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Shoulder Mechanical Impingement Risk Associated with Manual Wheelchair Tasks in Individuals with Spinal Cord Injury

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Abstract

Background—Most individuals with spinal cord injury who use manual wheelchairs experience shoulder pain related to wheelchair use, potentially in part from mechanical impingement of soft tissue structures within the subacromial space. There is evidence suggesting that scapula and humerus motion during certain wheelchair tasks occurs in directions that may reduce the subacromial space, but it hasn't been thoroughly characterized in this context.

Methods—Shoulder motion was imaged and quantified during scapular plane elevation with/without handheld load, propulsion with/without added resistance, sideways lean, and weight-relief raise in ten manual wheelchair users with spinal cord injury using biplane fluoroscopy and computed tomography. For each position, minimum distance between rotator cuff tendon insertions (infraspinatus, subscapularis, supraspinatus) and the coracoacromial arch was determined. Tendon thickness was measured with ultrasound, and impingement risk scores were defined for each task based on frequency and amount of tendon compression.

Findings—Periods of impingement were identified during scapular plane elevation and propulsion but not during pressure reliefs in most participants. There was a significant effect of activity on impingement risk scores ($P < 0.0001$), with greatest impingement risk during scapular plane elevation followed by propulsion. Impingement risk scores were not significantly different between scapular plane elevation loading conditions ($P = 0.202$) or propulsion resistances ($P = 0.223$). The infraspinatus and supraspinatus tendons were both susceptible to impingement during

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Conflict of interest statement

All authors declare no conflict of interest.

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scapular plane elevation (by acromion), whereas the supraspinatus was most susceptible during propulsion (by acromion and coracoacromial ligament).

Interpretation—The occurrence of mechanical impingement during certain manual wheelchair tasks, even without increased load/resistance, demonstrates the importance of kinematics inherent to a task as a determinant of impingement. Frequency of and technique used to complete daily tasks should be carefully considered to reduce impingement risk, which may help preserve shoulder health long-term.

Keywords

Rotator cuff; Subacromial Space; Kinematics; Fluoroscopy

1. Introduction

The majority of individuals with spinal cord injury (SCI) who use a manual wheelchair (MWC) report shoulder pain associated with MWC use (Dyson-Hudson and Kirshblum, 2004; McCasland et al., 2006). Shoulder mechanical impingement, which involves compression of soft tissue structures due to narrowing of the space between the humerus and coracoacromial (CA) arch of the scapula (subacromial space), represents one extrinsic mechanism theorized to contribute to shoulder pain (Mackenzie et al., 2015; Michener et al., 2003). Shoulder use is vital for mobility via propulsion, weight relief maneuvers to prevent pressure injury, and most other activities of daily living when operating from a MWC. Thus, shoulder pain and pathology can have great consequences on independence and quality of life in this population (Gutierrez et al., 2007).

Rotations of the humerus and scapula in directions presumed to cause a reduction in the subacromial space have been identified during MWC transfers, weight-relief raises, and propulsion (Finley et al., 2005; Morrow et al., 2011; Nawoczenski et al., 2012; Riek et al., 2008; Zhao et al., 2015), tasks which are routinely performed by individuals with SCI. Given that a positional change of the scapula of as little as 7° may lead to a 25% reduction in the subacromial space (Solem-Bertoft et al., 1993), the magnitude of the differences between certain activities and kinematic parameters reported in these studies deserves consideration. Recently, ultrasound imaging has been used to measure the acromiohumeral distance (minimum distance between the acromion and humerus) during MWC tasks in order to estimate the size of the subacromial space (Lin et al., 2014; 2015; Belley et al., 2017). Lin et al. demonstrated that the acromiohumeral distance was significantly reduced in a weight-relief raise position compared to a neutral resting position in individuals who use a MWC (Lin et al., 2014), but distances were not evaluated relative to the thickness of the underlying supraspinatus tendon. Given the complex relationship between kinematic parameters and changes in the subacromial space (Mozingo et al., 2019), which is further confounded by individual differences in bone morphology and tendon geometry, it is challenging to predict susceptibility of rotator cuff tendons to impingement by only comparing bone rotations or distance measures alone. Thus, the likelihood of mechanical impingement during MWC tasks is largely unknown.

In this study, biplane fluoroscopy and model-based tracking were used to directly and accurately measure subject-specific changes in the subacromial space during dynamic MWC tasks. These measures were evaluated relative to subject-specific tendon thickness measures obtained with ultrasound imaging in standard positions used clinically to visualize the rotator cuff. Mechanical impingement was defined as distance between a tendon insertion and the CA arch that was less than the tendon thickness. Although the focus of previous work related to impingement has mainly involved the supraspinatus tendon and acromion in able-bodied individuals, there is evidence that the infraspinatus and subscapularis tendons and the CA ligament and coracoid may also be involved (Dal Maso et al., 2016). For this reason, each of these structures was considered in the present study. Mechanical impingement risk, a metric defined herein to describe the frequency and amount of tendon compression that occurs during a task, was then quantified and compared between activities. We hypothesized that (1) Each MWC task examined would be defined by a period of mechanical impingement, (2) Differences in mechanical impingement risk would exist between tasks, and (3) Mechanical impingement risk would increase with increased external load and rolling resistance during scaption and propulsion, respectively.

2. Methods

2.1 Participants

Following approval by the Mayo Clinic Institutional Review Board, 10 participants (9 male, 1 female) with SCI who use a MWC as their primary mode of mobility were enrolled, and written informed consent was obtained (Mozingo et al., 2019). Individuals with hyper- or hypo-mobility of the shoulder joint and/or injury/surgery to either shoulder in which function had not fully returned, as determined by a licensed physical therapist, were excluded from the study. Participants were between 26 and 58 years of age (mean 45.8; SD 12.5) and had used a MWC for 1.5 – 35 years (mean 15.9; SD 10.7). Injury levels ranged from T3 to T12. Wheelchair User's Shoulder Pain Index (Curtis et al., 1995a, b) ranged from 0 to 52.1 (mean 15.2, SD 18.1).

2.2 Participant Imaging

A CT scan of the dominant shoulder (humerus and scapula) was obtained using a clinical scanner (128-slice SOMATOM Definition Edge; Siemens Healthcare; Erlangen, Germany) and clinical shoulder musculoskeletal imaging protocol (Mozingo et al., 2019). Data were reconstructed with 0.75 mm slice thickness and 0.35 mm slice increment, image volumes scaled to have 0.35 mm cubic voxels, and 3D models of each bone created via segmentation using AnalyzePro software (Robb et al., 1989). Triangular surface meshes were generated using the 3D Viewer plugin in Fiji software (Schmid et al., 2010). Meshes were uniformly resampled to a median edge length of 1 mm using MeshLab software (Cignoni et al., 2008). Meshes corresponding to the infraspinatus, subscapularis, and supraspinatus tendon insertions ("footprints") were created by delineating the regions of the humerus surface model corresponding to the facets of the greater tubercle (Fig. 1A), according to descriptions from anatomic studies (Curtis et al., 2006; Minagawa et al., 1998). The CA ligament was modeled as a plane extending between the coracoid process and anterior acromion on the

scapula surface model (Fig. 1A), with attachment sites based on anatomic descriptions (Chahla et al., 2018; Edelson and Luchs, 1995).

An ultrasound examination of the rotator cuff of the dominant shoulder was performed by a board-certified, fellowship-trained, musculoskeletal radiologist using a ML6-15 MHz probe in a musculoskeletal setting (LOGIQ E9; GE Healthcare; Chicago, Illinois; USA). Static images of the infraspinatus, subscapularis, and supraspinatus tendons were obtained using standard imaging planes, including in the modified Crass position (Crass et al., 1987). The thickness of each tendon was measured perpendicular to the surface of the humerus (Fig. 1B) using Fiji software (Schindelin et al., 2012). The infraspinatus and supraspinatus tendons were measured medially on long axis images, at the maximum width corresponding to the footprint (Karthikeyan et al., 2014). The subscapularis tendon was measured medially on short axis images, at the 3 locations corresponding to the separate tendon bundles, and the thicknesses were averaged. Mean thickness [mm] was 6.6 (SD 0.9) (infraspinatus), 6.2 (SD 1.1) (subscapularis), and 5.9 (SD 1.0) (supraspinatus).

Dynamic imaging was performed during MWC-based tasks using a clinical biplane fluoroscopy system (Artis zee biplane; Siemens Healthcare; Erlangen, Germany), described by Mozingo et al., 2019. Briefly, images of the glenohumeral joint of the dominant arm were collected at 15 frames/s in each plane (the X-ray sources alternate on clinical biplane systems) at a pulse width of 3.2 ms. Tasks included scapular plane elevation (scaption), MWC propulsion, and two pressure relief maneuvers, including a sideways lean and weight-relief raise. Participants completed each task at a steady pace seated in their personal MWC, to yield an approximate trial duration of 3.5 s. Scaption was performed with the arm fully extended and thumb pointed upward, with no handheld load and with handheld loads of 2 kg and 4 kg. Propulsion was completed on a passive wheelchair ergometer, and consisted of one cycle each starting from rest at 3 self-selected levels of increasing resistance. The rolling resistance was incrementally adjusted by increasing/decreasing the force exerted by a brake pad against the ergometer flywheel. Resistances were selected based on a participants' response to standardized questions related to effort level, and meant to simulate changes in resistance associated with propelling across different surfaces including tile (low), carpet (medium), and inclines (high). For the sideways lean, participants applied force to the wheel, pushrim, or armrest with their dominant arm and fully extended their elbow in order to lean, offloading the ipsilateral ischium (the dominant arm was imaged at the end range of the task, where offloading occurs). During the weight-relief raise, participants pushed up from the chair until their elbows were fully extended (the return to seated position was not imaged). After trials were complete, a calibration cube was statically imaged to define the global coordinate system.

2.3 Data Processing

Six degree-of-freedom kinematics of the humerus and scapula were determined by registration of the CT bone models to consecutive fluoroscopic image pairs using custom model-based tracking software (software described by Akbari-Shandiz et al., 2019), and Autoscooper software (Miranda et al., 2011) was used for further refinement of model position. Average glenohumeral angular speeds [$^{\circ}/s$] (measured from model-based tracking)

were 31 (SD 7.5) (scaption), 55 (SD 5.5) (propulsion), 25 (SD 10.3) (sideways lean), and 27 (SD 8.6) (weight-relief raise) and are estimated to add 0.4 – 0.81 mm and 0.15 – 0.26° error in glenohumeral kinematic measures based on a previous validation study (Mozingo et al., 2018). Scaption trials were analyzed over the largest glenohumeral elevation range spanned by all participants (40° – 80°). Bone coordinate systems were constructed by determining the coordinates of anatomical landmarks from the 3D bone models based on International Society of Biomechanics recommendations (Wu et al., 2005). Glenohumeral rotations and translations were quantified and are described by Mozingo et al., 2019.

Transformation matrices measured from model-based tracking were used to animate the 3D surface meshes of the bones, tendon footprints, and CA ligament. For a given footprint (infraspinatus, subscapularis, supraspinatus) and scapula structure (acromion, CA ligament, coracoid; full structure referred to as CA arch), the pairwise Euclidean distance between each vertex of the footprint to the nearest vertex of the structure was measured using custom MATLAB code (The MathWorks, Inc.; Natick, Massachusetts, United States), and the minimum distance across vertices was retained for analysis at each frame.

2.4 Quantification of Mechanical Impingement Risk

For each footprint – scapular structure combination, a time series representing the minimum distance between meshes was generated, yielding 9 time series (3 tendons, 3 structures) per activity per participant. Impingement was defined as distances (d) that were less than a given tendon's thickness, where 'n' indicates the number of data points that fall in this category (Fig. 2). For a given time series, data points that satisfied this criterion were individually subtracted from and normalized to the tendon's thickness. The resulting values were then summed, and the output was normalized to the total activity length in frames to account for differences in activity speed between participants. The final value was multiplied by 100% and is herein referred to as a score:

$$\text{Tendon Risk Score} = \frac{\sum_1^n \left[\frac{\text{tendon thickness} - d_n}{\text{tendon thickness}} \right]}{\text{total \# frames}} \times 100 \%$$

The max possible score for a single footprint – scapular structure combination of 100% indicates that the minimum distance between the specified footprint and structure was 0 for each frame of the activity, whereas a score of 0% indicates that the minimum distance was never below the tendon thickness. The following three metrics were defined:

1. **Tendon risk score:** determined using the minimum distance time series between a specified tendon and the CA arch (max score of 100%). Example time series shown in Fig. 2. (Tendons: infraspinatus, subscapularis, supraspinatus).
2. **Total activity risk score:** sum of infraspinatus, subscapularis, and supraspinatus tendon risk scores for a given activity (max score of 300%). (Activities: scaption, propulsion, sideways lean, weight-relief raise).
3. **Scapula structure involvement score:** determined using the minimum distance time series between a specified scapular structure and each tendon. The scores

from the separate time series are then summed for a given scapular structure (e.g. acromion score = acromion to infraspinatus score + acromion to subscapularis score + acromion to supraspinatus score) (max score of 300%). (Structures: acromion, CA ligament, coracoid).

A higher score indicates greater mechanical impingement risk (metrics 1 and 2) or a greater role in causing mechanical impingement (metric 3).

2.5 Statistical Analysis

Tendon risk, total activity risk, and scapula structure involvement scores were determined for each participant and activity. Descriptive statistics, histograms, and Q-Q plots were examined to determine if the assumption of normality had been violated, and type I error rate was set at .05 for all tests. To test the hypothesis that differences in mechanical impingement risk would exist between tasks, Friedman's test was conducted for total activity risk with activity as the within-subject factor (within-subject factors included scaption 0 kg (no load), propulsion low resistance, sideways lean, weight-relief raise). Friedman's tests were then also conducted to test the hypothesis that mechanical impingement risk would increase with increased external load (scaption) and rolling resistance (propulsion) (within-subject factors included (1) scaption 0 kg, 2 kg, 4 kg; and (2) propulsion low, medium, high resistance). When a significant effect of activity was found, activity pairwise comparisons were performed with Bonferroni adjustment. Following activity comparisons, tendon risk was compared for a given activity using separate Friedman's tests, with tendon as the within-subject factor (infraspinatus, subscapularis, supraspinatus). For scaption, the assumptions of normality and sphericity (confirmed by Mauchly's W) were not violated, and a one-way repeated measures ANOVA was used instead. Last, scapula structure involvement scores were compared for a given activity using separate Wilcoxon signed rank tests, with scapula structure as the within-subject factor (acromion, CA ligament, coracoid).

3. Results

The absolute minimum distance between each tendon and scapula structure was determined for each participant for each activity. For a given activity, median absolute minimum distances were smallest for the supraspinatus compared to the other tendons, and ranged from 1.0 mm (scaption 4 kg) to 11.2 mm (sideways lean) (Table 1). Median absolute minimum distances were second smallest for the infraspinatus and largest for the subscapularis, with the exception of the pressure reliefs (Table 1). During scaption, median absolute minimum distances were smallest from the acromion compared to the other scapula structures (1.0 – 1.5 mm) (Table 1). During the other tasks, median absolute minimum distances were smallest from the CA ligament, with the exception of high resistance propulsion, and ranged from 4.5 mm (low resistance propulsion) to 11.2 mm (sideways lean) (Table 1). The distance between the tendon footprints and scapula structures generally decreased or remained constant throughout the activity cycle, with the exception of propulsion (representative distance time series in Fig. 3) which had a characteristic u-shape (Figs. 2 and 3).

3.1 Total Activity Risk

Total activity risk scores were determined for each participant for each activity. Median scores and interquartile ranges (IQRs) are shown in Figs. 4 and 5. Results of statistical tests are provided with the degrees of freedom, test statistic, and p-value indicated. There were significant effects of activity on total activity risk score [$\chi^2(3)=26.93$, $P<0.0001$]. Median scores for scaption, propulsion, sideways lean, and the weight-relief raise were 110.8%, 4.0%, 0%, and 0%, respectively. Activity risk was significantly higher for scaption compared to each of the other activities (Fig. 4) (scaption vs. propulsion [$z=-2.80$, $P=0.005$], scaption vs. sideways lean [$z=-2.80$, $P=0.005$], scaption vs. weight-relief raise [$z=-2.80$, $P=0.005$]). Activity risk was also significantly higher for propulsion compared to both pressure reliefs (propulsion vs. sideways lean [$z=-2.67$, $P=0.008$], propulsion vs. weight-relief raise [$z=-2.70$, $P=0.007$]) (Fig. 4). The pressure reliefs were not significantly different from one another ($z=-0.45$, $P=0.655$), and only 1 participant per pressure relief had a non-zero risk score.

Activity risk scores were not significantly different between scaption loading conditions [$\chi^2(2)=3.2$, $P=0.202$] (Fig. 5A). However, scores for the 4 kg condition were greater than the no load condition for 6 of 10 participants (Fig. 5A). Median scores for scaption with no load, 2 kg, and 4kg were 110.8%, 124.5%, and 123.2%, respectively. Activity risk scores were not significantly different between propulsion resistance conditions [$\chi^2(2)=3$, $P=0.223$] (Fig. 5B). However, scores for the high resistance condition were greater than the low resistance condition for 5 of 10 participants (Fig. 5B). Median scores for propulsion with low, medium, and high resistances were 4.0%, 3.9%, and 4.6%, respectively. Due to the absence of a significant main effect for scaption loading trials and propulsion resistance trials, statistical analyses that follow were only performed on scaption 0 kg and propulsion low resistance trials.

3.2 Tendon Risk

Tendon risk scores were determined for each participant for each tendon. Median scores and IQRs are reported in Table A1 (Appendix). There were significant effects of tendon on tendon risk score for scaption [$F(2,18)=15.30$, $P<0.0001$] and propulsion [$\chi^2(2)=15.75$, $P<0.0001$], but not sideways lean [$\chi^2(2)=2$, $P=0.368$] or weight-relief raise [$\chi^2(2)=2$, $P=0.368$]. During scaption, subscapularis tendon risk (median=9.8%) was significantly lower than the infraspinatus (median=40.5%, $P=0.035$) and supraspinatus (median=9.8%, $P=0.002$) (Fig. 6A). Infraspinatus and supraspinatus scores were not significantly different ($P=0.112$). During propulsion, supraspinatus tendon risk (median=4.0%) was significantly greater than the infraspinatus (median=0%, $z=-2.66$, $P=0.008$) and subscapularis (median=0%, $z=-2.66$, $P=0.008$) (Fig. 6B). Infraspinatus and subscapularis scores were not significantly different ($z=-1.48$, $P=0.138$).

3.3 Scapula Structure Involvement

Median absolute minimum distances from the coracoid were large, ranging from 11.9 mm – 14.0 mm across activities (Table 1). Scapula structure involvement scores were determined for each participant for the acromion and CA ligament only. Median scores and IQRs are reported in Table A2 (Appendix). During scaption, acromion involvement (median=

100.6%) was significantly greater than the CA ligament (median= 17.6%, $z = -2.803$, $P = 0.005$) (Fig. 7A). During propulsion, acromion (median= 2.4%) and CA ligament (median= 3.6%) involvement were not significantly different ($z = -.533$, $P = .594$) (Fig. 7B). Scapula structure involvement scores were not significantly different for the sideways lean or for the weight-relief raise.

4. Discussion

Though the size of the subacromial space is predicated on the relative position of the humerus and scapula, it is challenging to predict susceptibility of rotator cuff tendons to impingement by only comparing bone rotations or planar distance measures, as done in previous MWC research (Belley et al., 2017; Finley et al., 2005; Lin et al., 2014; Nawoczenski et al., 2012; Riek et al., 2008). Furthermore, bone morphology and tendon geometry, which also influence the size of the space and likelihood of tendon compression, are not accounted for. As a result, mechanical impingement risk associated with MWC tasks is largely unknown. Thus, the primary goal of this work was to directly quantify subject-specific changes in the subacromial space during MWC tasks via bone-to-bone distance measures using a highly accurate biplane fluoroscopy-based approach. This information, coupled with subject-specific tendon thickness measures from ultrasound, was then used to quantify and compare mechanical impingement risk across tasks. Periods of impingement were identified during scapular plane elevation and propulsion but not during either pressure relief maneuver in most participants.

4.1 Scaption Risk

For the examined glenohumeral elevation range, mechanical impingement risk was greatest during scaption, with a median activity risk score that was an order of magnitude larger than those for each of the other tasks. Often, only the supraspinatus and acromion are considered in studies that have measured the subacromial space during arm elevation (Bey et al., 2007; Coats-Thomas et al., 2018; Giphart et al., 2012). The results of the present study do support the mechanism of the acromion as the primary impinging structure during scaption, with a significantly greater involvement score than the CA ligament (Fig. 7A), and thus greater responsibility for the total tendon risk scores. However, examination of the constituent tendon risk scores reveals that both the supraspinatus and infraspinatus contributed to the overall activity risk, and had scores that were not significantly different (Fig. 6A). Indeed, the distance between both the infraspinatus and supraspinatus footprints to the CA arch were generally less than their respective tendon thicknesses over the entire glenohumeral elevation range examined (representative distance time series in Fig. 3). Additionally, the median absolute minimum distance for a given tendon was smaller during scaption than during other tasks (Table 1), indicating that the amount of tendon compression was also likely greatest during this task. As a result, both the number of distance measures below the tendon thickness and the magnitude of the distances relative to the tendon thickness contributed considerably to the total scaption risk score. Collectively, these findings demonstrate the importance of considering tendons and scapular structures other than just the supraspinatus and acromion when quantifying mechanical impingement, and suggest that mechanical impingement risk during arm elevation tasks should not be dismissed.

4.2 Propulsion Risk

Propulsion had a significantly lower activity risk score than scaption, but significantly higher score than both pressure reliefs (Fig. 4). In addition to relatively few instances of impingement during the activity cycle compared to scaption, absolute minimum distances for each tendon were also larger (Table 1) (tendon compression was less frequent and by a lesser amount). Furthermore, the total activity risk scores were primarily the result of compression of just one tendon. The supraspinatus tendon was at significantly greater risk than each of the other tendons (Fig. 6B), with a median absolute minimum distance to the CA arch of 4.3 mm (IQR = 3.4 mm – 6.1 mm) across participants. Though data for the same activity is not available in the literature, Giphart et al. reported similar mean minimum distances of 3.2 mm – 6.3 mm during a forward flexion task (comparable to the push phase of the propulsion cycle) over the portion of the activity when the supraspinatus footprint passed under the acromion (Giphart et al., 2012). Whereas the plane of elevation remains relatively constant during scaption, the humerus moves between posterior and anterior planes of elevation during propulsion such that the footprints are more likely to pass beneath multiple scapula structures. Indeed, scapula structure involvement scores were not significantly different between the acromion and CA ligament (Fig. 7B). Thus, particularly during certain non-planar motions, more than one structure may be more likely to cause impingement.

Though a relatively small proportion of the total propulsion cycle was characterized by mechanical impingement, the frequency with which this task is completed is important to consider when comparing risk scores. On average, individuals with SCI who use a MWC propel for 1 hour per day, consisting of approximately 95 bouts lasting 35 seconds each (Sonnenblum et al., 2012). In this time, individuals are estimated to complete 1800 propulsion cycles (van der Woude et al., 2009). Thus, despite a higher activity risk score for a single arm raise compared to a single propulsion cycle, both tasks are likely important to consider in terms of impingement, especially when factoring in daily completion.

4.3 Effect of External Load and Rolling Resistance

The data did not support the hypothesis that an increase in external load and rolling resistance during scaption and propulsion would increase mechanical impingement risk. However, though differences in scaption activity risk scores were not significant, individual scores were greater for the 2 kg and/or 4 kg condition compared to the trial with no handheld load in the majority of participants (Fig. 5A). Additionally, median absolute minimum distances for the infraspinatus and supraspinatus footprints decreased as loading increased (Table 1). Similarly, for propulsion, no significant differences were found between activity risk scores for the various resistance conditions. However, individual scores were greater for the high resistance compared to low resistance in half of the participants (Fig. 5B).

Importantly, though loading was not found to have a statistically significant effect on activity risk, both scaption and propulsion exhibited periods of mechanical impingement, even in the absence of an external load or added resistance. This finding highlights the significance of the kinematics inherent to a task as a precipitating factor for impingement. Though outside the scope of this study, it is possible that greater loads/resistances during scaption/propulsion

than those used in the present study would have a greater impact on risk scores. Other factors, such as the level of incline encountered during propulsion, may also be important to consider due to the more direct impact this has on posture and subsequent shoulder kinematics.

4.4 Pressure Relief Risk

Previous studies characterizing shoulder motion in individuals with SCI who use a MWC have suggested that the weight-relief raise is likely associated with impingement based on joint kinematic measures (Morrow et al., 2011; Nawoczenski et al., 2012; Riek et al., 2008). As a result, these investigators advocate an alternate pressure relief approach, such as the sideways lean, which potentially lessens impingement risk by reducing superior migration of the humeral head beneath the CA arch (Kulig et al., 1998). Contrary to these studies, 9 of 10 participants had no footprint – CA arch distances that were less than the tendon thicknesses for either pressure relief technique, with distances that seldom fell below 8 mm (Table 1 and Fig. 3). Indeed, activity risk scores for both pressure reliefs were significantly lower than propulsion and scaption, and not different from one other (Fig. 4). This finding demonstrates the importance of direct measurement of the subacromial space rather than relying solely on kinematic measures to estimate impingement risk.

Despite minimal or no impingement risk during the pressure reliefs, recurrent exposure of the shoulder to high mechanical loads is worthy of consideration in terms of risk of pain and injury. Clinical practice guidelines recommend performing a pressure relief every 15 – 30 minutes (Garber et al., 2000), with an average duration of 2 minutes needed to allow complete reperfusion (Coggrave and Rose, 2003). Given the high loads imposed on the glenohumeral joint during the conventional weight-relief raise (van Drongelen et al., 2005; van Drongelen et al., 2011), cumulative fatigue could have downstream effects on posture and kinematics during this and other tasks. The sideways lean, which likely reduces loading of the shoulder compared to the weight-relief raise, may therefore still be preferred.

4.5 Limitations

This study had limitations that should be considered. First, tendon thicknesses were measured at a single long axis location along each tendon. Given the potential heterogeneity in tendon thickness within the footprint region, this simplification may have had an impact on the magnitude of the reported impingement metrics. Additionally, the subacromial bursa, which may reduce the distance required for tendon compression to occur, was not measured. For this reason, descriptive comparisons between absolute minimum distances were also included in order to comment on impingement risk independent of tendon and bursa geometry. Second, the analyzed region of glenohumeral elevation during scaption (40° – 80°), selected as the common range spanned by all participants, may have impacted risk scores. However, in a study that measured shoulder kinematics during unconstrained/self-selected overhead reaching, on average, glenohumeral elevation was found to start at -7.4° and peak at 96.9° (Braman et al., 2009). Thus, the range examined in the present study is functionally relevant and within the workspace that is perhaps more typically used during daily living. Third, propulsion resistances were set based on target effort levels. Differences in perceived effort among participants for a given level may have existed and been an added

source of variation in risk scores. However, the trials represented three distinct conditions of ascending resistance, and scores were compared using a within-subjects repeated measures approach. Last, differences in pain and pathology among participants may have had variable effects on risk scores.

4.6 Conclusions

This study provides initial insights into aspects of daily tasks that are potentially detrimental for the shoulder in individuals with SCI who use a MWC. These findings should be considered in evaluating the frequency of and technique used to complete activities of daily living, MWC and user-wheelchair interface design, and/or modifications to the surrounding environment in order to lessen impingement risk. The risk metric defined in this study provides an empirical approach to evaluate whether such modifications, such as plane of elevation during reaching or MWC drive wheel position during propulsion, have a beneficial effect in terms of reducing impingement risk. Further work aimed at determining the shoulder elevation range and region of the workspace most commonly used when functioning from a MWC, the daily frequency of completion of specific activities of daily living, and propulsion frequency and incline encountered in the free-living environment is warranted to build on these findings.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Highlights

- Shoulder pain is limiting for manual wheelchair users with spinal cord injury
- Mechanical impingement may contribute to shoulder pain in manual wheelchair users
- Subacromial space was directly and accurately measured during wheelchair use
- Impingement common in scapular plane elevation and propulsion, not pressure reliefs
- Frequency of and technique used for wheelchair tasks should be carefully evaluated

Fig. 1: Subject-Specific Models.

A: Humerus model (superior view) with tendon footprint meshes overlaid (red= infraspinatus, blue= supraspinatus, orange= infraspinatus/supraspinatus region of overlap, green= subscapularis), and scapula model with CA ligament mesh (purple= CA ligament). B: 2D ultrasound images of the infraspinatus and supraspinatus (long axis), and subscapularis (short axis). Thickness was measured at the medial footprint of each tendon (red lines) and included the separate bundles of the subscapularis.

Fig. 2:

Sample time series for minimum distance between supraspinatus footprint and CA arch (acromion, CA ligament, coracoid) throughout low resistance propulsion for a representative subject. Only distance measures (d) that were less than the measured tendon thickness (dashed line) were considered in tendon risk scores, and scores were normalized according to tendon thickness and activity length. In this example, the # of distance measures below the tendon thickness (n) is 6, whereas the activity length (total # frames) is 37 (see equation in methods section 2.4 for reference).

Fig. 3: Minimum Distance Time Series.

Sample time series of minimum distance between a given footprint and the acromion [A] and CA ligament [B] for each frame of each activity for a representative subject.

Fig. 4:

Activity Risk Comparison. Median (blue dashed line) and interquartile range (black solid lines; bottom of box = Q1, top of box = Q3) of activity risk score for scaption (0 kg), propulsion (low resistance), sideways lean, and weight-relief raise. One participant per pressure relief had a nonzero risk score (median scores and interquartile ranges = 0). Max possible score = 300% (sum of infraspinatus, subscapularis, and supraspinatus tendon risk scores). Asterisks indicate significant pairwise differences.

Fig. 5: Activity Risk Loading Comparisons.

Median (blue dashed line) and interquartile range (black solid lines; bottom of box = Q1, top of box = Q3) of activity risk score for scaption [A] and propulsion [B] at each of 3 external loads/resistances. Individual participant activity risk scores (indicated by separate colors) for each condition in right column for each activity. Max possible score = 300% (sum of infraspinatus, subscapularis, and supraspinatus tendon risk scores). Note the different y-axis scale for each task.

Fig. 6: Tendon Risk Comparison.

Median (blue dashed line) and interquartile range (black solid lines; bottom of box = Q1, top of box = Q3) of tendon risk score for scaption (0 kg) [A] and propulsion (low resistance) [B]. Infra.= infraspinatus, sub.= subscapularis, supra.= supraspinatus. One participant had a nonzero subscapularis risk score during propulsion (median score and interquartile range = 0). Max possible score = 100%. Asterisks indicate significant pairwise differences. Note the different y-axis scale for each task.

Fig. 7: Scapula Structure Involvement Comparison.

Median (blue dashed line) and interquartile range (black solid lines; bottom of box = Q1, top of box = Q3) of structure involvement score for scaption (0 kg) [A] and propulsion (low resistance) [B]. Acr.= acromion, CAL= coracoacromial ligament. Max possible score = 300%. Asterisks indicate significant pairwise differences. Note the different y-axis scale for each task.

Table 1:
Tendon and Scapula Structure Absolute Minimum Distances.

Group median absolute minimum distances and interquartile ranges by activity. For entries in the tendon column, the minimum distance across vertices within the specified footprint (infraspinatus, subscapularis, supraspinatus) to the nearest scapula structure was determined at each frame for a given activity for each participant. Similarly, for entries in the scapula structure column, the minimum distance across vertices within the specified structure (acromion, CA ligament, coracoid) to the nearest footprint was determined. The absolute minimum distance was then obtained by taking the minimum value across frames.

	Median (Q1 – Q3) [mm]	<i>Infraspinatus</i>	<i>Subscapularis</i>	<i>Supraspinatus</i>	<i>Acromion</i>	<i>CA Ligament</i>	<i>Coracoid</i>
Scaption	<i>0 kg</i>	2.6 (1.3 – 3.5)	4.4 (3.8 – 4.8)	1.5 (0.9 – 2.8)	1.5 (0.9 – 2.8)	4.1 (3.3 – 4.5)	13.7 (11.1 – 16.7)
	<i>2 kg</i>	1.7 (1.3 – 2.4)	4.2 (2.9 – 4.9)	1.2 (0.4 – 1.9)	1.2 (0.4 – 1.9)	4.4 (3.0 – 4.8)	13.8 (11.2 – 17.3)
	<i>4 kg</i>	1.7 (0.7 – 3.0)	4.4 (3.4 – 4.7)	1.0 (0.5 – 1.7)	1.0 (0.5 – 1.7)	4.3 (3.2 – 4.7)	14.0 (11.2 – 18.1)
Propulsion	<i>Low</i>	6.1 (4.6 – 9.1)	9.5 (7.0 – 10.3)	4.3 (3.4 – 6.1)	5.8 (4.2 – 9.3)	4.5 (3.4 – 6.3)	12.3 (9.9 – 15.5)
	<i>Medium</i>	6.7 (4.0 – 9.2)	9.4 (6.7 – 11.7)	4.7 (3.3 – 6.4)	6.2 (3.3 – 9.4)	5.1 (3.7 – 6.6)	13.4 (10.0 – 15.8)
	<i>High</i>	7.0 (4.5 – 9.3)	9.7 (6.9 – 12.0)	5.1 (3.6 – 6.7)	5.8 (3.7 – 8.6)	6.2 (3.8 – 6.9)	13.4 (11.1 – 15.9)
Pressure Reliefs	<i>Sideways Lean</i>	14.1 (12.7 – 15.7)	11.5 (10.0 – 15.7)	11.2 (8.4 – 14.0)	13.6 (12.9 – 14.0)	11.2 (8.4 – 13.5)	11.9 (10.2 – 16.4)
	<i>Weight-Relief Raise</i>	13.9 (11.1 – 15.0)	10.6 (8.7 – 14.3)	10.2 (8.2 – 12.5)	12.8 (9.4 – 14.3)	10.2 (7.5 – 12.6)	12.4 (9.8 – 14.9)