculature [Steenbrink et al., 2006; Overbeek et al., 2019], which may lead to fatigue and/or lead to discomfort more rapidly. With evidence that extensive interpersonal and intrapersonal variability of upper limb kinematics and muscle activity exists with fatigue, this suggests that there are many possible factors which may influence fatigue-related adaptations. Particularly, it is not yet known how an overhead work task, which places high demand on rotator cuff and scapular stabilizer musculature, affects upper limb motor control adaptations across subsequent sessions.

The current research explored whether (1) upper limb kinematics and static shoulder moments at baseline (pre-fatigue), (2) fatigue-related changes in upper limb muscle activity, kinematics, and kinetics, and (3) kinematic and kinetic variability, were different between repeated exposures to the same occupationally relevant overhead task designed to fatigue shoulder musculature, completed on two days that were separated one week apart. We hypothesized that upper limb kinematics and static shoulder joint moments would be different at baseline on day 2, which would reflect a potentially improved motor strategy for reducing muscle stress and static shoulder joint moment exposures. We also hypothesized that participants would display differences in which muscles reached fatigue between days [Mulla et al., 2018]. This reorganization of motor control is expected to drive an upper limb control strategy that will feature a reduction in shoulder flexion lending to a reduced static shoulder moment [Ebata, 2012]. Lastly, we also expected that interparticipant variability in kinematic and kinetic measures would be reduced on day 2 as participants converge towards a similar control strategy based on learned postural changes from their fatigue exposure on day 1 [Monjo et al., 2015; Hirashima & Oya, 2016].

2. Methods

The study reports data collected over two identical 3-h testing sessions. Data from the first collection, which explored the effect of fatigue on muscle co-activation and upper limb kinematics, was analyzed and presented separately [Russell, Vasilounis, Lefebvre, Drake, & Chopp-Hurley, 2024].

2.1. Participants

Thirty right-handed participants (15 male, 15 female; self-reported) were initially recruited for two identical 3-h collections.

Collections were separated by 7 days with the exception of one participant who completed their second collection after 6 days. Due to technical issues, the data from one female participant was unable to be analyzed, thus the final participant population consisted of 15 males (25.4 y ± 4.3, 24.3 kg/m^2 ± 2.7) and 14 females (22.8 y ± 3.6, 21.5 kg/m^2 ± 2.2). Participants were excluded if they self-reported any of the following: (1) working in an occupation with frequent overhead work demands within the past year, (2) pain or lifestyle factors indicative of arm or trunk disability assessed using the Disabilities of the Arm, Shoulder, and Hand (DASH) questionnaire (cutoff score of 25) and the Oswestry Low Back Pain Disability questionnaire (cutoff score of 20), respectively [Alcántara-Bumbiedro, Flórez-García, Echávarri-Pérez, & García-Pérez, 2006], and/or (3) psychological factors that reflect an avoidance of movement, exertion, or discomfort assessed using the Fear Avoidance Beliefs questionnaire subscale for physical activity (cutoff score of 11) [Williamson, 2006], as well as the Tampa Scale for Kinesiophobia (TSK) (cutoff score of 22) [Chimenti et al., 2021]. Additional exclusion criteria were: discomfort with needles, blood clotting disorders or currently taking blood thinning medications, HIV, Hepatitis B or C, diabetes, or respiratory conditions (Asthma, COPD, etc.), allergies to isopropyl alcohol, betadine, latex, or nickel, or were pregnant. This study received ethics approval from the York University Office of Research Ethics (#e2021–395). All participants provided written informed consent.

2.2. Protocol

Participants completed 64-s cycles of repetitive, overhead drilling at a 50 % duty cycle (32 s working, 32 s resting) with their right arm (Fig. 1). The overhead drilling task was based on previously predicted endurance times for overhead work [Sood, Nussbaum, Hager, & Nogueira, 2017], and involved pressing the tip of a 2 kg drill to four overhead targets, at 50 % of the participants maximal upward push force, using their dominant right hand (Fig. 2). Maximal upward drill press force was determined for each collection session as the peak force across two, 5-s maximal attempts with the right arm in a posture of 90° elbow flexion and 90° thoracohumeral plane of elevation (see *Centre* target location below). Maximal upward force collected in this posture was used as the target force for all overhead targets. All force output was collected using an ErgoFET push-pull force gauge (Hoggan Scientific, Salt Lake City, UT, USA) attached to the drill tip. Participants were instructed to not use their left arm and hand to support themselves or assist with the task in any way (i.e., contribute to drill force output, hold nearby structure for support, etc.). They were also not afforded any familiarization, as to not promote the consolidation of any musculoskeletal strategies prior to beginning the task which could have altered the muscular and kinematic variability observed during the baseline trials [Raviv, Lupyan, & Green, 2022; Qin et al., 2014]. During the 32-s rest portion of the duty cycle, participants were instructed to immediately place the drill on a table located at waist height, directly in front of them, and allow their arm to hang at their side until the next working cycle began (Fig. 2). Target locations in the transverse plane

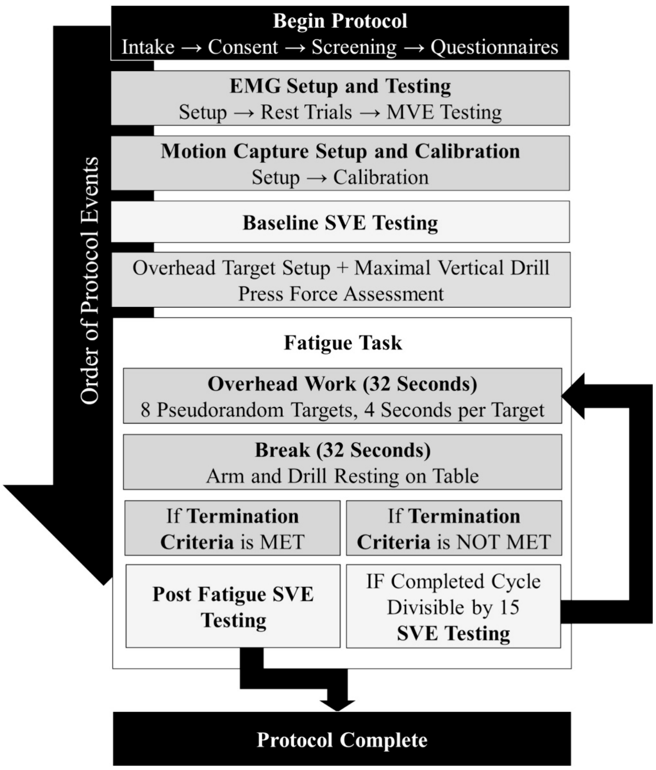

Fig. 1. Timeline of experimental protocol. Order of protocol events begins at "Begin Protocol" and proceeds down the flowchart. "Protocol Complete" is only reached when participants meet one of three protocol termination criteria.

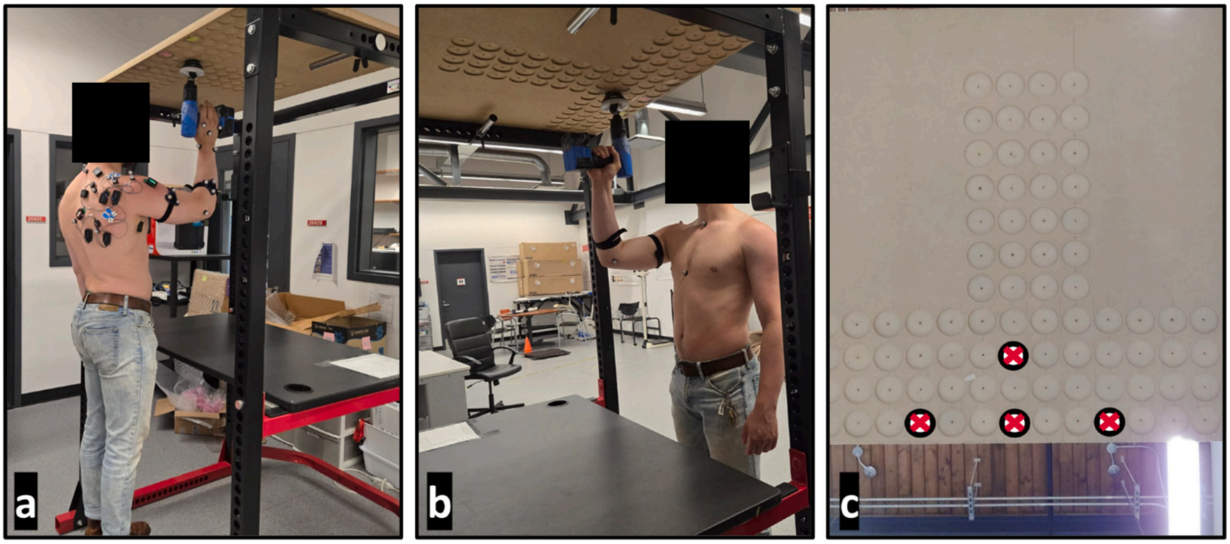

Fig. 2. Overhead drilling shoulder fatigue protocol target setup with kinematic markers and wireless electrodes; (a) posteriolateral view, (b) anteriolateral view, (c) overhead target configuration.

were set for each participant prior to beginning of the fatigue protocol using a goniometer to define all upper limb joint angles. Target locations were set to the following four positions which approximated the listed upper limb joints angles for each position below:

1. *Center* – 70 % distance from the greater trochanter to maximum overhead reach with 90° elbow flexion and 90° thoracohumeral plane of elevation.
2. *Far* – 70 % distance from the greater trochanter to maximum overhead reach with 45° elbow flexion and 90° thoracohumeral plane of elevation.
3. *Left* – shoulder plane of elevation increased to 125° from *center* position.
4. *Right* – shoulder plane of elevation reduced to 45° from *center* position.

Over the 32-s task cycle, each target was presented twice in a pseudorandom order, for 4 s each. Five 64-s overhead working cycles at a 50 % duty cycle constituted one set. The pseudorandom target order ensured that the otherwise random order of 8 targets per 64-s round of overhead work could not appear again within the same set.

Force and EMG were collected during two repetitions of isometric maximum voluntary exertion (MVE) tests which consisted of three 5-s trunk and upper limb muscle tests, completed in random order: empty can, external rotation, high flexion, [Boettcher, Ginn, & Cathers, 2008; Ginn, Halaki, & Cathers, 2011; McDonald, Sonne, & Keir, 2017]. MVE tests were selected from previously published

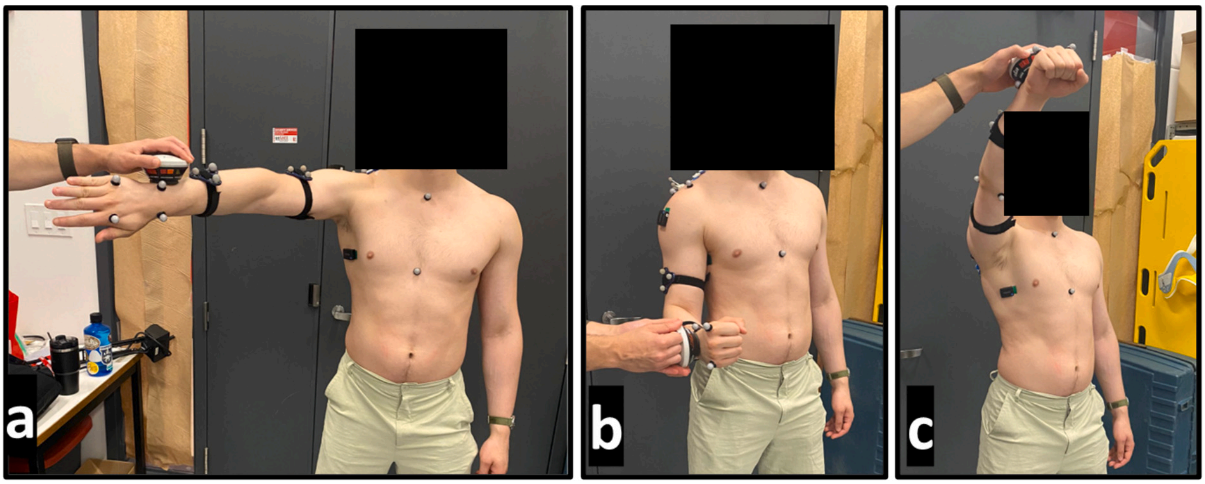

Fig. 3. Isometric muscle testing postures; (a) empty can, (b) external rotation, and (c) high flexion. For each test, isometric resistance is applied to the participant in the direction of the handheld force transducer.

guidelines on eliciting maximal muscle activity in the minimal number of muscle tests in effort to reduce testing time and participant effort/fatigue due to testing (Fig. 3). At baseline, after the completion of 15, 30, 45, and 60 cycles of overhead work, or at the point of protocol termination, EMG was collected during submaximal voluntary exertions (SVE) (Fig. 1). SVE tests were a single exertion of each MVE test scaled to 30 % of the peak MVE output determined at baseline. SVE tests were used to capture muscle EMG mean power-frequency (MPF) changes [McDonald et al., 2017]. All muscle testing was performed on the right side (dominant side). Protocol termination was defined when the participant met one of three completion criteria: 1) the participant reached RPE $\geq$ 9 and indicated they were unable to continue maintaining the 50 % maximal overhead force level, 2) they were unable to generate 50 % of their maximal overhead force in any of the target directions within the same cycle, 3) they completed 60 cycles (12 rounds) of the overhead drilling task and maintained a stable RPE that was not increasing.

Muscle activity was collected from seven muscles of the shoulder region of the right upper limb during MVE and SVE tests. Surface electromyography (sEMG) was used to record supraspinatus (SS), infraspinatus (IS), upper trapezius (UT), middle trapezius (MT), lower trapezius (LT), serratus anterior (SA), and middle deltoid (MD). In addition, two channels of intramuscular EMG (iEMG) were collected specifically from the supraspinatus (iSS) and infraspinatus (iIS). A Delsys Trigno system (Delsys Inc., 23 Strathmore Rd, Natick, MA, USA) was utilized to collect all EMG recordings. For sEMG recordings, Trigno Avanti sensors were placed on the muscle belly of interest, following established guidelines [Perotto, 2011; Stegeman & Hermens, 2007]. These sensors featured 10 mm spaced silver (99.99 %) bar electrodes aligned with the muscle fibers and recorded sEMG signals at a rate of 2148 Hz, within a bandwidth of 20–450 Hz. For intramuscular insertions, the insertion points were determined in accordance with established guidelines [Geiringer, 1999; Perotto, 2011]. Intramuscular insertions followed ultrasound guidance in addition to electromechanical confirmation from (1) muscle depolarization when the muscle is initially punctured, and (2) isolated muscle resistance testing after insertion to confirm correct placement with EMG feedback [Waite, Brookham, & Dickerson, 2010]. For each muscle, a 30 mm stainless surgical steel hypodermic needle housing two barbed 304 series stainless steel wires was used (0.051 mm diameter, 200 mm length, nylon coated) (Motion Lab Systems Inc., 15045 Old Hammond Way, Baton Rouge, LA, USA). iEMG sampled at 4370 Hz with a 10–2000 Hz pass band.

Kinematics were captured using a 7-MX40+ camera Vicon system (Vicon Motion Systems Ltd., 7388 S. Revere Pkwy, CO, USA) sampled at 100 Hz. 19 mm diameter reflective Vicon pearl markers were affixed to 14 bony landmarks of the trunk (7th cervical vertebrae, 8th thoracic vertebrae, suprasternal notch, xiphoid process), right scapula (trigonum spinae, inferior angle, acromion angle), right upper arm (acromion, lateral epicondyle, medial epicondyle), lower arm (radial styloid, ulnar styloid), and hand (based of the 2nd and 5th metacarpals), following the recommendations of the International Society of Biomechanics (ISB) (Fig. 4) [Wu et al., 2005]. Humeral and forearm tracking clusters were used, and a scapular tracking cluster was placed on the surface of the junction between the acromion and the scapular spine following the recommendations of Shaheen, Alexander, and Bull [2011]. This method previously displayed error measures within 5° for all scapulothoracic degrees of freedom with scapular calibration to anatomical scapular landmarks (trigonum spinae, inferior angle, acromion angle) performed at 90° thoracohumeral abduction for overhead postures.

2.3. Data analysis

The following EMG, kinematic, and kinetic data were processed using custom MATLAB software (MATLAB 2020a, Mathworks, Natick, MA).

2.3.1. Neuromuscular fatigue

To calculate EMG MPF and root-mean-squared (RMS) amplitude, EMG data was analyzed from each participant's pre-fatigue (baseline SVE) and post-fatigue (their last SVE, after reaching termination criteria) trials. For each muscle, MPF and RMS was analyzed for the SVE recommended for that particular muscle (empty can: SS; external rotation: IS; high flexion: UT, MT, LT, SA, and MD) [Boettcher et al., 2008; McDonald, Mulla, Stratford, & Keir, 2018].

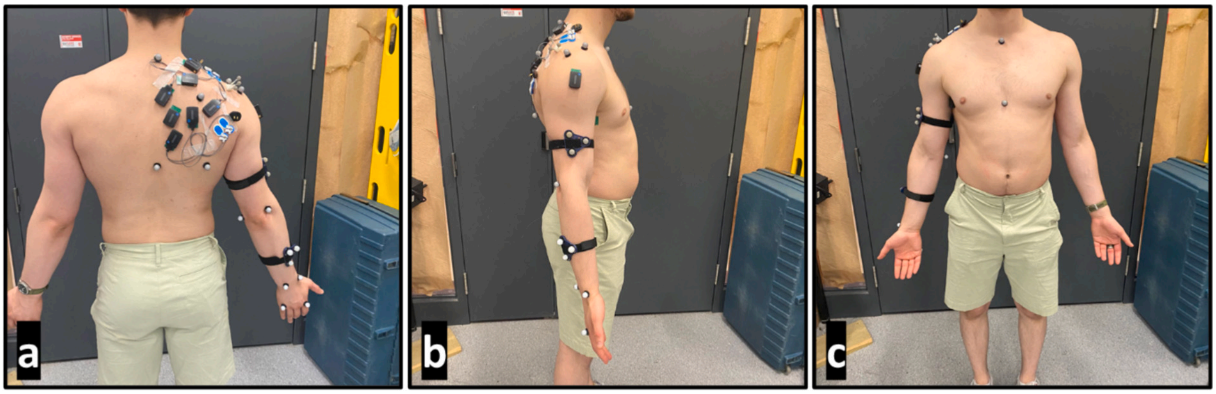

Fig. 4. (a) posterior, (b) lateral, and (c) anterior view of landmarking for motion capture.

2.3.1.1. Electromyographic mean power frequency. sEMG signals were dual-band-pass Butterworth filtered at 10–500 Hz, and iEMG signals were dual-band-pass Butterworth filtered at 20–1000 Hz [Stulen & De Luca, 1981; Öberg, Sandsjö, & Kadefors, 1990; Willigenburg, Daffertshofer, Kingma, & Van Dieën, 2012]. A discrete Fourier transform with a 0.5-s rectangular window was used to calculate MPF for the first 3-s of the 5-s SVE trial from which an overall mean was calculated [Hendrix et al., 2010]. The presence of muscle-specific fatigue was defined as a reduction in MPF ≥ 8 % [Öberg et al., 1990; Öberg, 1995].

2.3.1.2. Electromyographic root-mean-squared amplitude. sEMG signals were dual-band-pass Butterworth filtered at 30–500 Hz, and iEMG signals were dual-band-pass Butterworth filtered at 30–1000 Hz [Stulen & De Luca, 1981; Öberg et al., 1990; Drake & Callaghan, 2006; Willigenburg et al., 2012]. Peak amplitude was sampled from the middle 3-s of each 5-seond SVE waveform, and amplitude was normalized to MVE.

2.3.2. Upper limb kinematics

Upper limb joint angles were evaluated by comparing the scapulothoracic, thoracohumeral, elbow, and radiocarpal joints in both the pre-fatigue and post-fatigue state. Rather than analyzing upper limb kinematics during the SVE tasks, as was done with EMG processing, kinematic joint angle comparisons were performed for each of the four overhead targets (close, far, right, left). Pre-fatigue kinematic data was captured as participants approximated each of the four overhead targets during the fifth cycle of the fatigue protocol (approximately 5 min of overhead work). This process allowed for four work cycles of task familiarization. Post-fatigue kinematic data was captured from the final cycle of the fatigue protocol that was successfully completed (such that the target force output was achieved for all targets) before the protocol concluded. To calculate each joint angle, three-dimensional local coordinate systems (LCS) were established for the thorax, scapula, humerus, forearm, and hand [Wu et al., 2005]. LCS were also defined for each of the rigid clusters and the scapula tracking cluster. Relative rotation matrices were generated to describe the relationships between these clusters and anatomical markers. The Euler angles for the scapulothoracic, thoracohumeral, elbow, and radiocarpal joint angles were computed based on reconstructed virtual landmarks, following the recommended joint angle decomposition sequences suggested by Wu et al. [2005].

2.3.3. Shoulder joint moments

Static shoulder flexion moment exposures were calculated for the pre-fatigue and post-fatigue kinematic postures using a static inverse dynamics model. The model consisted of three body segments: hand, forearm, and upper arm. Joint center and segment center of mass (COM) locations were defined using the published guidelines by Dempster [1955] using kinematic anatomical marker positions as model input. Segment masses were calculated as percentages of total body mass, as defined in the regression equations by Churchill [1978]. Gravitational external forces were considered to be acting on the body segments at their center of mass. Static resistance to the upward force application of the drill was localized to be acting on the palm of the hand at the hand segment COM. Resultant shoulder joint moment was calculated from the vertical component of all loads (segment mass, drill mass, vertical drill press reaction force), multiplied by the horizontal moment arm from the shoulder, and reported in newton meters (Nm).

2.4. Statistical analysis

Statistical comparisons were evaluated between day 1 and day 2 electromyography, kinematic, and kinetic data. Outliers two standard deviations above or below the mean were first removed from the raw EMG, kinematic, and kinetic data. Keeping with the repeated measures design, if a data point was removed, any associated pairwise scores was removed as well [Miller, 1991].

Paired two-tailed *t* -tests were used to evaluate differences between day 1 and day 2 group-average baseline (pre-fatigue) measures for the following outcomes: (1) scapulothoracic (anterior/posterior tilt, upward rotation/downward rotation, internal/external rotation), thoracohumeral (plane of elevation, elevation, axial rotation), elbow (flexion/extension, axial rotation, carrying angle), and wrist (flexion/extension, ulnar/radial deviation, pronation/supination) joint angles for each target (close, far, left right) and grouped, and (2) shoulder joint moment for target grouped data.

Paired two-tailed *t*-tests were also used to evaluate differences in fatigue-related responses ($\Delta =$ post-fatigue – pre-fatigue) for (1) group-average percent muscle-specific MPF and RMS, (2) scapulothoracic, thoracohumeral, elbow, and wrist joint angles, and (3) shoulder moments between day 1 and day 2. Šídák correction was applied to adjust α values for multiple comparisons. Shapiro-Wilk tests assessed for normality and Wilcoxon signed-rank tests were used for non-parametric cases.

Changes in group kinematic and kinetic variability were compared between day 1 and day 2 using scores of median absolute deviation (MdAD) (Eq. 1).

$$MdAD = \text{median}[|X_i - \text{median}(X)|] \quad (1)$$

where, X_i represents each individual data point in the dataset, *median (X)* is the median of the dataset, and $|\cdot|$ denotes the absolute value.

MdAD is expressed as the median of absolute deviations of all data points from the median of the dataset, and is a more robust metric of variability when dealing with outliers compared to standard deviation (Eq. 1) [Chau, Young, & Redekop, 2005; Qin et al., 2014]. For the purpose of our analysis, MdAD was calculated from the between-participant measures of the 3-axis scapulothoracic, thoracohumeral, elbow, and wrist joints Euler angles, as well as for static shoulder joint flexion moment, and compared across day 1 and day 2. Thus, for each degree of freedom, as well as for the static shoulder joint flexion moment dataset, the median of participant deviations from the median of that dataset was reported as the MdAD, by day. MdAD was calculated at the pre-fatigue and post-fatigue kinematic/kinetic time profiles described in section 2.3.2., as well as a "mid-fatigue" timepoint. "Mid-fatigue" data was defined as the kinematic/kinetic strategy performed during the last 32-s working cycle within the 5-cycle round of overhead work performed approximately halfway through each participant's number of rounds to volitional fatigue ([total number of rounds to fatigue]/2), rounded up to the nearest multiple of 5. Since we analyzed kinematics from the last work cycle of each 5-cycle set, the lower limit of participants cycles to fatigue limited us to only be able to sample 3 kinematic trials from each participant. Hence, we analyzed MdAD for all participants at pre-fatigue, mid-fatigue, and post-fatigue. Kinematic target data was grouped by target to constrain the number of values presented; kinetic target data was not grouped. Increases in MdAD score represent an increase in variability. Since a single MdAD value constitutes the between-participant variability for a single variable, these values could not be tested statistically. Thus, MdAD values are reported observationally only.

Statistical analyses were performed using the Statistical Package for the Social Sciences (SPSS), version 28.0 (IBM Corp. Armonk, NY, USA), and Stata/IC 18.0 (StataCorp LP, College Station, TX).

3. Results

3.1. Baseline differences across days

The average of peak drill press forces recorded on day 1 was 178.7 N (± 65.1) and 188.6 N (± 65.0) on day 2, and participants increased their drill press force by 10.6 % on day 2, on average. With target data grouped, thoracohumeral elevation ($t_{80} = -2.79$, $p < 0.01$), elbow flexion ($t_{99} = -6.63$, $p < 0.001$), and wrist deviation ($t_{76} = -3.00$, $p < 0.01$) joint angles were significantly different across days. From day 1 baseline to day 2 baseline, thoracohumeral elevation increased by 5.0° (61.5° ± 13.2 to 66.5° ± 7.3), elbow flexion increased 8.6° (100.1° ± 12.7 to 108.7° ± 12.5), and wrist ulnar deviation decreased 5.9° (10.7° ± 13.7 to 4.8° ± 13.8) on day 2. No difference was found between pre-fatigue shoulder joint moment exposures between day 1 (37.7 Nm ± 10.4) and day 2 (36.0 Nm ± 12.7) ($t_{46} = 0.548$, $p = 0.707$).

3.2. Fatigue-related differences across days

3.2.1. Subjective volitional fatigue criteria

Subjective volitional fatigue (termination criteria 1) was achieved in 60 % females on day 1, and 67 % of females on day 2, and 53 % of males on day 1 and 47 % of males on day 2 (Table 1). Four participants who reached fatigue task completion due to volitions fatigue on day 1 reached fatigued task failure due to force insufficiency on day 2, and four other participants who reached fatigue task completion due to force insufficiency on day 1 reached fatigue task failure due to volitional fatigue on day 2.

3.2.2. Neuromuscular fatigue

Group mean EMG ΔMPF (post-fatigue – pre-fatigue) across all 7 recorded muscles (9 channels) ranged between a 12 % increase and a 5 % decrease on day 1, and a 6 % increase and a 5 % decrease on day 2 while group mean EMG ΔRMS (post-fatigue – pre-fatigue) ranged between a 31 % increase and a 4 % decrease on day 1, and a 19 % increase and a 4 % decrease on day 2. The only muscles that displayed a decrease in average MPF on both days were supraspinatus (intramuscular) (decreased by 5 % on both days), and infraspinatus (surface) (decreased by 2 % on day 1 and 1 % on day 2), while only infraspinatus (intramuscular) showed a decrease in RMS on either day (decreased by 4 % on both days). No difference in EMG ΔMPF between day 1 and day 2 was significant (Fig. 5a), however a significant 21.0 %MVE decrease in EMG ΔRMS was observed in serratus anterior ($t_{(27)} = 2.38$, $p = 0.026$) (Fig. 5b). 0–3 outliers were removed for all EMG channels, except for iIS which had 10 outliers removed. Removal of outliers did not change any channels average ΔMPF by more than 4.2 Hz (4.7 %); 0.37 Hz on average (0.39 %). Average ΔRMS did not change by more than 6.6 % MVC across channels; 1.2 % on average.

3.2.3. Joint angle kinematics

A significantly larger reduction in thoracohumeral elevation ($t_{(88)} = -3.55$, $p = 0.0003$; Fig. 6) and elbow flexion ($t_{(88)} = -4.43$, $p < 0.0001$; Fig. 7) was demonstrated on day 1 compared to day 2. With target data grouped, thoracohumeral elevation fatigue-related change decreased by 5.7° ± 12.8 on day 1 and increased by 0.4° ± 14.9 with fatigue on day 2 (Table 2). When separated by target, thoracohumeral elevation showed a significant decrease in fatigue-related joint angle changes between day 1 and day 2 at the *far* ($t_{(21)}$

Table 1
Sex distribution of protocol termination criteria on day 1 and day 2.*

Day	*1*			*2*		
Termination Criteria	*RPE[1]*	*Force[2]*	*Max[3]*	*RPE[1]*	*Force[2]*	*Max[3]*
Males	8	7	0	7	8	0
Females	9	5	1	10	4	1

* *Termination criteria as follows:* 1) participant reached RPE ≥ 9 and indicated they were unable to continue maintain force level, 2) participant unable to generate 50 % of their maximal overhead force in any of the target directions within the same cycle, 3) participant completed 60 cycles (12 rounds) of the overhead drilling task and maintained a stable RPE.

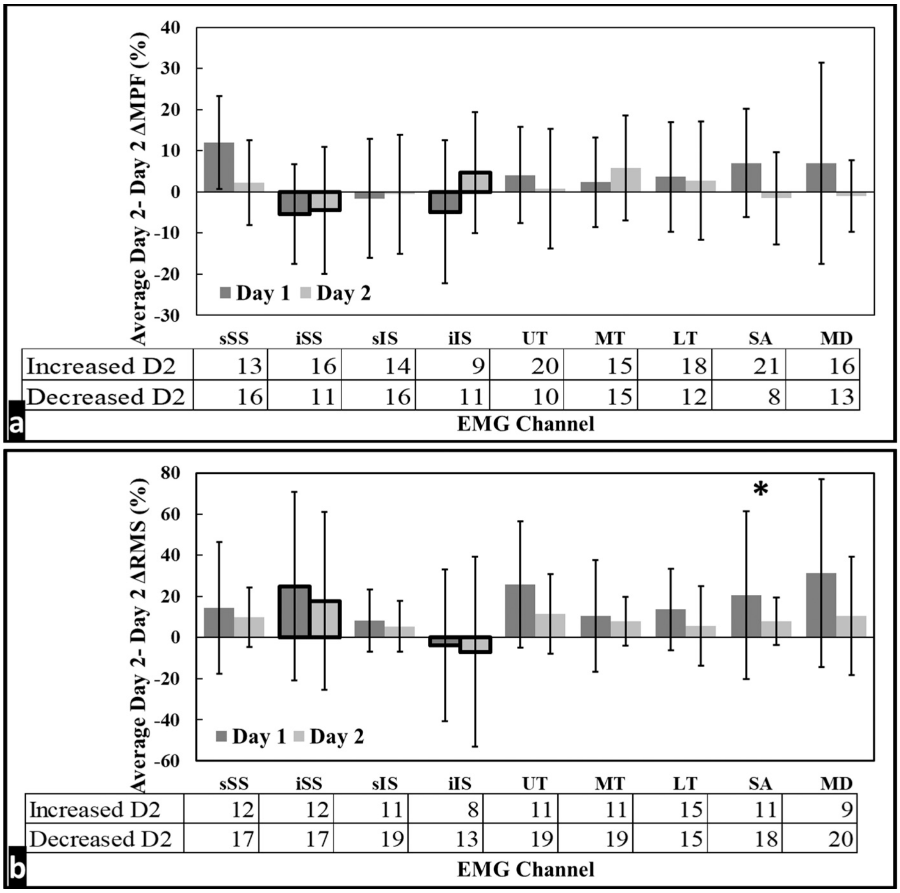

Fig. 5. Average difference between fatigue-induced (a) MPF and (b) RMS change on day 1 and day 2 (D2) [a: day 2 ΔMPF – day 1 ΔMPF, b: day 2 ΔRMS – day 1 ΔRMS]. The number of participants that displayed increased ΔMPF/RMS and decreased ΔMPF/RMS are indicated below each respective EMG channel. The sum of the number of participants that increase and decrease for each channel constitutes the study sample size ($n = 30$) minus any removed outliers. Muscles monitored with both surface and intramuscular EMG are identified with lowercase "s" and "i", and intramuscular channels are outlined in black. "*" denotes $p \leq 0.05$. Error bars represent 1 standard deviation.

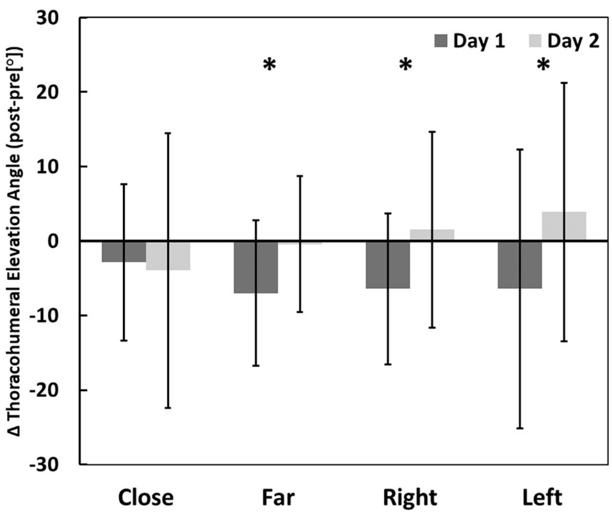

Fig. 6. Fatigue-induced changes in thoracohumeral elevation ($\Delta^{\circ}\beta_h$) for day 1 and day 2. * Indicates significance ($p < 0.05$). Error bars represent 1 standard deviation.

= −2.20, $p = 0.019$), *right* ($t_{(22)} = -2.51$, $p = 0.010$), and *left* ($t_{(22)} = -2.20$, p = 0.019) targets by 6.5°, 7.9°, and 10.3°, respectively (Fig. 6; Table 2). Elbow flexion across all targets showed an increase of 6.9° ± 13.1 from pre-fatigue to post-fatigue on day 1, and an increase of 1.7° ± 7.8 from pre-fatigue to post-fatigue on day 2 (Table 2). When separated by target, this decrease in fatigue-induced elbow flexion for day 1 relative to day 2 was evident for the *far* ($t_{(25)} = -3.46$, $p = 0.001$) and *right* ($t_{(21)} = -2.88$, p 0.005) targets, by 8.6° and 6.2°, respectively (Fig. 7; Table 2).

3.2.4. Shoulder joint moment

Shoulder joint flexion moments were largest at the *far* target for day 1 (pre-fatigue: 40.3 Nm ± 11.6, post-fatigue: 37.3 Nm ± 12.8) and day 2 (pre-fatigue: 39.3 Nm ± 14.6, post-fatigue: 37.2 Nm ± 13.0), and smallest at the *close* target for day 1 (pre-fatigue: 36.1 Nm ± 10.4, post-fatigue: 33.1 Nm ± 12.8) and day 2 (pre-fatigue: 33.8 Nm ± 12.1, post-fatigue: 33.1 Nm ± 12.2). The change in static shoulder flexion moment (ΔNm) from pre-fatigue to post-fatigue (grouped by target) revealed a significant reduction from day 1 (−3.2 ΔNm ± 6.4) to day 2 (−0.8 ΔNm ± 6.5) ($t_{(95)} = 02.51$, $p = 0.0068$) (Fig. 8; Table 3). When separated by target, only the *left* target showed a significant reduction in fatigued-induced static shoulder flexion moment from −3.70 ΔNm (± 5.20) on day 1 to −0.24 ΔNm (± 6.54) on day 2 ($t_{(23)} = -2.05$, $p = 0.026$) (Fig. 8; Table 3).

3.3. Changes in kinematic and kinetic variability between days

Average groupwise MdAD ranged from 12.8 to 41.3 on day 1 and 12.6 to 29.7 on day 2 at the scapulothoracic joint, 5.7 to 21.5 on day 1 and 4.5 to 16.6 on day 2 at the thoracohumeral joint, 3.4 to 24.2 on day 1 and 5.7 to 27.0 on day 2 at the elbow joint, and 4.9 to 9.9 on day 1 and 6.7 to 13.5 on day 2 at the wrist joint (Fig. 9). Groupwise static shoulder joint flexion moment MdAD was largest at the *far* target on day 1 (10.0) and day 2 (11.2), second largest at the *left* target on day 1 (9.6) and day 2 (8.3). The *right* target had the least variability on day 1 (8.0), but not on day (8.1), whereas the *close* target had the second least variability on day 1 (9.1) and the least variability on day 2 (7.8).

4. Discussion

4.1. Summary

This study sought to assess day-to-day muscle fatigue patterns and kinematic adaptations to an occupationally relevant overhead work task design to fatigue shoulder musculature. Specifically, musculoskeletal variability between days was assessed across three aspects: (1) between unfatigued, baseline postural states, (2) across fatigue-related changes from baseline, and (3) with respect to quantifying changes in fatigue-related kinematic and kinetic variability. While shoulder elevation, elbow flexion, and wrist deviation static joint angles were different at baseline on day 2 compared to baseline day 1, we found no significant changes in baseline static shoulder flexion moment exposures between day 1 and day 2 (Table 4). Thus, we partially accept our hypothesis as baseline joint angles, but not shoulder joint flexion moments, were different between days. Next, contrasting to our hypothesis, ΔMPF was highly variable and not significantly different between days, yet serratus anterior ΔRMS showed a significant reduction on day 2 (Table 4). Lastly, we hypothesized that on day 2, both upper limb joint angles and static shoulder flexion moments would deviate from baseline less on day 2; thereby displaying reduced variability. Thoracohumeral elevation and elbow flexion kinematics did deviate less from baseline on day 2, as did static shoulder flexion moment. We also expected a reduction in fatigue-related joint angle variability and

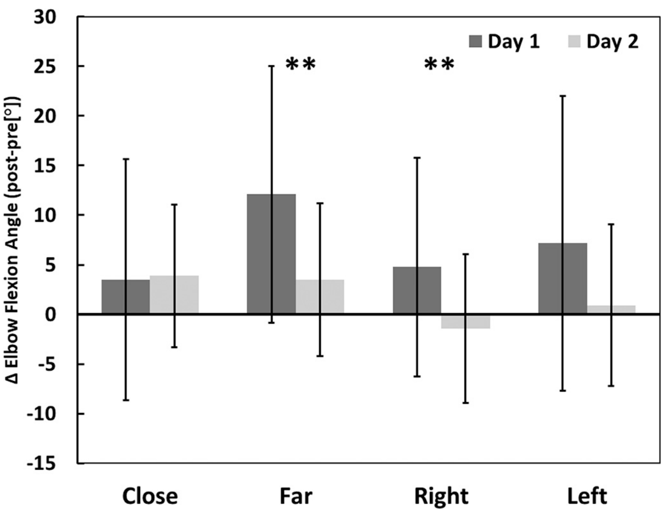

Fig. 7. Fatigue-induced changes in elbow flexion ($\Delta°\alpha_{hf}$) for day 1 and day 2. ** Indicates significance ($p < 0.01$). Error bars represent 1 standard deviation.

Table 2
Mean difference (standard deviation) and *p*-value (p) values for all fatigue-related kinematic joint angle degrees of freedom changes when compared across days. Values represent Šídák corrected significance values. Shaded rows indicate Wilcoxon signed-rank test results for non-parametric distributions, all other rows are paired *t*-test results.

Joint	*Degree of Freedom*	*Target*				
		Overall	*Close*	*Far*	*Right*	*Left*
Scapulothoracic	Anterior/Posterior Tilt	−10.3 (26.3) 0.918	−11.4 (25.2) 0.787	−18.8 (31.9) 0.790	3.4 (20.7) 0.382	−13.6 (26.0) 0.947
	Upward/Downward Rotation	−4.1 (26.2) 0.874	−6.8 (29.0) 0.716	0.4 (17.6) 0.456	−3.9 (32.9) 0.720	−5.8 (21.8) 0.821
	Protraction/Retraction	−2.7 (26.0) 0.998	−4.4 (28.5) 0.956	−0.20 (24.5) 0.981	1.8 (29.3)0.287	−7.9 (26.9)0.982
Thoracohumeral	Plane of Elevation (POE)	−10.2 (22.7) 0.997	−14.7 (23.3) 0.993	−7.7 (23.16) 0.959	−8.3 (22.1)0.933	−9.9 (22.9)0.974
	Elevation	**6.1** **(14.1)** **0.0003**	−1.1 (14.4) 0.452	**6.5** **(9.9)** **0.019**	**7.9** **(12.2)** **0.010**	**10.3** **(18.6)** **0.019**
	Axial Rotation	−0.3 (13.7) 0.38	−1.1 (12.1) 0.585	−3.1 (12.9) 0.711	0.4 (11.2)0.328	2.5 (17.2) 0.220
Elbow	Flexion/Extension	**5.2** **(11.2)** **< 0.001**	−0.4 (10.1) 0.336	**8.6** **(11.5)** **< 0.001**	**6.2** **(10.0)0.005**	6.3 (12.5) 0.054
	Carrying Angle	0.7 (9.8) 0.315	−1.4 (10.8) 0.706	1.4 (8.6) 0.215	0.9 (10.5)0.372	1.7 (9.1) 0.281
	Pronation/Supination	0.2 (17.9) 0.705	−4.9 (15.1) 0.915	11.6 (24.7) 0.078	−2.7 (13.4) 0.586	−4.7 (13.5) 0.953
Wrist	Flexion/Extension	−3.1 (10.5) 0.949	−4.4 (11.1)− 0.942	1.5 (9.2) 0.206	−5.5 (10.2)0.958	−3.9 (11.6) 0.905
	Radial/Ulnar Deviation	−1.2 (7.6) 0.805	−3.1 (10.1) 0.789	2.5 (9.3) 0.562	−0.6 (8.9) 0.515	−1.9 (7.5) 0.827
	Pronation/Supination	−0.8 (9.2) 0.388	−0.3 (7.3) 0.304	−1.9 (7.9) 0.489	−1.9 (7.1) 0.695	−0.8 (8.1) 0.33

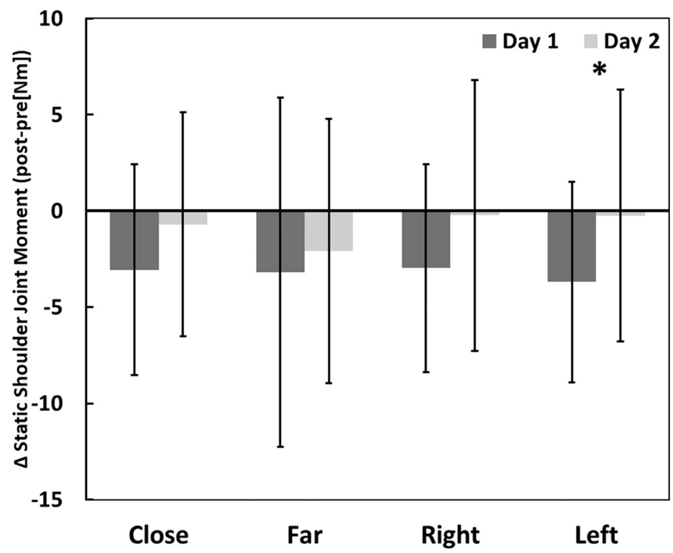

Fig. 8. Fatigue-induced changes in static shoulder flexion moment (ΔNm) for day 1 and day 2. * Indicates significance ($p < 0.05$). Error bars represent 1 standard deviation.

Table 3
Paired t-test mean difference (standard deviation) and significance (p) values for shoulder joint flexion moment at each overhead target, compared across days. Values represent Šídák corrected significance values.

Target	*Overall*	*Close*	*Far*	*Right*	*Left*
Significance (p =)	**2.3 (12.7) 0.007**	2.3 (12.1) 0.086	1.0 (14.6) 0.334	2.7 (11.7) 0.066	**3.4 (12.4) 0.026**

shoulder flexion moment variability on day 2. Yet, while scapulothoracic and thoracohumeral joint kinematics demonstrated reduced variability with fatigue (MdAD) from day 1 to day 2, elbow and wrist variability tended to increase between days (Table 4). Day-to-day trends in static shoulder joint flexion moment variability increased at the *far* and *right* targets but decreased at the *close* and *left* targets.

4.2. Differences in baseline kinematic and kinetic between days

Baseline upper limb kinematics and kinetics, recorded prior to completing the overhead drilling task to fatigue, were compared between the two testing sessions completed one week apart. Differences in baseline upper limb joint angles between sessions suggested that the experience of performing the specific overhead task until fatigue during the first visit may have promoted upper limb kinematic adaptations [Monjo et al., 2015; Hirashima & Oya, 2016]. In conjunction with past research investigating the modulation of anticipatory postural adjustments under dynamic and changing conditions, these findings may contribute to the narrative that the postural system can anticipate biomechanical conditions, and update from experience [Desmurget & Grafton, 2000]. While many previous works have demonstrated the ability of the nervous system to adapt its postural responses due to immediate changes in temporal constraints [Desmurget & Grafton, 2000; Aruin, 2006] and changes in perturbation magnitude or direction [Bouisset, Richardson, & Zattara, 2000], the current study may also infer that learned postural adjustments can be maintained up to 7 days later.

Interestingly, all significant baseline kinematic changes between days were related to the joint axis most associated with end effector placement in the sagittal plane, and no kinematic changes were observed that would alter the hand position mediolaterally. An increase in thoracohumeral elevation, in particular, was unexpected, as raising the arm would act to increase the upper arm moment and the task effort [Slobounov, Hallet, & Newell, 2004] and evidence that increased arm posture is associated with increase perceived effort (relative perceived discomfort scale), although the same study found no changes in EMG measures of fatigue (including MPF) with arm height [Sood, Nussbaum, & Hager, 2007]. Interestingly, the increase in baseline thoracohumeral elevation was not associated with a change in baseline shoulder joint flexion moments between day 1 (37.7 Nm) and day 2 (36.0 Nm). It is likely that the expected increase in shoulder flexion moment due to thoracohumeral elevation was offset by postural reorganization at other joints in effort to not raise the total shoulder joint flexion moment. Indeed, elbow flexion and wrist deviation both displayed changes at baseline on day 2 that would reduce the shoulder moment, with an 8.6° increase in baseline elbow flexion, and a 5.9° decrease in baseline ulnar wrist deviation. Overhead working tasks are also expected to interpose the tissues of the subacromial space and promote rapid fatigue and discomfort which would be relieved with lowering of the humerus [Bey et al., 2007; Graichen, Bonel, Stammberger, Reiser, & Eckstein, 2001; Nakajima, Rokuuma, Hamada, Tomatsu, & Fukuda, 1994; Lewis, Green, & Wright, 2005; Grieve & Dickerson, 2008]. However, it may be that the demands of the current work task, specifically the fixed overhead orientation of the drilling targets, may have been too incompliant as to allow significant lowering of the humerus to relieve subacromial tissue stress, thus necessitating an alternative strategy.

4.3. Fatigue-related changes between days

Fatigue-induced joint kinematic changes from the overhead drilling task were smaller for the second session compared to the first. These day-to-day changes in thoracohumeral elevation and elbow flexion could be motivated by a learning effect on day 2, as day 2 elbow flexion started closer to it's day 1 post-fatigue position [Monjo et al., 2015; Hirashima & Oya, 2016]. Yet the hypothesis that day 2 kinematics converged towards a similar strategy demonstrated at post-fatigue on day 1 seems unsupported by the day-to-day changes in thoracohumeral elevation which started 5° lower at baseline on day 1 and proceeded to lower by 5.7° with fatigue, yet day 2 presented with an elevated baseline posture that changed minimally by 0.4° with fatigue. Conversely, the reduction in fatigue-induced changes in shoulder and elbow angles across successive days of the fatiguing exposure may suggest a convergence across participants from their individually diverse motor strategies on day 1, towards a more common, learned motor strategy on day 2 that may not necessarily consolidate fatigue-related postural changes featured during day 1 [Scholz & Schöner, 1999; Magill & Anderson, 2010].

The relatively small changes in shoulder and elbow joint angles on day 2 may indicate that changes in baseline kinematics were mechanically advantageous, however time to fatigue, between-day changes in ΔMPF (Fig. 5a), and baseline shoulder joint flexion moments showed no significant changes. The only results that reflect a potential improvement in muscular and kinematic strategy is the reduction in serratus anterior ΔRMS on day 2 (Fig. 5b), and the 10 % increase in maximal drill press force on day 2. While limited literature exists on day-to-day kinematic and muscle activity changes during fatiguing manual tasks, one study [Ebata, 2012], previously investigated upper limb kinematic changes on successive attempts of an overhead drilling task and similarly showed that the humerus was 5° more elevated on the second day attempting the drilling task. Together with this study, these similar findings suggest that modest humeral elevation may permit a more efficient total arm strategy during overhead work. One potential motivation for elevating the thoracohumeral angle on day 2 posture may be to improve elbow flexor muscle length for elbow force production, which

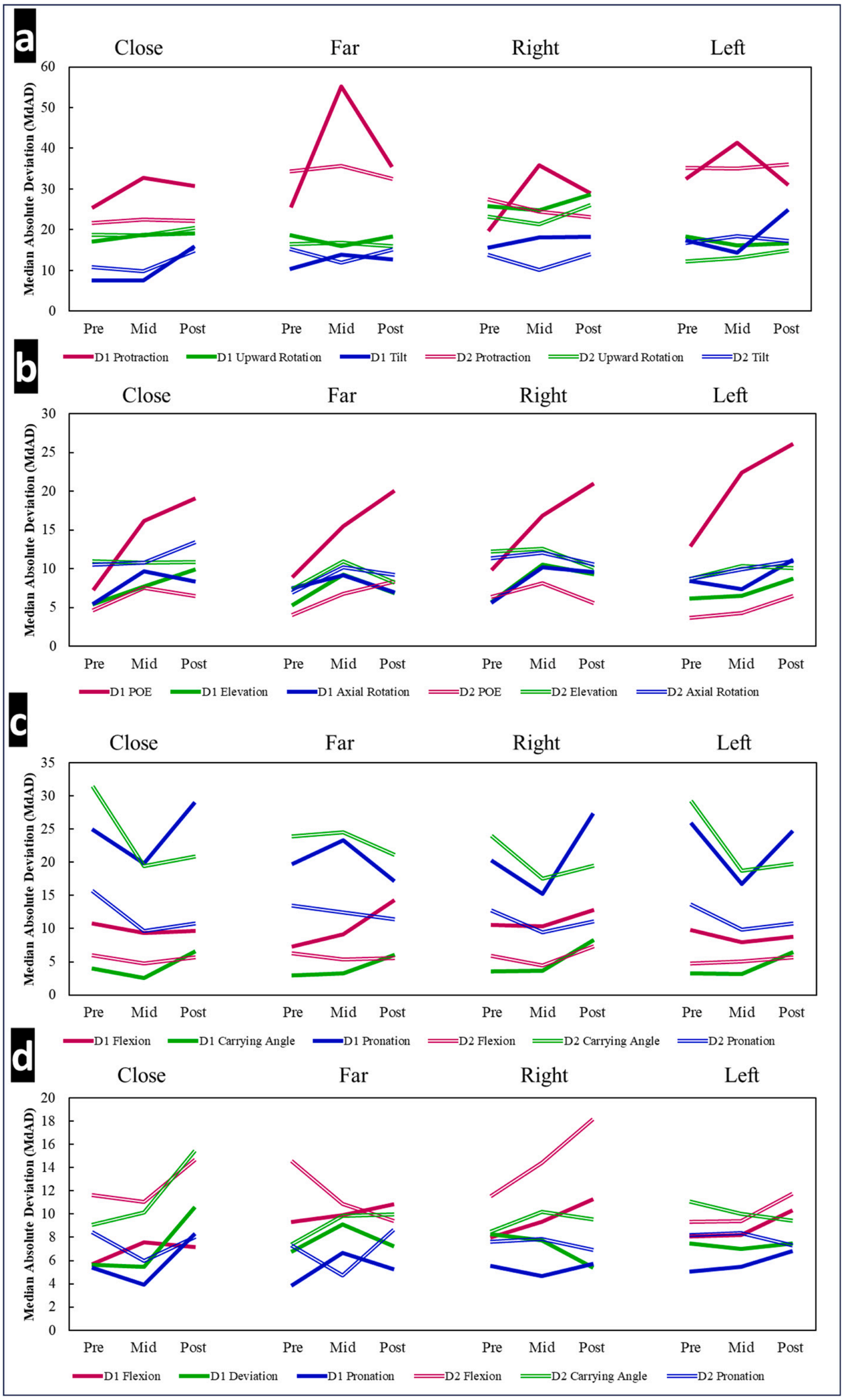

Fig. 9. MdAD values for the (a) scapulothoracic, (b) thoracohumeral, (c) elbow, and (d) wrist joints on day 1 and 2.

appears to be most optimally recruited at 70°-75° of humeral elevation [Moon et al., 2013; Langenderfer, LaScalza, Mell, & Carpenter., J. E., Kuhn, J. E., Hughes, R. E., 2005]. Coincidentally, overhead drilling has been previously identified as a particularly demanding task for the biceps brachii, demonstrating high myoelectric activity in overhead drilling postures that require extension of the elbow

Table 4

Summary of baseline and fatigue-related day-to-day changes observed following repeat exposure to an overhead work task completed until fatigue. Greyed regions indicate regions that were not examined.

		Baseline Changes	Day-to-day fatigue-related changes
EMG	*MPF*		• No significant differences
	RMS		• 21 % decrease in serratus anterior normalized amplitude
Upper Limb Kinematics	*Group-Mean Changes*	• 5.0° increase in thoracohumeral elevation • 8.6° increase in elbow flexion • 5.9° decrease in ulnar deviation	• Thoracohumeral elevation increased 93 % less due to fatigue on day 2. • Elbow flexion increased 75 % less due to fatigue on day 2 .
	Variability		• Decreases in scapulothoracic and thoracohumeral variability • Increases in elbow and wrist variability
Static Shoulder Joint Flexion Moment	*Group-Mean Changes*	• No significant differences	• Static shoulder flexion moment exposure decreased 75 % less due to fatigue on day 2
	Variability		• Variability changes between days were target-dependent

[Anton et al., 2001]. Thoracohumeral elevation may also improve load sharing between the deltoid and rotator cuff muscles, while negligibly impacting the deltoid muscle force-length relationship [Bechtol, 1980; Breteler, Spoor, & Van der Helm, 1999].

Shoulder joint flexion moments may have also been a driving factor of upper limb postural adaptations on day 2 as, similar to kinematics, fatigue-related changes in shoulder flexion moments deviated less from baseline on day 2. Specifically, within day fatigue-related changes in shoulder flexion moment were larger on day 1 (−3.2ΔNm compared to day 2 (−0.8 ΔNm). The small decrease in baseline shoulder joint flexion moment from day 1 (37.7 Nm) to day 2 (36.0 Nm) together with the marginal increase in pre-fatigue to post-fatigue shoulder flexion moment on day 2 results in a post-fatigue shoulder joint demand that was similar between day 1 (34.5 Nm) and day 2 (35.2 Nm). This could indicate that a more efficient kinetic strategy was unable to be found on day 2. Qin et al. [2014] previously studied upper limb joint angle and joint torque changes between the first and last session of a light, below chest height, assembly work task performed by both younger and older participants and reported that shoulder, elbow, and wrist joint moments reduced due to task related fatigue. This further suggests that the reduction of shoulder joint moments is a criterion driving upper limb postural adaptations, yet further work is needed to understand how postural adaptations of manual work may differ when completed on subsequent days.

The proportion of individuals who displayed increased ΔMPF on day 2 compared to day 1 in the current study ranged between 26 and 54 % across muscles, and those displaying increased ΔRMS on day 2 compared to day 2 ranged from 50 to 70 % across muscles, suggesting that muscle fatigue accumulation during overhead tasks is variable within individuals. These findings of considerable intra-participant and inter-participant variability in neuromuscular fatigue responses are supported by Mulla et al. [2018], and they have been suggested to arise from many degrees of freedom and musculoskeletal redundancy of multiple muscles at the shoulder [Madeleine, 2010; Hirashima & Oya, 2016]. Findings from past research similarly suggest that muscle fatigue during overhead tasks is highly variable between individuals [Ebata, 2012; McDonald et al., 2019]. Such considerable variability both between and within individual neuromuscular fatigue responses may make group-wise differences more difficult to detect with statistical tests. Further research investigating global shoulder fatigue tasks (e.g. those which are not designed to isolate fatigue accumulation on a discrete set of muscles), should consider using multiple indicators of fatigue (MPF, RMS, COV), or utilize the shoulder-specific multi-muscle fatigue score [McDonald et al., 2018] to more confidently evaluate the presence of fatigue.

4.4. Kinematic and kinetic variability changes between days

Comparisons of fatigue-related variability between days suggest that changes in fatigue-related kinematic variability on day 2 appeared joint dependent, with the scapulothoracic and thoracohumeral joints displaying decreased variability, and the elbow and wrist displaying increased variability. Scapulothoracic, thoracohumeral, and elbow joints prominently featured one degree of freedom with the most variability on day 1; those being scapulothoracic protraction, thoracohumeral POE, and elbow pronation. These same upper limb degrees of freedom showed substantial reductions in variability on day 2, with a reduced MdAD within the range of the other degrees of freedom. Interestingly, these upper limb degrees of freedom do not adjust for end effector position in the sagittal plane. While day-to-day changes in these joint angles did not reach significance, the substantial change in variability could suggest that these particular degrees of freedom of the upper limb have the most redundant kinematic solutions to this specific task. Yet on day 2 participants still converge on less variable postures despite the higher variability on day 1, suggesting that other joint angle configurations and muscle synergies exist which should achieve the same task performance [Scholz & Schöner, 1999]. This suggests that some system variable aside from target accuracy and force output would have constrained the variability observed at these degrees of freedom. Reductions in muscular and kinematic redundancy in humans are posited to arise from an optimization function that reduces the motor effort [Hirashima & Oya, 2016], which aligns with the observed reductions in shoulder flexion moments observed on day 2. Interestingly the same pattern did not emerge for the wrist joint, as there was no prominent degree of freedom with heightened variability on day 1. This could suggest that, unlike the other joints of the upper limb, task performance (e.g. 50 % upward force production) was the most sensitive to wrist kinematics and permitted the least variation. Another way to explain this finding is that the muscular or kinematic strategies available to the wrist which satisfied the task requirements of the drilling task may have featured much less redundancy than the other upper limb degrees of freedom, thereby constraining the observed kinematic variability at the wrist joint. While shoulder and scapular kinematic adaptations to fatigue have been reported to be highly variable [Chopp-Hurley et al., 2016; Mulla et al., 2018], the current study suggests that individual adaptations to fatigue may ultimately elicit lower group variability, expressed by MdAD on a repeated session of fatiguing shoulder work.

Both the effects of fatigue and day-to-day changes appeared to have differing effects on kinetic variability which appeared to be dependent on the overhead target position, making it difficult to draw inferences (Fig. 10). However, it is interesting to note that for all targets, kinetic variability peaked at the "mid-fatigue" time point on both days. Further, most targets showed a convergence in kinetic variability at "post-fatigue" on each day. The only instance where this was not observed was in the *right* target, where variability continued to rise after "mid-fatigue" on day 2 but dropped off at "mid-fatigue" on day 1. One possible speculation is that participants may have experienced less fatigue at the *right* target compared to the other targets on day 2, thus variability did not yet begin to drop but conceivably would have lowered if they have been able to continue the task.

4.5. Limitations

Certain limitations of this research should be considered. The fatigue protocol was completed in an average time of 29.3 (range: 16 to 64) minutes on day 1 and 29.5 (range: 10.7 to 64) minutes on day 2, therefore the findings of this study may not reflect that of an 8-h workday. Due to the high degree of variability inherent with shoulder postural control, sex-based analysis would be underpowered with a sample of 29 participants. Results from this study are generalized across males and females, however sex-specific results should be investigated further. The current study also only considered joint postures distal to, and including, the scapulothoracic joint. Future analyses may reveal more complex kinematic compensations to overhead task fatigue by employing a multivariate model that considers interactions between upper limb, trunk, and lower limb postural changes. Regarding the measurement of EMG data, rotator cuff muscle activity was recorded using both intramuscular (iEMG) and surface (sEMG) methods, in an attempt to characterize signal activity changes which may differ across recording methods due to limitations with the respective signal sensitivity and specificity [Merletti & Farina, 2009; Rainoldi et al., 1999]. Further, sEMG recordings of serratus anterior have been shown to be highly posture dependent [Hackett, Reed, Halaki, & Ginn, 2014]. While we endeavoured to select a serratus anterior muscle test (high flexion) which shows good comparisons between iEMG and sEMG amplitude [Ginn et al., 2011], variations in participant posture could introduce variability between tests. Regarding the processing of three-dimensional Euler angles, we decomposed thoracohumeral motion with a YXY sequence to maintain ISB standards, yet discontinuities associated with gimbal lock and other limitations have been noted; particularly at low levels of thoracohumeral elevation [Phadke, Camargo, & Ludewig, 2009]. In the current study, thoracohumeral elevation was near 90°, yet readers should be aware of bias and error associated with the Euler decomposition order for three-dimensional joint angles, with particular challenges being noted at the thoracohumeral and glenohumeral joints. Also concerning the kinematic and kinetic results presented, due to the comparison of kinematic data across day, target, and pre-fatigue to post-fatigue, pairwise removal of outliers resulted in 0–8 Δ joint angle scores being removed for each kinematic degree of freedom of the upper limb. The impact of removing these data on the results presented in this study are uncertain.

5. Conclusion

This study sought to identify the variability in muscle fatigue profiles and kinematic and kinetic strategies in response to an identical overhead shoulder fatigue task performed on successive days, one week apart. Upper limb kinematics showed significant changes in baseline joint angles on day 2, which also deviated less from baseline as fatigue accumulated. Baseline shoulder joint flexion moments did not change between days, yet static shoulder flexion moment exposures on day 2 showed a lower fatigue-related change compared to day 1. Kinematic variability generally increased with fatigue at all joints, yet day-to-day changes in fatigue variability were joint specific. Kinetic variability showed evidence of higher variability at mid-fatigue, and a convergence towards similar variability at post-fatigue on both days. While upper limb degrees of freedom responsible for positioning the end effector position in the sagittal plane showed significant changes in fatigue-related kinematic changes between days, degrees of freedom that do not directly motivate end effector changes in the sagittal plane displayed the greatest variability. Changes in baseline upper limb posture

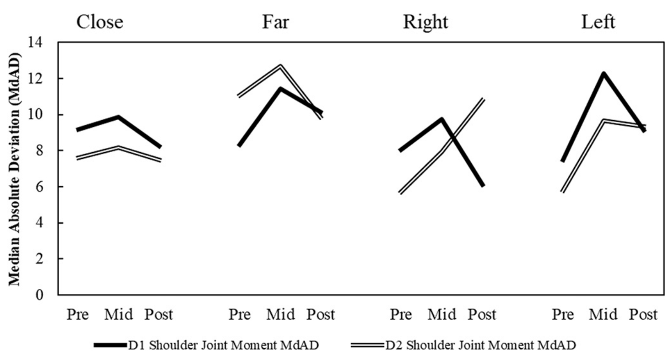

Fig. 10. Shoulder joint flexion moment MdAD On day 1 and day 2 at "Pre-Fatigue", "Mid-Fatigue", and "Post-Fatigue".

and decreases fatigue-related joint angle imply a learning effect aimed at sustaining a decreased shoulder joint flexion moment on day 2. However, adaptations to occupational overhead tasks require further examination, potentially focused on continuous or short-duration postural adaptations (adaptations within a work cycle, sampled over time). Future work should study trunk and lower limb kinetic and muscular strategies, as well as center of mass/pressure relationships, subjective factors (rate of perceived exertion/discomfort), and variability structure and entropy with overhead work tasks in order to fully understand how task variability is influenced by attempts on successive days.

Author statement

Title: Variability in musculoskeletal fatigue responses associated with repeated exposure to an occupational overhead drilling task completed on successive days.

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CRediT authorship contribution statement

Matthew S. Russell: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Sam S. Vasilounis:** Writing – review & editing, Methodology, Investigation, Data curation. **Emily Lefebvre:** Writing – review & editing, Methodology, Investigation, Data curation. **Janessa D.M. Drake:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Jaclyn N. Chopp-Hurley:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

None.

Data availability

Data available upon reasonable request

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References

Alcántara-Bumbiedro, S., Flórez-García, M., Echávarri-Pérez, C., & García-Pérez, F. (2006). Oswestry low back pain disability questionnaire. *Rehabilitacion Madrid, 40*(3), 150.

Anton, D., Shibley, L. D., Fethke, N. B., Hess, J., Cook, T. M., & Rosecrance, J. (2001). The effect of overhead drilling position on shoulder moment and electromyography. *Ergonomics, 44*(5), 489–501.

Aruin, A. S. (2006). The effect of asymmetry of posture on anticipatory postural adjustments. *Neuroscience Letters, 401*(1–2), 150–153.

Bechtol, C. O. (1980). Biomechanics of the shoulder. *Clinical Orthopaedics and Related Research, 146*, 37–41.

Bey, M. J., Brock, S. K., Beierwaltes, W. N., Zauel, R., Kolowich, P. A., & Lock, T. R. (2007). In vivo measurement of subacromial space width during shoulder elevation: Technique and preliminary results in patients following unilateral rotator cuff repair. *Clinical biomechanics, 22*(7), 767–773.

Boettcher, C. E., Ginn, K. A., & Cathers, I. (2008). Standard maximum isometric voluntary contraction tests for normalizing shoulder muscle EMG. *Journal of Orthopaedic Research, 26*(12), 1591–1597.

Bouillard, K., Jubeau, M., Nordez, A., & Hug, F. (2014). Effect of vastus lateralis fatigue on load sharing between quadriceps femoris muscles during isometric knee extensions. *Journal of Neurophysiology, 111*(4), 768–776.

Bouisset, S., Richardson, J., & Zattara, M. (2000). Are amplitude and duration of anticipatory postural adjustments identically scaled to focal movement parameters in humans? *Neuroscience Letters, 278*(3), 153–156.
Breteler, M. D. K., Spoor, C. W., & Van der Helm, F. C. T. (1999). Measuring muscle and joint geometry parameters of a shoulder for modeling purposes. *Journal of Biomechanics, 32*(11), 1191–1197.
Carpenter, J. E., Blasier, R. B., & Pellizzon, G. G. (1998). The effects of muscle fatigue on shoulder joint position sense. *The American Journal of Sports Medicine, 26*(2), 262–265.
Chau, T., Young, S., & Redekop, S. (2005). Managing variability in the summary and comparison of gait data. *Journal of Neuroengineering and Rehabilitation, 2*(1), 1–20.
Chimenti, R. L., Post, A. A., Silbernagel, K. G., Hadlandsmyth, K., Sluka, K. A., Moseley, G. L., & Rio, E. (2021). Kinesiophobia severity categories and clinically meaningful symptom change in persons with Achilles tendinopathy in a cross-sectional study: Implications for assessment and willingness to exercise. *Frontiers in Pain Research, 2*. https://doi.org/10.3389/fpain.2021.739051
Chopp, J. N., Fischer, S. L., & Dickerson, C. R. (2010). The impact of work configuration, target angle and hand force direction on upper extremity muscle activity during sub-maximal overhead work. *Ergonomics, 53*(1), 83–91.
Chopp-Hurley, J. N., O'Neill, J. M., McDonald, A. C., Maciukiewicz, J. M., & Dickerson, C. R. (2016). Fatigue-induced glenohumeral and scapulothoracic kinematic variability: Implications for subacromial space reduction. *Journal of Electromyography and Kinesiology, 29*, 55–63.
De Looze, M., Bosch, T., & Dieen, V. (2009). Manifestations of shoulder fatigue in prolonged activities involving low-force contractions. *Ergonomics, 52*(4), 428–437.
Desmurget, M., & Grafton, S. (2000). Forward modeling allows feedback control for fast reaching movements. *Trends in Cognitive Sciences, 4*(11), 423–431.
Dickerson, C. R., Meszaros, K. A., Cudlip, A. C., Chopp-Hurley, J. N., & Langenderfer, J. E. (2015). The influence of cycle time on shoulder fatigue responses for a fixed total overhead workload. *Journal of Biomechanics, 48*(11), 2911–2918.
Drake, J. D., & Callaghan, J. P. (2006). Elimination of electrocardiogram contamination from electromyogram signals: An evaluation of currently used removal techniques. *Journal of Electromyography and Kinesiology, 16*(2), 175–187.
Duchateau, J., & Baudry, S. (2014). The neural control of coactivation during fatiguing contractions revisited. *Journal of Electromyography and Kinesiology, 24*(6), 780–788.
Ebata, S. E. (2012). *Postural and muscular adaptations to repetitive simulated assembly line work*. McMaster University.
Ebaugh, D. D., McClure, P. W., & Karduna, A. R. (2006). Effects of shoulder muscle fatigue caused by repetitive overhead activities on scapulothoracic and glenohumeral kinematics. *Journal of Electromyography and Kinesiology, 16*(3), 224–235.
Enoka, R. M., & Stuart, D. G. (1992). Neurobiology of muscle fatigue. *Journal of Applied Physiology, 72*(5), 1631–1648.
Forestier, N., & Nougier, V. (1998). The effects of muscular fatigue on the coordination of a multijoint movement in human. *Neuroscience Letters, 252*(3), 187–190.
Gates, D. H., & Dingwell, J. B. (2011). The effects of muscle fatigue and movement height on movement stability and variability. *Experimental Brain Research, 209*, 525–536.
Geiringer, S. R. (1999). *Anatomical localization for needle electromyography*. Philadelphia: Hanley & Belfus.
Ginn, K., Halaki, M., & Cathers, I. (2011). Revision of the shoulder normalization tests is required to include rhomboid major and teres major. *Journal of Orthopaedic Research, 29*(12), 1846–1849.
Graichen, H., Bonel, H., Stammberger, T., Englmeier, K-H., Reiser, M., Eckstein, F. (2001). Sex-specific differences of subacromial space width during abduction, with and without muscular activity, and correlation with anthropometric variables. Journal of Shoulder and Elbow Surgery*,* 10*(2)*, 129–135.
Grieve, J. R., & Dickerson, C. R. (2008). Overhead work: Identification of evidence-based exposure guidelines. *Occupational Ergonomics, 8*(1), 53–66.
Hackett, L., Reed, D., Halaki, M., & Ginn, K. A. (2014). Assessing the validity of surface electromyography for recording muscle activation patterns from serratus anterior. *Journal of Electromyography and Kinesiology, 24*(2), 221–227.
Hendrix, C. R., Housh, T., Johnson, G., Mielke, M., Zuniga, J., Camic, C., & Schmidt, R. (2010). The effect of epoch length on the electromyographic mean power frequency and amplitude versus time relationships. *Electromyography and Clinical Neurophysiology, 50*(5), 219–227.
Hirashima, M., & Oya, T. (2016). How does the brain solve muscle redundancy? Filling the gap between optimization and muscle synergy hypotheses. *Neuroscience Research, 104*, 80–87.
Langenderfer, J., LaScalza, S., Mell, A., & Carpenter., J. E., Kuhn, J. E., Hughes, R. E.. (2005). An EMG-driven model of the upper extremity and estimation of long head biceps force. *Computers in Biology and Medicine, 35*(1), 25–39.
Lewis, J. S., Green, A., & Wright, C. (2005). Subacromial impingement syndrome: The role of posture and muscle imbalance. *Journal of Shoulder and Elbow Surgery, 14*(4), 385–392.
Maciukiewicz, J. M., Cudlip, A. C., Chopp-Hurley, J. N., & Dickerson, C. R. (2016). Effects of overhead work configuration on muscle activity during a simulated drilling task. *Applied Ergonomics, 53*, 10–16.
Madeleine, P. (2010). On functional motor adaptations: From the quantification of motor strategies to the prevention of musculoskeletal disorders in the neck–shoulder region. *Acta Physiologica, 199*, 1–46.
Magill, R., & Anderson, D. I. (2010). *Motor learning and control*. McGraw-Hill Publishing New York.
McDonald, A. C., Mulla, D. M., & Keir, P. J. (2019). Muscular and kinematic adaptations to fatiguing repetitive upper extremity work. *Applied Ergonomics, 75*, 250–256.
McDonald, A. C., Mulla, D. M., Stratford, P. W., & Keir, P. J. (2018). Submaximal normalizing methods to evaluate load sharing changes in the shoulder during repetitive work. *Journal of Electromyography and Kinesiology, 39*, 58–69.
McDonald, A. C., Sonne, M. W., & Keir, P. J. (2017). Optimized maximum voluntary exertion protocol for normalizing shoulder muscle activity. *International Biomechanics, 4*(1), 9–16.
McDonald, A. C., Tse, C., & Keir, P. J. (2016). Adaptations to isolated shoulder fatigue during simulated repetitive work. Part II: Recovery. *Journal of Electromyography and Kinesiology, 29*, 42–49.
McQuade, K. J., Dawson, J., & Smidt, G. L. (1998). Scapulothoracic muscle fatigue associated with alterations in scapulohumeral rhythm kinematics during maximum resistive shoulder elevation. *Journal of Orthopaedic and Sports Physical Therapy, 28*(2), 74–80.
Merletti, R., & Farina, D. (2009). Analysis of intramuscular electromyogram signals. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 367*(1887), 357–368.
Miller, J. (1991). Reaction time analysis with outlier exclusion: Bias varies with sample size. *The Quarterly Journal of Experimental Psychology, 43*(4), 907–912.
Monjo, F., Terrier, R., & Forestier, N. (2015). Muscle fatigue as an investigative tool in motor control: A review with new insights on internal models and posture–movement coordination. *Human Movement Science, 44*, 225–233.
Moon, J., Shin, I., Kang, M., Kim, Y., Lee, K., Park, J., … O'Sullivan, D. (2013). The effect of shoulder flexion angles on the recruitment of upper-extremity muscles during isometric contraction. *Journal of Physical Therapy Science, 25*(10), 1299–1301.
Mulla, D. M., McDonald, A. C., & Keir, P. J. (2018). Upper body kinematic and muscular variability in response to targeted rotator cuff fatigue. *Human Movement Science, 59*, 121–133.
Nakajima, T., Rokuuma, N., Hamada, K., Tomatsu, T., & Fukuda, H. (1994). Histologic and biomechanical characteristics of the supraspinatus tendon: Reference to rotator cuff tearing. *Journal of Shoulder and Elbow Surgery, 3*(2), 79–87.
Öberg, T. (1995). Muscle fatigue and calibration of EMG measurements. *Journal of Electromyography and Kinesiology, 5*(4), 239–243.
Öberg, T., Sandsjö, L., & Kadefors, R. (1990). Electromyogram mean power frequency in non-fatigued trapezius muscle. *European Journal of Applied Physiology and Occupational Physiology, 61*(5), 362–369.
Oomen, N. M., Graham, R. B., & Fischer, S. L. (2023). Exploring the relationship between kinematic variability and fatigue development during repetitive lifting. *Applied Ergonomics, 107*, 103922.
Overbeek, C. L., Kolk, A., de Groot, J. H., de Witte, P. B., Gademan, M. G., Nelissen, R. G., & Nagels, J. (2019). Middle-aged adults cocontract with arm ADductors during arm ABduction, while young adults do not. Adaptations to preserve pain-free function? *Journal of Electromyography and Kinesiology, 49*, 102351.
Perotto, A. O. (2011). *Anatomical guide for the electromyographer: the limbs and trunk*. Illinois: Charles C Thomas Publisher.

Pethick, J., & Tallent, J. (2022). The neuromuscular fatigue-induced loss of muscle force control. *Sports, 10*(11), 184.
Phadke, V., Camargo, P., & Ludewig, P. (2009). Scapular and rotator cuff muscle activity during arm elevation: A review of normal function and alterations with shoulder impingement. *Brazilian Journal of Physical Therapy, 13*, 1–9.
Punnett, L., Fine, L. J., Keyserling, W. M., Herrin, G. D., & Chaffin, D. B. (2000). Shoulder disorders and postural stress in automobile assembly work. *Scandinavian Journal of Work, Environment & Health*, 283–291.
Qin, J., Lin, J.-H., Faber, G. S., Buchholz, B., & Xu, X. (2014). Upper extremity kinematic and kinetic adaptations during a fatiguing repetitive task. *Journal of Electromyography and Kinesiology, 24*(3), 404–411.
Rainoldi, A., Galardi, G., Maderna, L., Comi, G., Conte, L. L., & Merletti, R. (1999). Repeatability of surface EMG variables during voluntary isometric contractions of the biceps brachii muscle. *Journal of Electromyography and Kinesiology, 9*(2), 105–119.
Raviv, L., Lupyan, G., & Green, S. C. (2022). How variability shapes learning and generalization. *Trends in Cognitive Sciences, 26*(6), 462–483.
Russell, M. S., Vasilounis, S. S., Lefebvre, E., Drake, J. D. M., & Chopp-Hurley, J. N. (2024). *Muscle coactivation changes following a fatiguing overhead drilling task: Implications for subacromial impingement syndrome*. Submitted: Applied Ergonomics.
Scholz, J. P., & Schöner, G. (1999). The uncontrolled manifold concept: Identifying control variables for a functional task. *Experimental Brain Research, 126*(3), 289–306.
Scholz, J. P., & Schöner, G. (1999). The uncontrolled manifold concept: identifying control variables for a functional task. *Experimental Brain Research, 126*(3), 289–306.
Shaheen, A. F., Alexander, C. M., & Bull, A. M. J. (2011). Effects of attachment position and shoulder orientation during calibration on the accuracy of the acromial tracker. *Journal of Biomechanics, 44*(7), 1410–1413.
Slobounov, S., Hallet, M., & Newell, K. M. (2004). Perceived effort in force production as reflected in motor-related cortical potentials. *Clinical Neurophysiology, 115*(10), 2391–2402.
Sohn, M. H., & Ting, L. H. (2018). The cost of being stable: Trade-offs between effort and stability across a landscape of redundant motor solutions. *bioRxiv*, 477083.
Sood, D., Nussbaum, M. A., & Hager, K. (2007). Fatigue during prolonged intermittent overhead work: Reliability of measures and effects of working height. *Ergonomics, 50*(4), 497–513.
Sood, D., Nussbaum, M. A., Hager, K., & Nogueira, H. C. (2017). Predicted endurance times during overhead work: Influences of duty cycle and tool mass estimated using perceived discomfort. *Ergonomics, 60*(10), 1405–1414.
Steenbrink, F., de Groot, J. H., Veeger, H., Meskers, C. G., van de Sande, M. A., & Rozing, P. M. (2006). Pathological muscle activation patterns in patients with massive rotator cuff tears, with and without subacromial anaesthetics. *Manual Therapy, 11*(3), 231–237.
Stegeman, D., & Hermens, H. (2007). Standards for surface electromyography: The European project Surface EMG for non-invasive assessment of muscles (SENIAM). *Roessingh Research and Development, 10*, 8–12.
Stulen, F. B., & De Luca, C. J. (1981). Frequency parameters of the myoelectric signal as a measure of muscle conduction velocity. *IEEE Transactions on Biomedical Engineering, 7*, 515–523.
Szucz, K., Navalgund, A., & Borstad, J. D. (2009). Scapular muscle activation and co-activation following a fatigue task. *Medical and Biological Engineering and Computing, 47*(5), 487–495.
Tse, C., McDonald, A. C., & Keir, P. J. (2016). Adaptations to isolated shoulder fatigue during simulated repetitive work. Part I: Fatigue. *Journal of Electromyography and Kinesiology, 29*, 34–41.
Vollestad, N. K. (1997). Measurement of human muscle fatigue. *Journal of Neuroscience Methods, 74*(2), 219–227.
Waite, D. L., Brookham, R. L., & Dickerson, C. R. (2010). On the suitability of using surface electrode placements to estimate muscle activity of the rotator cuff as recorded by intramuscular electrodes. *Journal of Electromyography and Kinesiology, 20*(5), 903–911.
Wiker, S. F., Chaffin, D. B., & Langolf, G. D. (1989). Shoulder posture and localized muscle fatigue and discomfort. *Ergonomics, 32*(2), 211–237.
Williamson, E. (2006). Fear avoidance beliefs questionnaire (FABQ). *The Australian Journal of Physiotherapy, 52*(2), 149.
Willigenburg, N. W., Daffertshofer, A., Kingma, I., & Van Dieën, J. H. (2012). Removing ECG contamination from EMG recordings: A comparison of ICA-based and other filtering procedures. *Journal of Electromyography and Kinesiology, 22*(3), 485–493.
Wu, G., Van der Helm, F. C., Veeger, H. D., Makhsous, M., Van Roy, P., Anglin, C., … Wang, X. (2005). ISB recommendation on definitions of joint coordinate systems of various joints for the reporting of human joint motion—Part II: Shoulder, elbow, wrist and hand. *Journal of Biomechanics, 38*(5), 981–992.