Exercises With Optimal Scapulothoracic Muscle Activation for Individuals With Paraplegia

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Background: Individuals with paraplegia and coexisting trunk and postural control deficits rely on their upper extremities for function, which increases the risk of shoulder pain. A multifactorial etiology of shoulder pain includes "impingement" of the supraspinatus, infraspinatus, long head of the biceps tendons, and/or subacromial bursa resulting from anatomic abnormalities, intratendinous degeneration, and altered scapulothoracic kinematics and muscle activation. Targeting serratus anterior (SA) and lower trapezius (LT) activation during exercise, as part of a comprehensive plan, minimizes impingement risk by maintaining optimal shoulder alignment and kinematics during functional activities. To prevent excessive scapular upward translation, minimizing upper trapezius (UT) to SA and LT activation is also important. **Objectives:** To determine which exercises (1) maximally activate SA and minimize UT:SA ratio and (2) maximally activate LT and minimize UT:LT ratio. **Methods:** Kinematic and muscle activation data were captured from 10 individuals with paraplegia during four exercises: "T," scaption (sitting), dynamic hug, and SA punch (supine). Means and ratios were normalized by percent maximum voluntary isometric contraction (MVIC) for each muscle. One-way repeated measures analysis of variance determined significant differences in muscle activation between exercises. **Results:** Exercises were rank ordered: (1) maximum SA activation: SA punch, scaption, dynamic hug, "T"; (2) maximum LT activation: "T," scaption, dynamic hug, SA punch; 3) minimum UT:SA ratio: SA punch, dynamic hug, scaption, "T"; and (4) minimum UT:LT ratio: SA punch, dynamic hug, "T," scaption. Exercise elicited statistically significant changes in percent MVIC and ratios. Post hoc analyses revealed multiple significant differences between exercises ($p < .05$). **Conclusion:** SA punch produced the greatest SA activation and lowest ratios. Dynamic hug also produced optimal ratios, suggesting supine exercises minimize UT activation more effectively. To isolate SA activation, individuals with impaired trunk control may want to initiate strengthening exercises in supine. Participants maximally activated the LT, but they were not able to minimize UT while upright. **Key words:** *exercise, paraplegia, serratus anterior, surface electromyography, trapezius*

Individuals with paraplegia rely on their upper extremities for essential activities of daily living, including reaching overhead from a seated position, bed mobility, wheelchair propulsion, and transferring. The reliance on the upper extremities is hindered by musculoskeletal shoulder pain, a common secondary complaint following spinal cord injury (SCI).[1] In individuals with paraplegia, prevalence of shoulder pain ranges up to 66%.[2-6] Per Alm et al.,[4] 92% of individuals with paraplegia reported no shoulder pain before becoming a wheelchair user, whereas 67% reported a history of shoulder pain since becoming a wheelchair user. Shoulder pain is commonly attributed to chronic rotator cuff impingement syndromes and tears.[2,3] Akbar et al.[7] reported a 10-fold higher risk of rotator cuff rupture in individuals with long-term paraplegia than in age-matched controls.

Musculoskeletal pain is the most common type of pain following SCI[8] and frequently affects the shoulder joint.[9] Although risk factors associated with musculoskeletal shoulder pain have been studied in SCI, there is a dearth of SCI literature regarding the specific biomechanical etiology of this pain. Therefore, using best evidence as informed by non-SCI literature, a multifactorial etiology of shoulder pain from "impingement" includes anatomic abnormalities, posterior capsule or pectoralis minor tightness, and altered scapulothoracic kinematics and muscle activation. In non-weightbearing reaching activities, expected scapulothoracic joint motion during humerothoracic elevation in healthy

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shoulders includes upward rotation, posterior tilt, and, although there is variability between studies and planes of motion, external rotation.[10,11] Simultaneously, the humerus laterally rotates between 20 and 120 degrees of elevation, increasing subacromial space and decreasing impingement risk.[10] Prior investigations demonstrated that individuals with subacromial impingement syndrome have altered kinematics, including decreased scapular posterior tilt,[12-16] external rotation,[12,17-19] and upward rotation,[12,14-15,20] and increased scapular elevation[13] during arm elevation tasks. In weightbearing weight-relief raises, bed mobility, and transfer activities, individuals with SCI must also rely on reverse actions to lift the trunk and pelvis relative to a fixed scapula and humerus. Controlled motion during these newly acquired skills can be particularly challenging when performed by individuals with balance deficits.

Muscle activation guides glenohumeral and scapular kinematics. The serratus anterior (SA), referred to as the "prime mover" of the scapula, contributes to all components of optimal scapular motion (posterior tilt, external and upward rotation) with respect to the thorax during non-weightbearing arm elevation.[21] The lower trapezius (LT) is also responsible for external and upward rotation, although not posterior tilt. Collectively, the SA, LT, and upper trapezius (UT) position the glenoid to maximize glenohumeral elevation. However, without balanced activation of the rotator cuff and other scapulothoracic musculature, the UT can contribute to unwanted scapular upward translation with an excessive "shoulder-shrug" during humeral elevation, as demonstrated in individuals with impingement or rotator cuff damage.[22] Although variable in the literature, a reduction in SA,[12-13,15,23] LT,[23,24] and/or excessive UT[12,23,25] activation has been observed in individuals with shoulder pain and symptoms of impingement. Muscles also work synergistically and can be depicted as ratios (UT:SA, UT:LT) with the goal to minimize excessive UT activation with respect to SA and LT. For example, Michener et al.[26] reported that individuals with subacromial impingement syndrome had a higher UT:LT ratio during arm elevation. In weightbearing weight-relief raises, bed mobility, and transfer activities, the thoracohumeral depressor muscles, including the latissimus dorsi and pectoralis major, are also responsible for elevating the trunk and pelvis, protecting the rotator cuff from impingement. Although not the focus of this article, deficient thoracohumeral depressor muscles have been linked to impingement and resultant shoulder pain in this population.

Addressing the causes of shoulder pain is complicated and requires a comprehensive approach. Targeted exercise is an important element of this multifaceted rehabilitation program along with seating and postural improvements, glenohumeral exercises, and activity selection and performance. Home exercise programs varying from a scapula-focused exercise program[27] to hypertrophy and endurance exercises[28] to a high-dose scapular stabilizer and rotator cuff strengthening program[29] have resulted in shoulder pain reduction up to 30% as measured by the Wheelchair User's Shoulder Pain Index (WUSPI).

Although previous SCI interventions have reduced shoulder pain, there is room for improvement as pain is not consistently eliminated.[27-29] Instead of muscle-specific strengthening purposefully guiding optimal shoulder kinematics, many investigations rely on global strengthening.[28-30] Additionally, there is an absence of biomechanical analysis to verify that specific musculature is effectively targeted during selected exercises in individuals with paraplegia.[28-30] Alternatively, exercises can be selected that target specific musculature, either by decreasing UT and/or increasing SA or LT activation. These muscles can be represented collectively as ratios, UT:SA and UT:LT. Recall that individuals with paraplegia, seated at a wheelchair level, by necessity overuse their upper extremities for essential functional activities. Overuse occurs during non-weightbearing reaching overhead from the seated position and during weightbearing to lift the body to and from various surfaces including the bed, wheelchair, commode, and car. Targeted strengthening of scapular muscles has the potential to mimic muscle activation required during daily functional activities. For example, by targeting the scapular stabilizers, scapulothoracic rhythm can be optimized for reaching into a cupboard, for example, and a stable base can be created for humerus movement in both non-weightbearing and dynamic weightbearing activities.

Exploring non-SCI literature and prioritizing the "prime mover," we investigated exercises that emphasize SA activation and provide the lowest UT:SA ratio. Examples of exercises that produced high SA activation included standard push-up plus (123% maximum voluntary isometric contraction [MVIC]),[31] dynamic hug (109% MVIC [greatest peak]),[32] loaded scaption (55.2% MVIC),[33] and unilateral shoulder press (62% MVIC).[34] Examples of exercises with low UT:SA ratio (<0.2) included standard push-up plus (<0.2),[31] bilateral scapular protraction (0.13),[34] and supine press (0.11).[34] Informed by non-SCI literature, four common exercises were selected that were hypothesized to maximize SA activation and minimize UT:SA ratio, and they could be easily performed in rehabilitation and/or home settings by individuals with paraplegia. Additionally, exercises were selected to eliminate confounding factors as necessitated in a surface electromyography (EMG) study comparing exercises (i.e., length of muscle, type of muscle contraction) and were physically possible in a group with paraplegia (i.e., standing or pushup on toes not required).

In summary, a potential primary cause of shoulder pain in individuals with paraplegia is rotator cuff impingement due to altered muscle activation and kinematics. Although exercise interventions focused on muscle groups have had some success, there is potential for targeted muscle strengthening interventions, as a component of a comprehensive program, to increase effectiveness. However, there is a lack of investigations into exercises that optimize SA while minimizing UT muscle activation. The primary aim of this study was to determine which exercises maximally activate the SA and minimize the UT:SA ratio in individuals with paraplegia. The secondary aim was to determine which exercises maximally activate the LT and minimize the UT:LT ratio. It was hypothesized that SA punch would produce the greatest SA activation with a minimal UT:SA ratio.

Methods

Design and participants

A convenience sample of 10 individuals with paraplegia (52.6 ± 7.6 years; range, 39-62), nine SCI and one hereditary/familial spastic paraplegia, who were primary wheelchair users participated in this cross-sectional observational design study (**Table 1**). Participants self-reported their activity

Table 1. Participant characteristics

Etiology of paraplegia	Age, years	Sex	Time since injury, years	Level of injury	AIS
Traumatic SCI	NS	Female	24	T4/5	AIS B
Traumatic SCI	NS	Male	21	T6/7	AIS C
Traumatic SCI	NS	Male	2	T10/12	AIS A
Traumatic SCI	NS	Male	5	T4	AIS C
Traumatic SCI	NS	Male	3	T10/11	AIS C
Traumatic SCI	NS	Male	22	T10	AIS A
Traumatic SCI	NS	Male	10	T4	AIS A
Traumatic SCI	NS	Male	24	T10/12	AIS A
Traumatic SCI	NS	Male	26	T7/8	AIS A
Hereditary spastic paraplegia	NS	Male	NA	NA	NA
Mean (total sample traumatic SCI/total sample paraplegia)	53.6/53.1	NA	13.9/NA	NA	NA
SD (total sample traumatic SCI/total sample paraplegia)	8.3/7.9	NA	9.8/NA	NA	NA

Note: AIS = American Spinal Injury Association Impairment Scale; N/A = not applicable; NS = not specified (to ensure de-identification of participants); SCI = spinal cord injury.

level with an average of 17.7 ± 6.5 transfers/day. Based on pilot data, a sample size of at least 10 participants was calculated with a power analysis for a within-factors repeated-measures analysis of variance (RM-ANOVA) to detect differences in SA, LT, and UT muscle activation across exercises while achieving a moderate effect size of at least 0.4 with an alpha set at 0.05 and 80% power. A 0.4 effect size is a conservative estimate because it allows between-exercise differences of 10% to 15% to be statistically identified with variables that are twice that magnitude. Additionally, with a repeated-measures design, each participant is compared with themselves, which decreases variance in the error term. Inclusion criteria included at least 1-year post SCI from congenital conditions or trauma, vascular, or orthopedic origin resulting in American Spinal Injury Association (ASIA) International Standards for the Neurological Classification of Spinal Cord Injury (ISNCSCI)[35] classification at or distal to the second thoracic neurological level of injury. Although enrollment was not specifically restricted based on ASIA Impairment Scale (AIS),[35] participants were required to use a manual wheelchair for primary mobility. To rule out shoulder pain that potentially interferes with exercise performance or muscle activation, exclusion criteria included positive clinical tests (painful arc, Hawkins-Kennedy, Neer),[36-39] shoulder pain greater than 3 out of 10 during one-repetition maximum (1RM) testing, or a score greater than 10/150 on the WUSPI. Participants signed university-approved human subject informed consent documents prior to participation.

Instrumentation

Three-dimensional kinematic data of the right humerus relative to the thorax were captured by the 11-Camera Vicon Motion Capture System (Oxford, UK) at a 100 Hz sampling rate. Right shoulder surface EMG data were captured by 16-channel Delsys Trigno Wireless EMG System (Natick, Massachusetts) using Trigno Avanti sensors (27 × 37 × 13 mm) with interelectrode spacing of 10 mm. The sensors have a noise level of <0.75 μV, a common mode rejection ratio of less than -80 dB at 60 Hz, and a bandwidth of 20 to 450 Hz. The EMGworks oscilloscope (Delsys Inc., Natick, MA) was used to verify raw signals, and Vicon Nexus software (Oxford Metrics plc, Yarnton, UK) was used to acquire data.

Procedures

Participants attended a single session lasting 1 to 2 hours and were overseen by the same licensed physical therapist. During the musculoskeletal examination, demographic and medical data were collected from each participant (i.e., sex, age, height, weight, and activity level). Activity level was self-reported by the participant describing transfers performed within a typical day. The investigator tallied each transfer, scoring both to and from each surface as a single transfer. All participants were tested in their custom wheelchair.

Three-dimensional kinematics

To identify the concentric phase of each exercise, motion capture markers were applied to determine the joint axis and track three-dimensional motion of the right humerus relative to the thorax. Markers were applied with double-sided adhesive to the following locations: seventh cervical and sixth thoracic spinous processes, midway between the medial border of both the right and left scapula and spine, midway and inferior to the left scapular spine, superior aspect of the right acromion, lateral mid portion of right upper arm, superior and lateral to right lateral epicondyle, manubrium, center of radius, and radial and ulnar styloid processes (**Figure 1**).

EMG electrode placement

After skin preparation with an alcohol swab, surface electrodes were attached parallel to muscle fibers on the right upper extremity: SA (level of scapular inferior angle, anterior to latissimus dorsi), UT (halfway between the seventh cervical spinous process and acromion process), LT (55-degree oblique angle, 5 cm down from the scapular spine, next to scapular medial border), and middle deltoid (lateral aspect upper arm, 3 cm below the acromion) (**Figure 1**).

Exercise Description	Standardized Video Instructions
(A) Scaption  **Start Position:** Sit in wheelchair. Grasp dumbbell in hand with thumb facing up and shoulder at 60° scapular plane elevation. Opposite hand grasp wheelchair for support/safety. **End Position:** Shoulder at 90° scapular plane elevation with thumb facing up.	1. Follow the metronome to keep a slow and controlled pace of 3 seconds up and 3 seconds down. 2. Do not hold your breath. 3. Sit straight in chair. 4. With opposite arm, hold wheelchair for balance. 5. Start with arm out to the side and slightly forward. 6. Slowly raise arm to horizontal with thumb pointing up. 7. Lower arm back down to start position. 8. Repeat for a total of 8 repetitions.
(B) "T"  **Start Position:** Sit in wheelchair, leaning forward. Shoulder at 60° abduction. Opposite hand grasp table for support/safety. **End Position:** Shoulder at 90° abduction.	1. Follow the metronome to keep a slow and controlled pace of 3 seconds up and 3 seconds down. 2. Do not hold your breath. 3. Sit in chair. Lean forward onto pillow, keeping good posture (try not to round your back). 4. Raise one arm out to the side, by squeezing your shoulder blades together. 5. Lower arm back down to start position. 6. Repeat for a total of 8 repetitions.

Figure 1. Exercises. (A) scaption; (B) "T"; (C) dynamic hug; (D) serratus anterior punch.

Exercise Description	Standardized Video Instructions
(C) Dynamic Hug  **Start Position:** Lie supine. Elbows flexed to 90° and shoulders at 70° abduction and neutral rotation. Exercise performed bilaterally to ensure balance/correct movement pattern. **End Position:** Elbows flexed ~45° and shoulders horizontally adducted to 70° of shoulder elevation with neutral pronation (palms facing each other) and scapular protraction.	1. Follow the metronome to keep a slow and controlled pace of 3 seconds up and 3 seconds down. 2. Do not hold your breath. 3. Lie on your back. 4. Place elbows away from body and bent, hands up towards ceiling. 5. Keep elbows bent. 6. Hug the air with palms facing each other, bringing shoulder blades away from each other. 7. Return to start position. 8. Repeat for a total of 8 repetitions.
(D) SA Punch  **Start Position:** Lie supine. 90° shoulder flexion with elbow fully extended, scapula retracted. Opposite hand grasp mat table for support/safety. **End Position:** 90° shoulder flexion with elbow extended and scapula protracted.	1. Follow the metronome to keep a slow and controlled pace of 3 seconds up and 3 seconds down. 2. Do not hold your breath. 3. Lie on your back. 4. Straighten one arm up towards the ceiling. 5. Keeping elbow straight, punch toward the ceiling by lifting your shoulder blade off the mat. 6. Return to start position. 7. Repeat for a total of 8 repetitions.

Figure 1. *(cont.)*

Normalization of EMG data

To compare EMG data across participants and exercises, muscle activation during each exercise was normalized to the maximum voluntary isometric contraction (MVIC) for each muscle. Standardized muscle testing positions were used.[40] Each muscle's resting level was recorded to identify baseline background activity. Data were then recorded for two repetitions of manually resisted MVICs for each muscle. Mean EMG value of the middle 3 seconds of two trials was used to normalize EMG data for each muscle. During the concentric phase of each exercise, data for each muscle were reported as percent (%) MVIC.

Exercise training and resistance determination

After the musculoskeletal examination, participants were shown standardized instructional exercise videos. Participants practiced with a 1-lb weight to ensure correct form without risk of fatigue. Similar to other SCI investigations,[41-43] the Mayhew Regression[44] was utilized to safely predict the 1RM for each exercise in a potentially vulnerable population. For each exercise, weight was increased incrementally until the participant was able to complete greater than three but fewer than eight repetitions with a dumbbell. Completed weight (Wt) and number of repetitions (Reps) were input into the Mayhew Regression: [$1RM = Wt / (0.533 + 0.419 \times e^{-0.055 \times Reps})$].

Exercise trials

Participants completed eight repetitions per exercise: "T" and scaption in sitting and dynamic hug and SA punch in supine (**Figure 1**). Exercises were tested using dumbbells at 60% 1RM in random order and paced by a metronome. To lessen fatigue potential, a minimum of 5 minutes of rest was allocated between exercises. Exercises were performed unilaterally with the exception of dynamic hug, which was performed bilaterally to accomplish the movement pattern and to keep the participant balanced (**Figure 1**). Simultaneous kinematic and muscle activation data were captured during the exercises.

Data reduction and statistical analysis

Using C-Motion Visual3D software, muscle activation data were normalized as %MVIC as described earlier. Mean SA, LT, and UT muscle activation during the concentric phase of each exercise were calculated; from these means, UT:SA and UT:LT ratios were calculated for each participant. Means, standard deviations, and confidence intervals of SA, LT, and UT muscle activation and UT:SA and UT:LT ratios across all participants were then calculated. One-way RM-ANOVA was conducted using PASW software

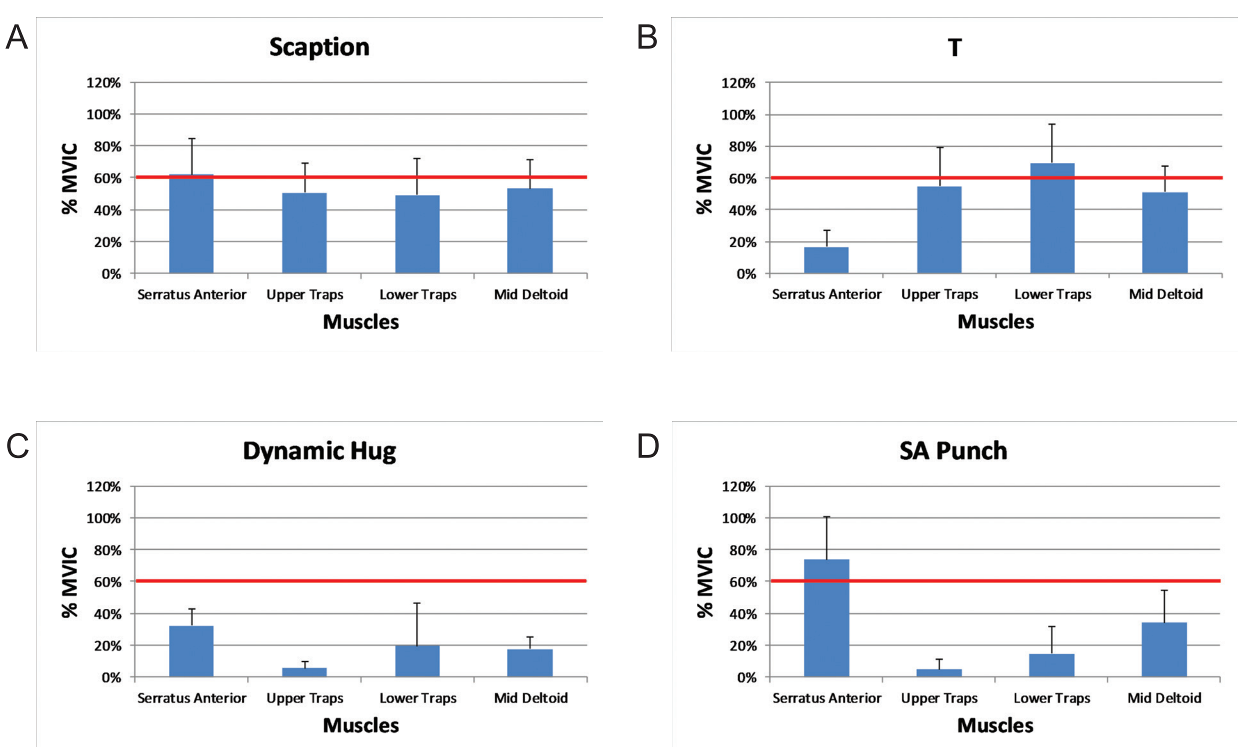

Figure 2. Percent muscle activation across exercises. (A) Scaption; (B) "T"; (C) dynamic hug; (D) serratus anterior (SA) punch. % MVIC = percent maximum voluntary isometric contraction.

version 27.0 (SPSS, Inc., Chicago, IL) to determine statistically significant differences in muscle activation (%SA, %LT, or %UT) or ratios (UT:SA or UT:LT) between the four exercises. Data were assessed for outliers and normal distribution. If assumption of sphericity was violated as demonstrated by Mauchly's test of sphericity, Greenhouse-Geisser correction was used.

Results

Using Greenhouse-Geisser correction when indicated, exercise intervention elicited statistically significant changes in UT muscle activation [$F(2.264, 0.657) = 31.004$, $p < .0005$, partial eta squared (η^2) = 0.775], SA muscle activation [$F(3,27) = 36.924$, $p < .0005$, partial $\eta^2 = 0.804$], LT muscle activation [$F(1.914, 17.228) = 20.727$, $p < .0005$, partial $\eta^2 = 0.697$], UT:SA ratio [$F(1.010, 9.086) = 12.074$, $p < .007$], and UT:LT ratio [$F(3, 27) = 12.588$, $p < .0005$, partial $\eta^2 = .583$]. Bonferroni post hoc analysis revealed multiple significant differences between exercises ($p \leq .05$) (**Tables 2** and **3**). For each muscle, exercises are rank ordered from most to least optimal muscle activation (**Table 2**). Similar to prior investigations, each exercise is also categorized by activation level: low (0%-20% MVIC), moderate (21%-40% MVIC), high (41%-60% MVIC), and very high (>60% MVIC) (**Table 2**).[45] Exercises are also rank ordered from most to least optimal UT:SA and UT:LT ratios (**Table 3**).

Discussion

Although prior interventions offer some shoulder pain relief with global strengthening exercises, individuals with paraplegia must continue using their upper extremities for functional independence without the luxury of resting painful joints. A current guide to address shoulder pain includes scapular stabilizer strengthening, as a component of a comprehensive program, alongside strengthening of the thoracohumeral depressor muscles, stretching to maintain shoulder joint flexibility, and activity modification.[46] Despite an abundance of evidence in non-SCI literature supporting exercises that target specific scapulothoracic musculature, we cannot assume individuals with paraplegia will respond similarly. Individuals with paraplegia and strength deficits involving the trunk often perform exercises while stabilizing with their upper extremities to maintain their balance and in positions of poor postural alignment. To our knowledge, this is the first study to examine targeted muscle activation across commonly prescribed upper extremity exercises selected specifically for individuals with paraplegia.

Our hypothesis was supported that SA punch produced the greatest SA activation and most optimal UT:SA ratio. Although seated scaption produced comparable levels of SA activation to SA punch (>60% MVIC; **Table 2** and **Figure 2**), it resulted in a higher UT:SA ratio (.87; **Table 3**). Only dynamic hug, a supine exercise, was able to maintain a comparably low UT:SA ratio (0.2; **Table 2**). Conversely, LT was activated significantly more in sitting ("T" and scaption) versus either supine exercise (**Figure 2**). Sitting exercises also had highest UT activation, resulting in UT:LT at 0.86 and 1.28, respectively. These results in a population with impaired trunk control are consistent with non-SCI investigations that noted increased UT activity when upper extremity exercises are performed in a vertical trunk position.[47]

Three out of four exercises in this investigation achieved a comparably low UT:SA ratio (**Table 3**) as compared with standard pushup plus[31] and all phases of weighted scapular plane elevation in a non-SCI control group (0.92-1.27).[47] Our findings for UT:SA ratios during supine exercises were slightly lower ($\leq$0.2) than Huang et al.[48] reported for the concentric phases of weighted forward flexion (0.67), knee pushup plus (0.45), and side lying external rotation (1.02). Supine UT:LT ratios were slightly higher than those for UT:SA (**Table 3**), which was not surprising considering the extremely low LT activation in supine (**Table 2**). Our recommendations are consistent with prior recommendations of ratios of less than 0.6 being considered optimal.[49,50]

Importantly, our investigation included commonly performed exercises in positions feasible for those with paraplegia and explored options from supine to sitting (leaning anteriorly with opposite hand or forearm supported on table) to sitting (upright). These findings support a logical progression of exercises transitioning from supine with more trunk support to a more challenging, yet functional upright position. Investigations using surface EMG performed in the non-SCI

Table 2. Descriptive statistics for serratus anterior, lower trapezius, and upper trapezius muscle activity level represented as maximum voluntary isometric contraction (% MVIC) and associated 95% confidence intervals (95% CI)

Exercise	Activation level category	Mean (% MVIC)	*SD* (% MVIC)	Lower boundary 95% CI (% MVIC)	Upper boundary 95% CI (% MVIC)	Post hoc analysis
Serratus anterior						
SA punch	Very high	73.7	± 19.2	59.9	87.4	> T, DH
Scaption	Very high	62.1	± 19.9	48.2	76.3	> T, DH
Dynamic hug	Moderate	32.4	± 8.8	26.1	38.6	< S, > T, < SAP
"T"	Low	16.5	± 12.0	8.0	25.1	< S, DH, SAP
Lower trapezius						
"T"	Very high	69.3	± 38.9	41.5	97.1	> DH, SAP
Scaption	Moderate	49.1	± 30.4	27.3	70.8	> DH, SAP
Dynamic hug	Low	19.4	± 22.1	3.6	3.5	< S, T
SA punch	Low	14.6	± 13.6	4.9	2.4	< S, T
Upper trapezius						
SA punch	Low	4.9	± 5.0	1.3	8.4	< S, T
Dynamic hug	Low	5.6	± 5.1	2.0	9.3	< S, T
Scaption	High	50.6	± 21.4	35.3	65.9	> DH, SAP
"T"	High	54.9	± 29.9	33.5	76.3	> DH, SAP

Note: Bonferroni post hoc analysis revealed multiple significant differences between exercises ($p < .05$). Differences between exercises are identified by the following abbreviations: scaption (S), T (T), dynamic hug (DH), SA punch (SAP). Exercises are displayed in rank order for each muscle from most to least optimal muscle activation. Each exercise is categorized by activation level from low (0%-20% MVIC), moderate (21%-40% MVIC), high (41%-60% MVIC), and very high (>60% MVIC).

population frequently use positions like pushups in various prone (i.e., standard,[31,32] knee,[31,32] or elbow pushup plus[31]) or standing (i.e., wall pushup plus,[31] towel wall slide[33]) that are not always feasible for individuals with paraplegia to perform. Similar to the pushup exercises utilized in the non-SCI population, the supine exercises (SA punch and dynamic hug) emphasize protraction, which is a primary function of the SA. Undoubtedly, active scapular upward rotation during humeral elevation would necessitate more coordinated, balanced activation from all muscles in the force couple, SA, LT, and UT, thus supporting the progression from supine to more challenging sitting exercises.

Limitations

The complex nature of shoulder pain undisputedly requires a complex solution, including but not limited to targeted muscle activation, hand positioning during functional activities, and seated posture. Although attention to altered scapulothoracic

Table 3. UT:SA and UT:LT ratios and associated 95% confidence intervals (95% CI)

Exercise	Mean	*SD*	Lower boundary 95% CI	Upper boundary 95% CI	Post hoc analysis
UT:SA					
SA punch	0.06	± 0.05	0.03	0.10	< S, T
Dynamic hug	0.20	± 0.20	0.06	0.35	< S, T
Cutoff mean values < 0.6					
Scaption	0.87	± 0.38	0.60	1.14	> DH, SAP
T	5.46	± 4.77	2.05	8.88	> DH, SAP
UT:LT					
SA punch	0.38	± 0.24	0.21	0.55	< S, T
Dynamic hug	0.53	± 0.61	0.10	0.97	< S
Cutoff mean values < 0.6					
T	0.86	± 0.33	0.62	1.10	> SAP
Scaption	1.28	± 0.62	0.83	1.73	> DH, SAP

Note: Bonferroni post hoc analysis revealed multiple significant differences between exercises ($p < .05$). Differences between exercises are identified by the following abbreviations: scaption (S), T (T), dynamic hug (DH), SA punch (SAP). A cutoff is displayed with mean values < 0.6 considered optimal. Exercises are displayed in rank order from smallest to largest ratio with arrows pointing toward the most optimal ratios. UT:LT = upper trapezius to lower trapezius ratio; UT:SA = upper trapezius to serratus anterior ratio.

kinematics and muscle activation is considered an important element of a comprehensive rehabilitation program, it is unclear whether these alterations are a primary cause of or consequence of shoulder pain.[51] Despite consistent improvements in pain and disability with therapeutic interventions,[51] the most essential elements in prevention and treatment of subacromial impingement pain are unknown. In individuals with paraplegia, who perform frequent overhead reaching from a wheelchair level, the important role of the upper trapezius, assisting with scapular upward rotation and suspending the shoulder girdle, must be acknowledged. The goal should not be to eliminate upper trapezius functioning during exercise prescription but rather to balance its functioning alongside the other muscles within the force couple. Although limited to two muscles at a time, muscle ratios are one way to appreciate balanced muscle contributions. Despite the symbiotic relationship, glenohumeral musculature was not included in this investigation. There is a fair amount of evidence on incidence, prevalence, and risk factors of shoulder pain after SCI. However, there is a dearth of SCI literature on biomechanical or neuropathic origin of shoulder pain, which necessitates reliance on non-SCI literature as best evidence. Biomechanical origin of shoulder pain (muscle activation or kinematics) may differ in individuals with paraplegia. Additionally, our interventions focused on the mechanisms of impingement during non-weightbearing reaching activities such as reaching overhead while in bed or from a wheelchair. Our interventions did not target the weightbearing mechanisms of impingement in SCI, including the role of thoracohumeral depressors during critical functional tasks, such as lifting the trunk and pelvis during bed mobility, weight relief, and transfers. Likewise, our interventions did not focus on the mechanisms of impingement during non-weightbearing static activities such as the role of pectoralis minor flexibility or glenohumeral musculature strength in achieving upright posture and shoulder alignment in seated positions. Our sample included individuals with paraplegia without shoulder pain. It is feasible that participants with musculoskeletal shoulder pain may have different muscle activation than those without pain. Additionally, we had a heterogenous population with paraplegia by including one individual with hereditary spastic paraplegia, who could theoretically respond differently from those with traumatic SCI. However, data were consistent without notable outliers. It was beyond the scope of this study to determine if various etiologies of paraplegia or levels of injury including tetraplegia factor into results.

Controlling for potential confounding factors (length, type of muscle contraction, and velocity) allowed us to more confidently interpret surface EMG as an indirect measurement of muscle force. Specifically, exercises were selected where arm elevation remained between 60 and 90 degrees, only concentric phases were analyzed, and a metronome ensured consistent pacing. We were not able to compare and contrast other potentially beneficial exercises including those in prone positions in which we could not control for confounding factors. For instance, prone "Is" and "Ys" would surpass the 60 to 90 degree elevation requirement. Despite all four exercises ensuring humeral elevation between 60 and 90 degrees, the two supine exercises (dynamic hug and SA punch) produce predominantly scapular protraction, without necessitating the same degree of active upward rotation as the sitting exercises ("T" and scaption). Therefore, one should expect more isolation of the SA during supine exercises, with minimal UT or LT activation. As noted, we used surface EMG for all muscles, including SA, which can be challenging in participants with higher body mass index. Mean (*SD*) for body mass index for our population (27.0 ± 6.0) is considered outside the normal range (24.9) recommended by the Centers for Disease Control and Prevention.[52] To verify electrode placement, an oscilloscope was used during initial MVIC testing.

Clinical implications

Addressing potential biomechanical origin of musculoskeletal shoulder pain following paraplegia, a comprehensive rehabilitation program should include targeted muscle activation. Findings from this investigation demonstrated that SA punch produced the greatest SA activation and lowest UT:SA and UT:LT ratios. Dynamic hug also produced optimal UT:SA and UT:LT ratios, suggesting that supine exercises are better at minimizing excessive UT activation. Individuals with more impaired trunk control may initially perform strengthening exercises in supine to more selectively isolate muscle activation. However, to maximally activate the LT, an upright position may be indicated. Upright positioning may be preferred for some wheelchair users to limit transfers or to improve access in public gyms, for example, or to simulate functional positions. Biofeedback may provide valuable insight with isolating muscle activation with a vertical, unsupported trunk.

Conflicts of Interest

The authors declare no conflicts of interest.

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