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Spatial dependency of shoulder muscle demand during dynamic unimanual and bimanual pushing and pulling

Daniel C. McFarland, Michael N. Poppo, Emily M. McCain, Katherine R. Saul*

North Carolina State University, Raleigh, NC, United States

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ABSTRACT

Work involving extensive pushing and pulling is associated with higher frequency of shoulder complaints. While reports of shoulder muscle demand during submaximal isometric tasks are abundant, dynamic submaximal push-pull exertions are not well understood. We evaluated how muscle demand (weighted EMG average) of surface glenohumeral muscles varies with task type and target. Seventeen healthy young adults performed seated unimanual and bimanual pushes and pulls to 3 thoracohumeral elevations (20°, 90°, 170°) and 4 elevation planes (0°, 45°, 90°, 135°) with loading at 15% of isometric push-pull capacity. Pulling required less demand than pushing ($p < 0.0001$). Muscle demand varied more with elevation than elevation plane. The lowest target had highest demand for pulling ($p < 0.01$), and the most elevated target had highest demand for pushing ($p < 0.0001$). Working above the shoulder is known to increase demand during isometric tasks, however, these results suggest that for dynamic tasks working against gravity has a larger effect on demand than task target.

1. Introduction

Work-related musculoskeletal disorders (MSD) place a large burden on the economy and workers' health, with MSD accounting for 29–35% of all occupational injuries and illnesses involving days away from work in private industries (Bhattacharya, 2014). Physically demanding occupations such as military service have high occurrence of musculoskeletal disorders, with active duty non-deployed service members having an injury rate of 62.8% per person-years (Hauret et al., 2010). Annual total cost from work-related MSD in the United States ranges between $45 and $54 billion (National Academy of Science, 2001). Shoulder injuries, in particular, are taxing on worker health and the economy. A study of worker compensation claims found that 30.6% of claims involving the shoulder resulted in over seven days of lost work and that shoulder claims resulted in the second highest total cost behind lumbar spine claims (Dunning et al., 2010).

Ergonomics research has identified push-pull tasks as related to shoulder complaints (Hoozemans et al., 2002). Since Hoozemans et al. (1998) identified a lack of knowledge regarding the biomechanical demands placed on shoulder muscles and joints as a result of these exertions, numerous efforts have been made to characterize such tasks. Much of the push-pull literature considers how various conditions including exertion direction and task location influence strength capacity (Calé-Benzoor et al., 2016; Chaffin et al., 1983; Chow and Dickerson, 2009, 2016; Das and Wang, 2004; La Delfa et al., 2014; La Delfa and Potvin, 2016; MacKinnon, 1998). When designing workspaces to prevent MSD, it is important to evaluate demand at the muscular level in addition to overall strength capacity. Since most modern industrial workspaces are characterized by predominantly light repetitive work (Das and Sengupta, 1996), several studies have characterized total muscular demand, a sum or average of individual EMG signals, during submaximal isometric tasks (Chow et al., 2017; McDonald et al., 2012, 2014; Meszaros et al., 2018; Nadon et al., 2016). These studies report that muscular demand during these isometric tasks including pushing and pulling are spatially dependent. In general, superiorly located tasks increase muscle demand, although exertion direction also plays a large role in determining muscular demand (Meszaros et al., 2018) and the resulting spatial dependency (McDonald et al., 2012, 2014; Meszaros et al., 2018; Nadon et al., 2016). All these studies, however, evaluated isometric tasks and the results may not be directly applicable to dynamic exertions since EMG and force exertion under dynamic conditions frequently differ (Antony and Keir, 2010; Kumar, 1995). There has been some effort to characterize muscular loading during dynamic tasks (Bennett et al., 2011; Kao et al., 2015; Lin et al., 2010), but these studies involve full-body cart pushing and may not be applicable to seated or stationary dynamics tasks, such as work on an assembly line or opening and closing hatches on military equipment, since foot placement is known to influence push-pull capacity (Rancourt and Hogan,

* Corresponding author. North Carolina State University, 911 Oval Drive, Raleigh, NC, 27606, United States.
E-mail address: ksaul@ncsu.edu (K.R. Saul).

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2001).

Therefore, to effectively design workplaces involving dynamic force tasks to minimize work-related shoulder MSD, additional understanding of the demands placed on shoulder muscles during these tasks is needed. To characterize a workspace, a combination of task targets, i.e. target hand location at the end of motion, covering the entire space is needed. One obvious solution to reduce muscular demand at the shoulder is to perform task bimanually and split the loading over two shoulders; however, studies comparing unimanual to bimanual strength capacity report unimanual capacity as greater than 50% of bimanual capacity (Chaffin et al., 1983; Warwick et al., 1980), suggesting that there may be limited muscular demand benefits seen by switching to bimanual operation. While muscle demand during bimanual pushing and pulling has been previously evaluated (Chow et al., 2017), to the authors' knowledge no study has directly compared muscular demand between bimanual and unimanual pushing and pulling. Therefore, our objective was to quantify how muscle demand, a measure of the overall load placed on the muscular system, of superficial muscles crossing the glenohumeral joint varies with both task type (unimanual and bimanual pushing and pulling) and task target for dynamic tasks. This research aims to expand understanding of how task design contributes to overuse injuries, thereby enabling the development of preventive measures to reduce risk of shoulder MSD and lower the associated economic burden.

2. Methods

2.1. Experimental protocol

Seventeen healthy young adults (8 males/9 females) between the ages of 20 and 32 years participated in this study. The participants were recruited from the local community using the following inclusion criteria: 1) no history of injury or pathology of the upper limb, 2) no neuromuscular impairments, and 3) no physical impediments to performing the required physical exertions. Fifteen of the subjects were right-dominant, and two were left-dominant. Hand dominance was self-reported by subjects, and their dominant hand was used for all unimanual tasks. All subjects provided written informed consent in accordance with North Carolina State University Institutional Review Board. Each subject completed the testing protocol in a single session on a single day.

Unimanual surface electromyographic (EMG) recordings of the anterior, middle, and posterior deltoid, biceps brachii, lateral head of triceps brachii, latissimus dorsi, and pectoralis major were collected. The skin overlying the location of markers was shaved and cleaned with alcohol prior to electrode placement. Electrodes were placed over each muscle belly in line with muscle fibers using published placement locations (Cram and Criswell, 2011). Recordings were made at 2000 Hz using 1-cm Ag/AgCl dual electrodes with 16-channel capacity (Noraxon Telemyo DTS system, Noraxon, Scottsdale, AZ) (input impedance > 100Mohm, CMRR > 100 dB, gain 500).

Subjects performed a series of isometric joint moments on a Biodex System 4 Quick Set (Biodex, Shirley, NY), and EMG data collected during these trials was used in subsequent EMG normalization. Maximum isometric joint moments of shoulder abduction and elbow flexion for the dominant hand were collected following a previously described standard protocol (Holzbaur et al., 2007a). Subjects were seated with their torso restrained in a vertical posture with straps to prevent changes in posture during the trials. At the shoulder, maximum isometric abduction moment was assessed with the shoulder abducted to 60° and the elbow braced in full extension. At the elbow, maximum isometric flexion moment was assessed with the shoulder in neutral abduction and the elbow flexed to 90°. Three trials of each moment were obtained, and participants received standardized verbal and visual feedback to encourage MVC. To minimize the effects of fatigue, 60 s of rest was provided in between trials.

Additionally, maximal isometric push-pull capacity with the arm in 90° forward flexion was determined for each participant using a closed-chain attachment for the Biodex. This location was chosen for maximal push-pull testing as it represents a neutral baseline task location for the subsequent testing protocol. Six trials using the dominant hand were collected (three push/three pull) where subjects received standardized visual and verbal feedback to encourage maximum force production (Holzbaur et al., 2007a). EMG recordings during these trials were also used in subsequent EMG normalization. Force production was only measured along the single axis aligned with the task. The maximal push-pull force sustained for at least 0.5 s, determined by a custom Matlab script (The Mathworks, Natick, MA), during these six trials was used to determine loading for the testing protocol. Studies of sustained isometric, continuous dynamic, and intermittent isometric contractions have reported fatigue thresholds ranging from 7% to 25% maximum isometric strength (Bjorksten and Jonsson, 1977; Hagberg, 1981; Rohmert, 1973), with intermittent contractions associated with higher thresholds. Therefore, loading was set at 15% of the maximal push-pull force in the tested baseline posture to avoid participant fatigue. This load was applied as a set weight to a pulley system that allowed resistance for each task to be explicitly controlled. This load did not change between task targets or task type (unimanual or bimanual pushing and pulling) in the testing protocol.

A series of unimanual and bimanual push and pull tasks were performed by subjects. Tasks were performed to a combination of 3 thoracohumeral elevation angles (20°, 90°,170°) and 4 planes of elevation (0°/abduction, 45°, 90°/flexion, and 135°) as defined by the International Society of Biomechanics (Wu et al., 2005) for a total of 12 task targets (Fig. 1). These task targets represent the angle of the dominant arm at the end of the push task and start of the pull task. Subjects performed both unimanual and bimanual pushes and pulls at each task target for a total for 48 unique tasks. Three repetitions of each unique task were performed for a total of 144 exertions per subject. To prevent fatigue, participants were provided with a rest period of 1 min between each task. For each task, all three repetitions were performed consecutively without a rest period. The order of tasks was randomized to avoid any ordering effects.

Participants performed tasks in a seated position (chair height: 0.53 m) with their torso restrained by straps to standardize incline across participants. Tasks were performed on a custom pulley resistance system (Fig. 2) to reduce variability in the direction of applied force between participants and trials. The custom device has a resistance pulley system employing a linear track that allows for height adjustments and locks at 3 angles to achieve the thoracohumeral elevation angle targets (Powertec Strength, Powertec Fitness, Long Beach, CA). Plane of elevation angle selection was achieved by rotating the seat. For pulling, participants held a fixed-length handle in the dominant hand (unimanual tasks) or both hands (bimanual tasks). The handle was mounted on a carriage that slides along a linear track. Handle orientation was perpendicular to the linear track. Hand trajectory was controlled by the linear tack, but other joint angles were not controlled

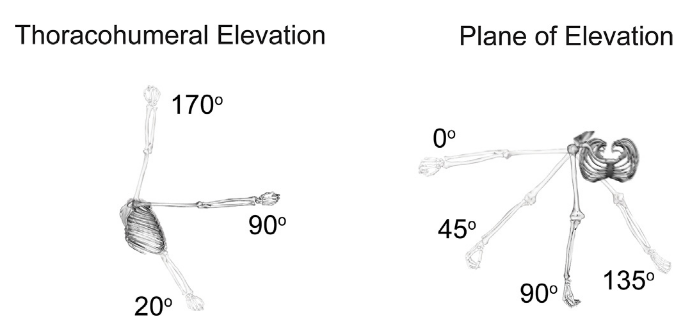

Fig. 1. Task targets. Subjects reached to a combination of 3 thoracohumeral elevations (20°, 90°, and 170°) and 4 planes of elevation (0°, 45°, 90°, and 135°) for a total of 12 distinct task targets.

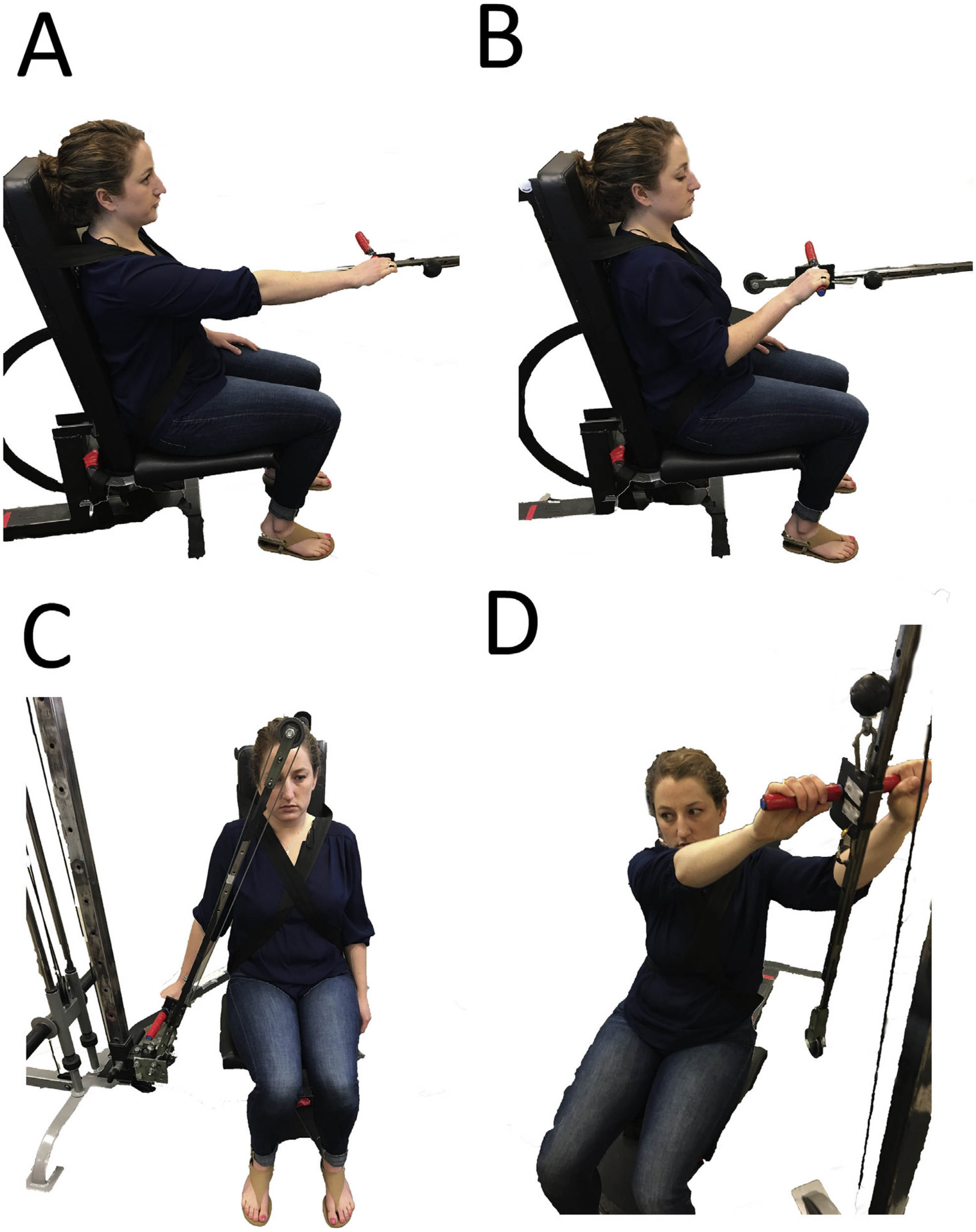

Fig. 2. Custom pulley resistance system. Subjects performed push-pull tasks on a custom device designed to reduce variability in force applied between participants and trials. The custom device has a resistance pulley system employing a linear track that allows for height adjustments and locks at the 3 angles to achieve the thoracohumeral elevation targets. Planes of elevation selection were achieved by rotating the seat. The start (A) and stop (B) for a pull task at the baseline target (90° thoracohumeral elevation/90° plane of elevation). The final position (C) for a unimanual push task at the 20° thoracohumeral elevation/0° elevation target. The starting position (D) for a bimanual pull trial at the 170° thoracohumeral elevation/135° plane of elevation target.

to encourage natural movement choices. For pulling, subjects began with the handle away from the body along the desired trajectory at approximately 80% of full limb length (Fig. 2A) and pulled until the humerus was in a neutral posture (Fig. 2B), approximately 0° thoracohumeral elevation. Pushing tasks were accomplished in a similar manner. Subjects received instructions on desired timing, approximately 1 s (60bmp) although task speed was not explicitly controlled with a metronome to prevent jerky movement. Trials that deviated noticeably from these instructions were repeated.

2.2. Data analysis

Raw EMG data from the push/pull testing protocol were post-processed by removing the DC offset, highpass filtering with a 4th order Butterworth filter with a cutoff frequency of 30 Hz, full-wave rectifying, and RMS filtering with a 200 msec window. Cutoff of 30 Hz was used to eliminate electrocardiogram contamination from EMG signals (Drake and Callaghan, 2006). Data for each muscle in the dominant arm were normalized to the peak value recorded for that muscle during the maximum isometric trials including the maximal push-pull capacity trials.

Muscle demand of the superficial glenohumeral muscles evaluated was calculated for each task as an average of each participant's weighted total of normalized EMG output (Nadon et al., 2016). Physiological cross-sectional areas (PCSAs) were used to determine weightings for EMG signals. Deltoid, bicep brachii, triceps, latissimus dorsi, and pectoralis major PCSA were as reported by Holzbaur et al. (2007b), and the deltoid weighting was divided into anterior, middle and posterior components using PCSA fraction from Langenderfer et al. (2004). $\sum_{i=1}^{7} Norm\_EMG_i \left[\frac{PCSA_i}{\sum_{i=1}^{7} PCSA_i}\right]$.

2.3. Statistical analysis

Differences in peak muscle demand were analyzed across thoracohumeral elevation angles, plane of elevation angles, and task type (unimanual and bimanual pushing and pulling) using a three-way ANCOVA ($\alpha < 0.05$) with sex as a covariate. When interactions were not present, they were removed from the model and a Tukey's honest

Table 1
Subject push-pull strength capacity and demographic information.

Age	Height (in)	Weight (lbs)	Isometric Pull (lbs)	Isometric Push (lbs)	Dynamic Loading Males (lbs)	Dynamic Loading Females (lbs)
24.00 ± 3.36	68.80 ± 3.27	173.3 ± 24.92	75.49 ± 24.47	99.5 ± 30.36	19.06 ± 3.48	11.92 ± 2.35

significant difference post-hoc test was used to analyze results. If an interaction was present, simple main effect test was performed at each factor level using a sequential Bonferroni correction to adjust the α.

3. Results

Isometric push strength was greater than isometric pull strength (Table 1). This was true for all subjects; therefore, the constant task loading was higher than 15% of subjects' isometric pull capacity, but exactly 15% of their push capacity. Task duration for a subset of the trials was evaluated to confirm that subjects performed the trials at similar speeds. Task duration for this subset of task was 0.96 ± 0.3 s. During the testing protocol, one subject was unable to complete the trial at the 170° thoracohumeral elevation/135° plane of elevation target.

All factors were present as main effects ($p < 0.0001$) for thoracohumeral elevation and task type, ($p = 0.0148$) for plane of elevation. Post hoc analysis of the main effect for plane of elevation revealed that only the 0° and 45° target were significantly different from each other, with the most lateral 0° target being more demanding (Fig. 3), although difference in demand between these targets was only 0.03. The only interaction present was between task type and thoracohumeral elevation angle ($p < 0.0001$); therefore, the interaction rather than the main effects for these factors were analyzed with a simple main effects tests at each level of the interaction.

For pulling, elevation targets below the shoulder were most demanding, but for pushing, elevation above the shoulder was most demanding. When pulling, the 20° elevation target was more demanding than other targets ($p < 0.0001$) (Fig. 4). Moving the task target to a low elevation from baseline 90° elevation resulted in an average increase in demand of 111% and 103% for unimanual and bimanual pulling, respectively (0.22 and 0.13 increase in weighted demand, respectively). When pushing, the 170° elevation target required the most demand ($p < 0.0001$) (Fig. 4). Moving the task target to a high elevation from baseline 90° elevation resulted in 45% and 51% average increase in demand for unimanual and bimanual pushing, respectively (0.16 and 0.13 increase in weighted demand, respectively). Additionally, for bimanual pushing, the 90° target was more demanding than the 20° target ($p = 0.0014$). Moving the task target to a low

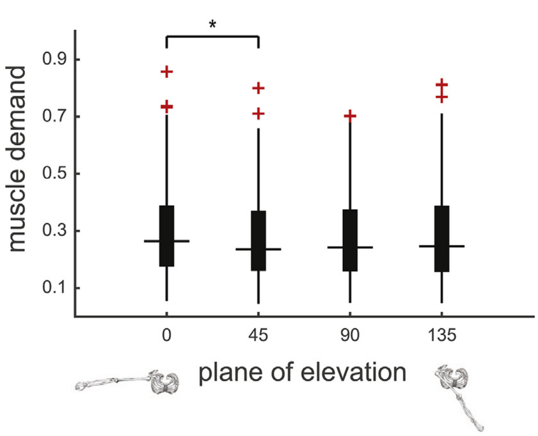

Fig. 3. Main effect of plane of elevation. Post hoc analysis revealed that only the 0° and 45° target were significantly different from each other ($p = 0.0148$), with the most lateral 0° target being more demanding.

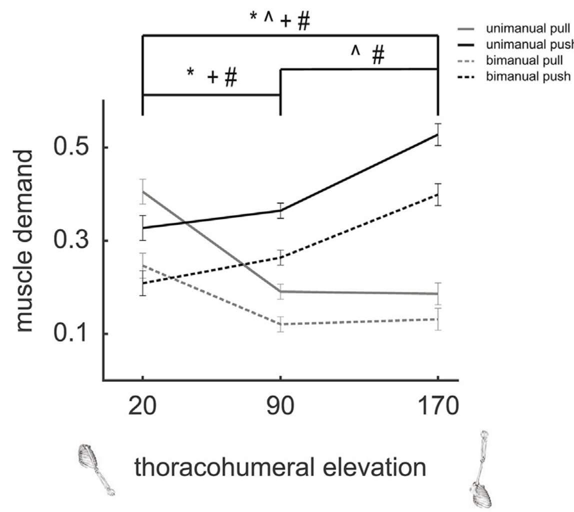

Fig. 4. Task type by thoracohumeral elevation interaction. Low elevation angle increased demand for pull tasks ($p < 0.0001$) whereas high elevation increased demand for push tasks ($p < 0.0001$). Unimanual tasks were always more demanding than their bimanual counterpart at every elevation target, and in general pushing required more demand than pulling. All task types are significantly different from each other for the 90° and 170° elevation, ($p < 0.0001$) for all comparisons except bimanual and unimanual pulling at 170° elevation ($p = 0.0068$). For 20° elevation, bimanual pushing and pulling were not significantly different. All other task type comparisons at 20° were significantly different ($p < 0.001$). Significance among elevation angles is denoted by * for unimanual pulling, ^ for unimanual pushing, + for bimanual pulling, and # for bimanual pushing. Error bars represent 95% confidence interval for adjusted means.

elevation from baseline 90° elevation for bimanual pushing resulted in an average 21% reduction in demand (0.06 reduction in weighted demand).

Unimanual tasks were always more demanding than their bimanual counterpart at every elevation target, and in general pushing required more demand than pulling. At targets at or above shoulder height (90° and 170° elevation), when pulling, bimanual operation resulted in a 36% ($p < 0.0001$) and a 29% ($p = 0.0068$) average reduction in demand compared to unimanual operation, respectively; when pushing, bimanual operation resulted in a 28% and a 24% average reduction in demand, for 90° and 170° elevation, respectively ($p < 0.0001$). Overall differences in demand between bimanual and unimanual demand at these targets were less than 0.15 (Fig. 4). For both of these elevation targets, both pushing task types were more demanding than both pulling task types ($p < 0.0001$). Unimanual pulling required 47% and 65% average lower demand compared to unimanual pushing for elevations of 90° and 170° respectively (0.18 and 0.34 decrease in weighted demand, respectively). Bimanual pulling required 54% and 67% average lower demand compared to bimanual pushing for elevations of 90° and 170° respectively (0.15 and 0.27 decrease in weighted demand, respectively). At targets below shoulder height (20° elevation), when pulling, bimanual operation resulted in a 39% average reduction in demand and when pushing resulted in a 36% reduction in demand ($p < 0.001$). Overall differences in demand between bimanual and unimanual demand at these low targets were less than 0.16 on average (Fig. 4). At the low targets, unimanual pulling was more demanding than unimanual pushing ($p = 0.0004$), but there was no difference between bimanual tasks. Unimanual pushing resulted in a 19% average reduction in demand from unimanual pulling (overall demand difference 0.08) (Fig. 4).

4. Discussion

We evaluated the effects of task target and task type (unimanual and bimanual pushing and pulling) on muscle demand of superficial glenohumeral muscles during dynamic tasks. Muscular demand for superficial glenohumeral muscles was primarily dependent on the interaction between thoracohumeral elevation target and task direction (e.g. push or pull). Pushing to the highest thoracohumeral elevation target increased muscular demand, whereas pulling from the lowest thoracohumeral elevation target increased muscular demand. Furthermore, pushing was more demanding than pulling at all elevation angles except the low target, suggesting that exertion direction with respect to gravity plays a larger role in determining demand than task target or task, i.e. pushing or pulling, alone. Working against gravity to elevate the handle during the pull from the lowest target and the push to the highest target likely makes these tasks more demanding. Prior work with isometric force exertions suggest that, in general, more elevated tasks increase muscular demand (McDonald et al., 2012, 2014; Meszaros et al., 2018; Nadon et al., 2016), although task direction plays an integral role in determining spatial dependency. Contextualizing our results against the spatial dependency for a given exertion in these studies is somewhat difficult as their exertion directions are defined relative to a fixed axis and our exertions are defined relative to the torso. Of these isometric studies, Meszaros et al. (2018), however, directly evaluated the effect of task direction, reporting that downward exertions were the least demanding over a range of task targets whereas upward exertions were the most demanding. Despite differences in task definition, our current study agrees with this isometric study that working against gravity increases demand. The results from the current dynamic study are also consistent with isometric strength data that has found inferiorly directed force to be the strongest for both males and females (Chow and Dickerson, 2009; La Delfa et al., 2014; La Delfa and Potvin, 2016). While it is well documented that maintaining elevated postures is a risk for fatigue and MSD (Grieve and Dickerson, 2008; Hagberg and Wegman, 1987), this present study highlights that shoulder loading during dynamic conditions is more dependent on exertion direction with respect to gravity than actual location of the task target or task type alone. With this in mind, workspaces involving dynamic tasks can be designed to make better use of the whole reachable workspace without compromising safety conditions for shoulder loading by requiring that elevated tasks move with gravity rather than against it.

Plane of elevation was only present as a main effect and had a limited effect on muscular demand for superficial glenohumeral muscles. Only the lateral 0° target was significantly more demanding than the 45° target and differences in demand values between these task targets were minimal (less than 0.03). Previous studies of isometric anterior/posterior pushing and pulling have reported increased total muscular activity at both horizontal extremes (McDonald et al., 2012). Studies of upward isometric exertions showed similar increases in total muscle activity with more lateral targets (Nadon et al., 2016); however, studies of downward (Nadon et al., 2016) and lateral (McDonald et al., 2014) isometric exertions did not show the same trend. These additional studies support the claim that exertion direction can influence how muscle demand varies across horizontal targets throughout the workspace. For the dynamic tasks in this study, our exertion direction (pushing/pulling) was defined as away from/towards the torso, while the isometric studies used exertions relative to a fixed frame. Meszaros et al. (2018) evaluated 6 force exertion directions (anterior/posterior, upward/downwards, and medial/lateral) and found no influence of medial/lateral targets on muscle demand. The results of this current dynamic study lie between the single direction isometric studies and the multidirectional study, since we saw limited horizontal dependency, but only at the lateral extreme. This makes sense, since our task direction is most similar to a combination of the isometric exertion directions. Furthermore, a study of isometric strength by La Delfa and Potvin (2016) suggested that maximal capacity is higher when the direction of applied force is parallel to a vector for the shoulder to the knuckles. All of our exertions in the current study were in this direction and may contribute to why there was limited effect of elevation plane. One explanation for why the 0° target required slightly more demand than the 45° target is that subjects have reduced stability from the backrest of the chair for this test target. These results highlight that task definition needs to be considered before generalizing results to workspace design for a specific task.

Pushing, in general, resulted in higher demand than pulling except for the low thoracohumeral elevation target. Even at the neutral elevation angle 90° in which motion with respect to gravity was not in play, pulling required 47% and 54% lower demand compared to pushing for unimanual and bimanual tasks respectively. This is true even though pulling tasks occurred at a higher percentage of isometric capacity because the resistance was defined based on 15% max push-pull exertion (which for these participants was always a push exertion; Table 1). Two primary factors explain this result. First, differences in dynamic strength capacity between pushing and pulling may contribute. Previous studies of strength capacity report varying results as to whether pushing or pulling is stronger depending on experimental conditions (Das and Wang, 2004; Chaffin et al., 1983; Calé-Benzoor et al., 2016; Chow and Dickerson, 2016; Kumar, 1995). In the current study, isometric strength was measured in a seated posture with the torso restrained. Other work by Das and Wang (2004) and Kumar (1995) have reported stronger pull strength, in contrast to our results; however, in Kumar (1995) pushing and pulling were measured in a standing posture with the legs stabilized, while Das and Wang (2004) used seated tests without a torso restraint. Our strength results agree with the isometric results of Chaffin et al. (1983) and Chow and Dickerson (2016) which both evaluated standing push-pull capacity without external stabilization of the lower limb. Importantly, dynamic measures of strength suggest that isometric push-pull relative strength may change with movement. Calé-Benzoor et al. (2016), measured isokinetic strength ratio between pushing and pulling in a similar seated and restrained manner as the testing protocol in this present study. They found push:pull ratios for dominant and non-dominant arm to be near 1 at a slower velocity 12.22 cm/s. However, at a faster speed of 36.67 cm/s these ratios decreased to 0.81 and 0.82 for dominant and non-dominant arms. This decrease in push strength relative to pull strength at speeds similar to the dynamic tasks in the present study could account for some of the increase in muscle demand between task direction. A second factor influencing comparisons of push to pull task types is the selection of muscles evaluated in the present study. Because our interest was with muscles crossing the glenohumeral joint, we chose a balanced selection of antagonist pairs of muscles that play important roles in the actuation of the glenohumeral joint. However, other muscles, such as trapezius which plays an important role in pull tasks at close reach distances (MacKinnon and Vaughan, 2005), were omitted and not included in the demand calculation. If more omitted muscles play important roles in pulling than in pushing, this may artificially lower the pulling demand measured. Evidence from other work nevertheless supports that pushing may be more demanding than pulling. For example, a prior study of submaximal isometric anterior/posterior pushing and pulling (McDonald et al., 2012) did not directly compare total muscle demand between two task directions, but similarly reported that muscle activity as a percentage of MVC was greater in pushing than pulling. The increase in muscle demand during dynamic pushing may make it more likely to cause fatigue and lead to MSD than pulling.

Bimanual operation of a task can reduce the demand placed on a single shoulder, but these improvements were less than 50%. Our results show that bimanual tasks reduced muscle demand on a single shoulder by 32% on average, although reductions depended on task target. Our results support the claim that bimanual tasks can reduce the risk of MSD, however, improvements in muscle demand may be undermined if overall loading is increased for bimanual tasks since reduction in demand is less than 50%. In a study of non-seated push pull forces, Chaffin et al. (1983) reported one arm strength averages were approximately 73% of the two arm values. This study demonstrates that push-pull capacity is only partially dependent on arm strength which may contribute to the limited decrease in muscle demand we saw when switching from unimanual to bimanual operation. Another potential reason for the limited reduction in demand is uneven load sharing between dominant and non-dominant arms. Chow et al. (2017) evaluated muscle demand on both arms during bimanual pushing and pulling. Their statistical analysis did not directly compare left and right demands, but they report different interactions between sex and handle height for left and right weighted EMG and show differences in weighted EMG divided by hand force, suggesting that demand during bimanual tasks may not be evenly distributed. Therefore, this limited reduction in demand in the current study may be a combination of uneven load sharing and differences of strength between unimanual and bimanual operation.

Study limitations should be considered when interpreting these results. Participant history of upper limb injury was self-reported, and subjects were not screened for the presence of an asymptomatic injury. The presence of asymptomatic injury can alter strength capacity (Kim et al., 2009). Altered strength capacity in the dominant arm would have resulted in lower loading for the testing protocol, and thereby introduced confounding factors into analysis. Additionally, asymptomatic rotator cuff tears alter muscle activity patterns (Kelly et al., 2005), although these injuries are primarily present in older adults and our population was young healthy adults. The objective of this study was to analyze muscle demand in a healthy population and altered muscle activation strategies resulting from injuries would confound results of this study. Our study population included both left and right dominant subjects, and hand dominance could be a potentially confounding factor; however, all task targets were defined relative to the dominant shoulder and we present data by the dominant side to mitigate any confounding effects. While other muscles play a role in push-pull tasks, we chose a balanced subset of push-pull muscles crossing the glenohumeral joint, since MSD at the shoulder often manifests at the glenohumeral joint (e.g. impingement and bursitis). Additionally, we acknowledge that many dynamic force exertions have variable force profiles, but in order to isolate the effects of task target and task type (unimanual and bimanual pushing and pulling) a constant force profile was used. Neither isometric individual muscle MVC (Cram and Criswell, 2011) nor dynamic MVC (Hodder and Keir, 2013) were collected; rather, we normalized EMG data to isometric joint moments and maximal push-pull exertions. These four maximal exertion trials were chosen to elicit contraction in our selected muscles in an efficient manner, but the lack of individual muscle MVC data may have altered normalized peak values, as we saw some peaks above 1.0. Our analysis, however, was intended to identify how demand varies according to task location rather than absolute value per se. Since EMG data of the maximal push-pull exertions were taken at a neutral location, the spatial dependency observed should be unaffected by the normalization scheme. In addition, EMG recordings were made with surface EMG which limited our selection of muscle to superficial glenohumeral muscles. Rotator cuff muscles also cross the glenohumeral joint but were not included in our muscle selection since they are more accurately recorded with intramuscular recordings of EMG signals (Rajaratnam et al., 2014). The primary function of the rotator cuff is joint stabilization; therefore, demand of these muscles should be related to demand of superficial glenohumeral muscles. A single PCSA ratio was used for all subjects since muscle volume distribution is highly conserved across adults (Holzbaur et al., 2007b; Saul et al., 2015; Vidt et al., 2012). Muscle volume distribution among subjects in this study may have been different from reported values in the literature, which would influence muscle demand calculations; however, we did not have imaging data available to evaluate this. One subject was unable to complete the push trial at 170° thoracohumeral elevation/135° plane of elevation. Other subjects, however, did not struggle with this target. Subjects were free to choose their own coordination strategies to complete tasks, and this subject may have made kinematic choices that made this task target particularly difficult for them. Excluding this task for this subject underestimates the average demand of this task target. Task speed was not explicitly controlled during the testing protocol, although subjects received instructions regarding approximate trial timing, and trials were reperformed if they noticeably deviated from instructions. During study development, we explored the use of a metronome to control task speed; however, when using a metronome, subjects tended to perform the tasks less smoothly which was undesirable. By not controlling for task speed we introduce another variable into the analysis; however, workers typically perform tasks at a self-selected speed and thus this approach may be more representative of industrial settings. Lastly, participants performed tasks in a seated posture with their torso restrained to isolate the effects of task target and task direction on shoulder muscle demand. In an industrial setting, workers are typically unconstrained and may rely more heavily on back muscles to complete tasks or employ altered movement strategies. Our task definition in this study was necessary to isolate the effects of task target and task type on glenohumeral muscles, but future work should consider contributions of the back as well.

5. Conclusions

Submaximal dynamic pushing and pulling are common industrial tasks whose muscle demand has been previously unexplored. In particular, we found that elevating the limb during dynamic pushing and pulling results in increased muscle demand for superficial glenohumeral muscles. Thus, workspace design involving dynamic pushing and pulling should avoid tasks that result in motion against gravity. Plane of elevation, however, appears to have reduced influence on muscle demand, and is thus a less important constraint. Furthermore, priority should be given to locating push tasks at low demand locations since pushing is in general more demanding than pulling. Additionally, where possible workspaces should be designed to enable bimanual operation of tasks since dividing load over two-hands reduces muscle demand placed on a single shoulder and can help reduce worker fatigue and prevent MSD. Single shoulder demand was reduced by 32% on average as a result of bimanual operation, suggesting that while task type can greatly reduce demand on a single shoulder, this reduction is somewhat limited by factors such as uneven load sharing. The current study found that dynamic pushing and pulling tasks have different muscle demand and workspace location dependence compared to previous studies of spatial dependence using isometric tasks and various exertion directions, although both isometric and dynamic exertions require increased demand when working against gravity. Thus, care should be used when generalizing from isometric to dynamic tasks and across exertion directions for workplace design.

Author contributions

Daniel C. McFarland – Co-developed the study design, collected data, performed data analysis, drafted the paper, approved the paper for submission.

Michael N. Poppo – Built custom device for data collection, collected data, approved the paper for submission.

Emily M. McCain – Collected data, approved the paper for submission.

Katherine R. Saul – Co-developed the study design, drafted the paper, approved paper for submission.

All authors have read and approved the final submitted manuscript.

Conflicts of interest

None.

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