Improving Shoulder Kinematics in Individuals With Paraplegia: Comparison Across Circuit Resistance Training Exercises and Modifications in Hand Position

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Background. Circuit resistance training (CRT) should promote favorable kinematics (scapular posterior tilt, upward rotation, glenohumeral or scapular external rotation) to protect the shoulder from mechanical impingement following paraplegia. Understanding kinematics during CRT may provide a biomechanical rationale for exercise positions and exercise selection promoting healthy shoulders.

Objective. The purposes of this study were: (1) to determine whether altering hand position during CRT favorably modifies glenohumeral and scapular kinematics and (2) to compare 3-dimensional glenohumeral and scapular kinematics during CRT exercises.

Hypotheses. The hypotheses that were tested were: (1) modified versus traditional hand positions during exercises improve kinematics over comparable humerothoracic elevation angles, and (2) the downward press demonstrates the least favorable kinematics.

Design. This was a cross-sectional observational study.

Methods. The participants were 18 individuals (14 men, 4 women; 25–76 years of age) with paraplegia. An electromagnetic tracking system acquired 3-dimensional position and orientation data from the trunk, scapula, and humerus during overhead press, chest press, overhead pulldown, row, and downward press exercises. Participants performed exercises in traditional and modified hand positions. Descriptive statistics and 2-way repeated-measures analysis of variance were used to evaluate the effect of modifications and exercises on kinematics.

Results. The modified position improved kinematics for downward press (glenohumeral external rotation increased 4.5° [P=0.016; 95% CI=0.7, 8.3] and scapular external rotation increased 4.4° [P<0.001; 95% CI=2.5, 6.3]), row (scapular upward rotation increased 4.6° [P<0.001; 95% CI=2.3, 6.9]), and overhead pulldown (glenohumeral external rotation increased 18.2° [P<0.001, 95% CI=16, 21.4]). The traditional position improved kinematics for overhead press (glenohumeral external rotation increased 9.1° [P=0.001; 95% CI=4.1, 14.1], and scapular external rotation increased 5.5° [P=0.04; 95% CI=1.8, 9.2]). No difference existed between chest press positions. Downward press (traditional or modified) demonstrated the least favorable kinematics.

Limitations. It is unknown whether faulty kinematics causes impingement or whether pre-existing impingement causes altered kinematics. Three-dimensional modeling is needed to verify whether “favorable” kinematics increase the subacromial space.

Conclusions. Hand position alters kinematics during CRT and should be selected to emphasize healthy shoulder mechanics.
Shoulder Kinematics in Individuals With Paraplegia

Spinocord injury (SCI) is the second most common cause of paralysis in the United States, with a prevalence exceeding 1.3 million people. Of those people with SCI, approximately 45% are classified as having paraplegia. Relying heavily on their upper extremities for functional independence, up to 67% of people with paraplegia report having existing shoulder pain. Chronic shoulder pain following SCI is consistently reported during activities of daily living, including transfers, wheelchair propulsion and management, and lifting objects from overhead. Due to the risk of developing shoulder pain following paraplegia and its impact on functional independence, maintenance of shoulder health and prevention of shoulder pain are essential.

The majority (>70%) of shoulder pain is diagnosed as mechanical impingement. Impingement can be categorized as either subacromial (external) or internal based on the structures that are compressed or mechanically irritated. Subacromial impingement occurs at lower ranges of humerothoracic elevation (45°–60°) and affects structures that pass between the coracoacromial arch and the humeral head (Fig. 1A). Subacromial impingement is a contributor to rotator cuff tendinopathy development in people with SCI, as wheelchair users frequently function in lower ranges of humerothoracic elevation during functional tasks including transfers and wheelchair propulsion. Conversely, internal impingement occurs at higher ranges of humerothoracic elevation (above 105°) and affects the articular surface of structures that pass between the glenoid fossa and humeral head (Fig. 1B). Beyond approximately 90 degrees of arm elevation, internal impingement is more likely occurring than subacromial impingement. Internal impingement is also a likely contributor to rotator cuff tendinopathy development in people with SCI, as wheelchair users frequently function in higher ranges of humerothoracic elevation during functional tasks including reaching activities. Because individuals with SCI have the need to function at both lower and higher ranges of humerothoracic elevation, mechanical impingement (subacromial or internal) is believed to be a primary mechanism in the development of rotator cuff disease, which can progressively result in rotator cuff tears.

To date, shoulder kinematics, a potentially important etiologic factor for shoulder impingement, has primarily been described during exercise or functional activities in the able-bodied population. A study by Nawoczenski et al. in individuals with SCI and impingement, however, demonstrated potentially detrimental glenohumeral and scapular kinematics during weight-bearing tasks including transfers. For instance, findings include nearly 6 degrees of increased scapular anterior tilt on the trailing arm for the group with shoulder pain versus the group without shoulder pain during the lift-pivot phase of a transfer. As opposed to a preventive measure, exercise traditionally has been used following SCI as an intervention to treat shoulder impingement after it occurs.

Circuit resistance training (CRT) is one form of exercise that also is recommended across the rehabilitation spectrum to facilitate independent functioning with the upper extremities (Appendix). Despite the evidence to support physiological benefits of CRT exercise, few studies in the able-bodied population or SCI literature have analyzed or verified which exercises to select based on kinematic rationale for minimizing mechanical impingement risk. Furthermore, it also is unknown whether modifications to the exercises via changes in hand position can favorably influence kinematics during CRT. A recent study that investigated shoulder kinematics during execution of CRT demonstrated that certain exercises pose more mechanical impingement risk than others. Exercises were rank ordered from highest to lowest subacromial mechanical impingement risk (downward press, horizontal row, chest press, overhead pulldown, and overhead press) and internal mechanical impingement risk (overhead press and overhead pulldown) based on collective kinematic and exposure data.

Recommended upper extremity exercise programs ideally should promote the most favorable scapular or glenohumeral kinematics (scapular posterior tilt, upward rotation, or external rotation or glenohumeral or external rotation) during the exercise regimen to maximize the subacromial space and protect the shoulder from mechanical impingement. A more comprehensive understanding of the kinematics that occur during CRT at specific humerothoracic elevation ranges, linked to impingement risk, may provide guidance on which exercises to emphasize, modify, or eliminate with regard to maintaining a healthy shoulder.

The purposes of this study were: (1) to determine whether glenohumeral and scapular kinematics can be favorably modified during wheelchair-based CRT exercises by altering hand position and (2) to compare 3-dimensional (3D) glenohumeral and scapular kinematics during CRT exercises prescribed for individuals with paraplegia. We hypothesized that modified hand positions during 5 CRT exercises (overhead press, chest press, overhead pulldown, horizontal row, and downward press), as opposed to traditional hand positions, would result in more favorable scapular and glenohumeral kinematics (scapular posterior tilt, upward rotation, or external rotation or glenohumeral external rotation) when averaged over comparable humerothoracic elevation angles. We also hypothesized that during the 5 CRT exercises (traditional or modified position), the downward press would demonstrate the least favorable kinematics. The ultimate goal was to develop specific recommendations regarding exercise positions and selection of specific exercises for CRT that emphasize healthy shoulder mechanics.

Method

Study Design

We used a pure within-subject design with factors being hand position (2 levels) and exercise (5 levels for the lower range of humerothoracic elevation and 2 levels for the upper range of humerothoracic elevation).
Participants
Participants were part of a broader study and were recruited from the community as a sample of convenience. Twenty individuals (15 men, 5 women), ranging in age from 25 to 76 years, with paraplegia and minimal to no shoulder pain met the inclusion and exclusion criteria. Inclusion criteria were: greater than 1 year after SCI; SCI from trauma or of vascular or orthopedic origin, with an injury at the second thoracic level or below; and requiring a manual wheelchair for primary mobility. Exclusion criteria were trauma, dislocation or surgery of the glenohumeral or acromioclavicular joints, shoulder pain (pain/H11022 on the Wheelchair User’s Shoulder Pain Index), and positive impingement tests (including Hawkins, Neer, resisted external rotation, and painful arc) that may alter or prevent completion of exercise testing. All data collection and testing were conducted at a local community fitness center. Prior to participation in the study, all participants provided university-approved informed consent.

Exercise Protocol
Participants were seen for 2 sessions. During the first session, participants underwent a clinical evaluation that included a musculoskeletal evaluation and the completion of the Wheelchair User’s Shoulder Pain Index to ensure inclusion and exclusion criteria were met. The primary purpose of the initial session was to establish the 1-repetition maximum (1RM) that would be used during the subsequent session. The Mayhew regression equation was used to calculate the 1RM for each CRT exercise (overhead press, chest press, overhead pulldown, horizontal row, and downward press) and was calculated as follows:

\[ 1\text{RM} = \frac{W_t}{0.533 + 0.419e^{-0.055\times\text{reps}}} \]

where “Wt” is the resistance used in the last set in which between 3 and 8 repetitions were completed, and “reps” is the number of repetitions completed in the last set. This method of establishing the 1RM has been documented in previous SCI resistance training studies and is used to establish a safe starting point for CRT.

The testing protocol for the initial visit consisted of up to 10 warm-up repetitions for each CRT exercise at a minimum resistance. The protocol for traditional hand positions was followed for the chest press, overhead pulldown, and downward press and was selected based on the manufacturer’s recommended position (Appendix). The manufacturer’s recommended position for the horizontal row and overhead press were not explicit; therefore, the traditional hand positions were selected during pilot testing based on collective user preference. Testing was completed using the participant’s custom-designed wheelchair, each exercise was completed over 6 seconds and timed with a metronome, and 5 minutes of rest was allotted between exercises.

During the second session, scapular and glenohumeral kinematic data were acquired during CRT performed at a resistance set at 50% 1RM. One set of 10 repetitions using both a traditional hand position and a modified hand position for each CRT exercise was assessed (Appendix). The modified hand position was selected following pilot testing and based on the ultimate goal of maximizing overall favorable shoulder kinematics (scapular posterior tilt, upward rotation, or external rotation or glenohumeral external rotation) for each exercise. Modified hand positions were within the capacity of the equipment. The order of testing (traditional and modified hand positions) for all 5 CRT exercises was randomized to minimize potential systematic effects of fatigue. Similar to the initial visit, all participants were tested in their custom-designed wheelchair, each exercise was completed with a 6-second pattern, and 5 minutes of rest was allotted between hand positions and exercises.

Data Collection (Instrumentation)
An electromagnetic system (Flock of Birds mini-BIRD model 800, Ascension Technology Corp, Milton, Vermont) was used to collect 3D shoulder kinematic data during CRT at 100 Hz. Due to the
configuration of the CRT equipment and ease of access, the left upper extremity was tested. Electromagnetic surface markers were taped to the skin overlying the manubrium, superior surface of the acromion, and distal humerus via a thermoplastic cuff (Appendix). The reliability and accuracy of surface marker measures of shoulder kinematics with electromagnetic systems have been described previously.25,26,43–45

Consistent with previous investigations in our laboratory,32,39 International Society of Biomechanics standards, modified to include the posterior acromioclavicular notch rather than the posterior lateral acromion, were used to digitize bony anatomical points on the thorax, scapula, and humerus.46 These digitized anatomical points were used to transform sensor data to clinically relevant joint coordinate systems (the humerus with respect to the scapula and the humerus and the scapula with respect to the thorax). Scapular orientation relative to the thorax was described as internal/external rotation (z-axis), downward/upward rotation (y-axis), and anterior/posterior tilt (x-axis). Glenohumeral orientation relative to the thorax was described as internal/external rotation (z-axis) (Fig. 2).

**Configuration of the CRT equipment and ease of access, the left upper extremity was tested.**

**Data Analysis**

Descriptive statistics were used to analyze the demographic variables for the sample, including age, sex, body mass index, years after SCI, and number of transfers per day. Because of the potential (but unknown) effect on kinematics, the following covariates were considered: sex, arm dominance, level of injury, body mass index, floor-to-acromion height, and arm length. Covariates of potential interest were first assessed for correlation with the dependent variables. If covariates did not reach a threshold of at least 0.5 and demonstrate consistent correlations across levels of a factor, they were not entered into the model. If entered, the specific covariate was retained if significant (P<.05) in the particular model.

The kinematic data for the 10 repetitions for each exercise and with each hand position were averaged across comparable humeral elevation angles during the concentric phase synchronized with the metronome. All 5 exercises were performed between 30 and 78 degrees of humerothoracic elevation and were considered the lower-range exercises for this study. Two CRT exercises were performed between 102 and 120 degrees of humerothoracic elevation and were considered the upper-range exercises. These lower and upper ranges were selected to most closely approximate impingement risk ranges corresponding to subacromial and internal impingement, respectively, while still incorporating exercises completed in a portion of that range. Ranges of humerothoracic elevation from 30 to 78 degrees (lower range) and from 102 to 120 degrees (upper range) were selected to represent angles corresponding to subacromial and internal impingement potential, respectively. Humerothoracic elevation angles were adjusted from 45 to 60 degrees (lower range) and from 105 to 120 degrees (upper range) to incorporate all relevant exercises and participants. Data were assessed for normality and variance homogeneity. If non-normal data were present, appropriate transformation methods were utilized.

A 2-way repeated-measures analysis of variance (ANOVA) with factors of hand position (traditional and modified) and exercise (overhead pulldown, overhead press, chest press, horizontal row, and downward press) was used to determine the effects on each dependent variable (scapular anterior/posterior tilt, upward/downward rotation, and internal/external rotation and glenohumeral internal/external rotation) at the lower range. Ultimately, the participant’s sex was the only covariate entered into the model with adequate correlation, and this was exclusively for glenohumeral internal/external rotation at the lower range.

A second 2-way repeated-measures ANOVA with factors of hand position (traditional and modified) and exercise (overhead pulldown and overhead press) was used to determine the effect on each scapular and humeral dependent variable at the upper range. The other 3 exercises (chest press, horizontal row, and downward press) were not performed in the upper range. In the event of a significant interaction, pair-wise comparisons with Bonferroni correction for each ANOVA were used to explore the effect of one factor (exercise) at each level of the other factor (hand position). The threshold value for significance was set at P<.05. When the assumption of sphericity was violated for the interaction term, as demonstrated by the

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**Figure 2.**

Shoulder Kinematics in Individuals With Paraplegia

Mauchly test. Greenhouse-Geisser adjusted \( P \) values were used. Statistical analysis was performed using IBM SPSS Statistics for Windows, version 19.0 (IBM Corp., Armonk, New York). Sample size was based on a power analysis to detect angular differences across conditions or exercises of 10 degrees or more with 80% power, based on standard deviations of 12 degrees or less. This is a conservative estimate for the statistical power of main effects for these analyses for variables such as scapular and glenohumeral internal/external rotation, which demonstrate the largest variance. Adequate power was present with this sample size to detect smaller condition or exercise differences for other variables.

Results

Kinematic data were lost on 2 participants, resulting in the analysis on 18 participants (14 men, 4 women; mean age=16.1 years, SD=8.8). Additional participant characteristics are presented in Table 1. Kinematic results are presented for lower-range and upper-range humerothoracic elevation. Partial eta squared (\( \eta^2 \)) is reported as a measurement of effect size.

Kinematics: Lower Range (30°–78°)

Scapular anterior/posterior tilt. A kinematic summary of scapular anterior/posterior tilt is displayed in Table 2 and Figure 3 (graph A). There was no exercise x hand interaction. There were significant main effects for hand position (\( F_{1,17}=5.8, P=.028, \) partial \( \eta^2=.3 \)) and exercise (\( F_{4,68}=12.9, P=.001, \) partial \( \eta^2=.4 \)). Specifically, with exercise collapsed, the modified hand positions had significa- nctly more scapular anterior tilt versus traditional hand positions. With hand position collapsed, the downward press had significantly more anterior tilt than all other exercises. The chest press had significantly more scapular anterior tilt than the overhead press.

Scapular internal/external rotation. A kinematic summary of scapular internal/external rotation is displayed in Table 2 and Figure 3 (graph B). There was a significant interaction effect for exercise and hand position (\( F_{2,956.68}=15.3, P<.001, \) partial \( \eta^2=.5 \)). To compare hand position by exercise, the modified hand position for chest press, overhead pulldown, and overhead press each had significantly more internal rotation versus the traditional hand position. The modified hand position for downward press had significantly less internal rotation versus the traditional hand position. To compare exercise by hand position, for the traditional hand position, the overhead press had significantly less internal rotation than the chest press, overhead pulldown, horizontal, and downward press. For the modified hand position, there were no significant differences among the exercises.

Scapular upward/downward rotation. A kinematic summary of scapular upward/downward rotation is displayed in Table 2 and Figure 3 (graph C). There was a significant interaction effect for exercise and hand position (\( F_{4,68}=3.3, P=.015, \) partial \( \eta^2=.2 \)). To compare hand position by exercise, the modified hand positions for overhead pulldown, overhead press, and horizontal row had significantly more upward rotation versus the traditional hand position. To compare exercise by hand position, for the traditional hand position, the horizontal row had significantly more upward rotation than the chest press and downward press. The overhead pulldown had significantly more upward rotation than the downward press. For the modified hand position, the horizontal row had significantly more upward rotation than the chest press, overhead press, and downward press. The overhead pulldown had significantly more upward rotation than the chest press and downward press.

Glenohumeral internal and external rotation. A kinematic summary of glenohumeral internal/external rotation is displayed in Table 2 and Figure 3 (graph D). Controlling for sex, there was a significant interaction effect for exercise and hand position (\( F_{4,64}=4.013, P=.006, \) partial \( \eta^2=.2 \)). To compare hand position by exercise, the modified hand position for the downward press and horizontal row had significantly more glenohumeral external rotation versus the traditional hand position. The modified hand position for the overhead press had significantly less glenohumeral external rotation than the traditional hand position. To compare exercise by hand position, for the traditional hand position, the overhead pulldown had significantly more glenohumeral external rotation than the chest press, downward press, and horizontal row. The overhead press had significantly more glenohumeral external rotation than the chest press, downward press, and horizontal row. The horizontal row had signifi-

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**Table 1.** Participant Characteristics

<table>
<thead>
<tr>
<th>Variable</th>
<th>n</th>
<th>Ratio</th>
<th>( \bar{X} \pm SD )</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sex (men:women)</td>
<td>14:4</td>
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<td></td>
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<tr>
<td>Years postinjury</td>
<td>16.1±8.8</td>
<td>2-28</td>
<td></td>
<td></td>
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<tr>
<td>BMI (kg/m(^2))</td>
<td>25.7±4.1</td>
<td>18.7-36.0</td>
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<tr>
<td>Self-reported activity level (transfers/day)</td>
<td>18.0±14.3</td>
<td>4-70</td>
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<tr>
<td>WUSPI (0–150)</td>
<td>1.2±2.2</td>
<td>0-8.4</td>
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<tr>
<td>Level of injury</td>
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<td>High thoracic (T2–6)</td>
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<tr>
<td>Low thoracic (T7–12)</td>
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<tr>
<td>Lumbar</td>
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<td></td>
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<td></td>
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<tr>
<td>Extent of injury</td>
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<td></td>
<td></td>
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</tr>
<tr>
<td>Complete (AIS A)</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Incomplete (AIS B or C)</td>
<td>8</td>
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</tbody>
</table>

\( \bar{X} \) = body mass index, WUSPI = Wheelchair User’s Shoulder Pain Index, AIS = American Spinal Injury Association (ASIA) Impairment Scale.
Table 2.
Mean (Standard Deviation) Rotations at Upper and Lower Ranges of Humerothoracic Elevation and Mean Change (95% Confidence Interval) Between the Traditional and Modified Hand Positions*  

<table>
<thead>
<tr>
<th>Exercise (Preferred Position)</th>
<th>Traditional ATPT (−/+), °</th>
<th>Modified ATPT (+/−), °</th>
<th>Traditional IRER (+/−), °</th>
<th>Modified IRER (+/−), °</th>
<th>Traditional URDR (−/+), °</th>
<th>Modified URDR (+/−), °</th>
<th>Traditional GHIRER (+/−), °</th>
<th>Modified GHIRER (+/−), °</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chest press (either)</td>
<td>−17.7 (13.8)</td>
<td>−20.1 (13.2)</td>
<td>41.5 (13.4)</td>
<td>43.8 (13.3)</td>
<td>−14.7 (10.1)</td>
<td>−16.4 (9.4)</td>
<td>−36.0 (17.3)</td>
<td>−37.3 (17.8)</td>
</tr>
<tr>
<td>Change</td>
<td>−2.4 (−3.8, −1.0)</td>
<td>2.3 (0.4, 4.2)</td>
<td>−1.7 (−4.3, 0.9)</td>
<td>41.3 (13.8)</td>
<td>−1.3 (−4.9, 2.3)</td>
<td>−1.3 (−4.9, 2.3)</td>
<td>−1.3 (−4.9, 2.3)</td>
<td>−1.3 (−4.9, 2.3)</td>
</tr>
<tr>
<td>Row (modified)</td>
<td>−16.6 (11.9)</td>
<td>−17.0 (11.1)</td>
<td>44.4 (14.3)</td>
<td>45.0 (15.1)</td>
<td>−22.9 (10.7)</td>
<td>−27.5 (9.6)</td>
<td>−45.0 (10.2)</td>
<td>−47.1 (11.1)</td>
</tr>
<tr>
<td>Change</td>
<td>−0.4 (−2.3, 1.5)</td>
<td>0.6 (−0.7, 1.9)</td>
<td>−4.6 (−6.9, −2.3)</td>
<td>14.7 (10.1)</td>
<td>−2.1 (−4.1, −0.1)</td>
<td>−2.1 (−4.1, −0.1)</td>
<td>−2.1 (−4.1, −0.1)</td>
<td>−2.1 (−4.1, −0.1)</td>
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<tr>
<td>Overhead pulldown (modified)</td>
<td>−14.3 (8.6)</td>
<td>−15.3 (8.6)</td>
<td>42.4 (12.3)</td>
<td>45.5 (12.9)</td>
<td>−21.5 (10.3)</td>
<td>−24.2 (11.6)</td>
<td>−66.9 (14.8)</td>
<td>−66.4 (12.1)</td>
</tr>
<tr>
<td>Change</td>
<td>−0.9 (−21.0, 0.3)</td>
<td>3.1 (1.7, 4.5)</td>
<td>−2.7 (−4.7, −0.7)</td>
<td>−2.4 (−8.3, 3.6)</td>
<td>0.4 (−2.8, 3.6)</td>
<td>0.4 (−2.8, 3.6)</td>
<td>0.4 (−2.8, 3.6)</td>
<td>0.4 (−2.8, 3.6)</td>
</tr>
<tr>
<td>Overhead press (traditional)</td>
<td>−12.2 (13.9)</td>
<td>−13.8 (12.0)</td>
<td>34.4 (11.2)</td>
<td>39.9 (9.1)</td>
<td>−16.4 (12.0)</td>
<td>−19.5 (10.0)</td>
<td>−70.2 (13.5)</td>
<td>−61.1 (12.8)</td>
</tr>
<tr>
<td>Change</td>
<td>−1.6 (−4.0, 0.8)</td>
<td>5.5 (1.8, 9.2)</td>
<td>−3.1 (−6.0, −0.2)</td>
<td>9.1 (4.1, 14.1)</td>
<td>9.1 (4.1, 14.1)</td>
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<td>9.1 (4.1, 14.1)</td>
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<tr>
<td>Downward press (modified)</td>
<td>−23.8 (10.5)</td>
<td>−23.1 (11.7)</td>
<td>46.9 (12.7)</td>
<td>42.5 (12.8)</td>
<td>−14.8 (10.7)</td>
<td>−13.7 (10.6)</td>
<td>−30.6 (21.0)</td>
<td>−35.1 (19.5)</td>
</tr>
<tr>
<td>Change</td>
<td>0.7 (−1.1, 2.5)</td>
<td>−4.4 (−6.3, −2.5)</td>
<td>1.1 (−1.4, 3.6)</td>
<td>−4.5 (−8.3, −0.7)</td>
<td>0.7 (−1.1, 2.5)</td>
<td>−4.4 (−6.3, −2.5)</td>
<td>1.1 (−1.4, 3.6)</td>
<td>−4.5 (−8.3, −0.7)</td>
</tr>
</tbody>
</table>

* ATPT (−/+)=scapular anterior/posterior tilt, where the negative sign indicates less anterior tilt, and the positive sign indicates more posterior tilt; IRER (+/−)=internal rotation/external rotation, where the positive sign indicates more internal rotation, and the negative sign indicates less external rotation; URDR (−/+)=upward rotation/downward rotation, where the negative sign indicates less upward rotation, and the positive sign indicates more downward rotation; and GHIRER (+/−)=glenohumeral internal rotation/external rotation, where the positive sign indicates more internal rotation, and the negative sign indicates less external rotation. Green font indicates modified position resulted in a favorable kinematic change. Red font indicates modified position resulted in a detrimental kinematic change. An asterisk (*) indicates a clinically meaningful change. When a significant interaction effect for exercise and hand position occurred, a dagger (†) indicates a pair-wise difference where the modified hand position resulted in improved kinematics over the traditional hand position.
cantly more glenohumeral external rotation than the downward press. For the modified hand position, the overhead pulldown had significantly more glenohumeral external rotation than the chest press, downward press, and horizontal row. The overhead press had significantly more glenohumeral external rotation than the chest press, downward press, and horizontal row. The horizontal row had significantly more glenohumeral external rotation than the downward press.

Kinematics: Upper Range (102°–120°)

Scapular anterior/posterior tilt. A kinematic summary of scapular anterior/posterior tilt is displayed in Table 2 and Figure 4 (graph A). There was a significant interaction effect for exercise and hand position ($F_{1,17}=5.358$, $P=.033$, partial $\eta^2=.2$). To compare hand position by exercise, the modified hand position for overhead pulldown had significantly more anterior tilt than the traditional hand position. For the modified hand position, overhead pulldown had significantly more anterior tilt than overhead press.

Scapular internal/external rotation. A kinematic summary of scapular internal/external rotation is displayed in Table 2 and Figure 4 (graph B). There was no exercise × hand interaction. There were significant main effects for hand position ($F_{1,17}=16.832$, $P=.002$, partial $\eta^2=.5$) and exercise ($F_{1,17}=4.8$, $P=.001$, partial $\eta^2=.3$). Specifically, with exercise collapsed, the modified hand position had significantly more scapular internal rotation than the traditional hand position. With hand position collapsed, the overhead pulldown had significantly more scapular upward rotation than the overhead press.

Scapular upward/downward rotation. A kinematic summary of scapular upward/downward rotation is displayed in Table 2 and Figure 4 (graph C). There was no exercise × hand interaction. There were significant main effects for hand position ($F_{1,17}=16.832$, $P=.001$, partial $\eta^2=.5$) and exercise ($F_{1,17}=37.3$, $P<.001$, partial $\eta^2=.7$). Specifically, with exercise collapsed, the modified hand position had significantly more scapular upward rotation than the traditional hand position. With hand position collapsed, the overhead pulldown had significantly more scapular upward rotation than the overhead press.

Glenohumeral internal/external rotation. A kinematic summary of glenohumeral internal/external rotation is displayed in Table 2 and Figure 4 (graph D). There was a significant interaction effect for exercise and hand position ($F_{1,17}=38.086$, $P<.001$, partial $\eta^2=.7$). To compare hand position by exercise, the modified hand position for overhead
pulldown had significantly more glenohumeral external rotation than the traditional hand position. The modified position for overhead press had significantly more glenohumeral external rotation than the traditional hand position. To compare exercise by hand position, for the modified hand position, overhead pulldown had significantly more glenohumeral external rotation than overhead press. For the traditional hand position, there was no significant difference for glenohumeral external rotation between the overhead pulldown and the overhead press.

Discussion
Upper extremity strengthening is considered a critical element of a comprehensive rehabilitation program following SCI. In light of this consideration, exercises should be recommended, with an emphasis on healthy shoulder mechanics. This study described an in-depth analysis of the 3D shoulder kinematics that occurred during the execution of wheelchair-based, upper extremity CRT exercises. The unique findings suggest that shoulder kinematics can be favorably improved (increased scapular posterior tilt, external rotation, or upward rotation or glenohumeral external rotation) through selection of hand positions that may positively influence shoulder kinematics during execution of CRT exercises. Currently, there are no other studies that provide recommendations for hand positions that positively influence shoulder kinematics during CRT, nor are there descriptive data on kinematics during the exercises.

In this investigation, all hypotheses were tested using a threshold at which kinematic changes ranging between 5 to 10 degrees or greater over comparable humerothoracic elevation angles could influence the subacromial space. This threshold was based on a prior investigation that linked scapular kinematics and the subacromial space. Relatively small changes of approximately 7 degrees of scapular protraction, in contrast to retraction (similar to scapular internal/external rotation in our investigation), were shown to significantly narrow the anterior opening width of the subacromial space (located between the anterior aspect of the acromion and the humeral head) by 25%. Although the findings were limited to 4 healthy individuals in static positions, small changes in scapular position equated to decreases in subacromial space. Our significant findings ranged in magnitude from 1.4 to 18.2 degrees. It may be that some of these changes are not meaningful with regard to affecting the subacromial space. Little is known about the relationship between angular kinematic changes and impact on rotator cuff mechanical impingement, and more investigation is needed. The angular change needed to affect the subacromial space also varies across individuals depending on their anatomy and glenohumeral kinematics during a specific exercise. The measurement system has an angular accuracy of 0.5 degrees. Because the instrumentation error is less than a degree, we do know that changes

Figure 4.
Mean rotations at upper-range humerothoracic elevation: (A) Scapular anterior/posterior tilt, (B) scapular internal/external rotation, (C) scapular upward/downward rotation, (D) glenohumeral internal/external rotation. Green arrows point to favorable kinematic directions (increased scapular posterior tilt, external rotation, or upward rotation or glenohumeral external rotation). Red arrows point to potentially detrimental kinematic directions (scapular anterior tilt, internal rotation, or downward rotation or glenohumeral internal rotation).
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identified in our study were not due to instrumentation error.

In this study, 2 hand positions were compared. When compared with the traditional hand position, the modified hand position resulted in a favorable change in shoulder kinematics (in one or more rotations) for 3 CRT exercises (horizontal row, downward press, and overhead pulldown). These changes included increased scapular upward rotation (4.6°) for the horizontal row and increased glenohumeral external rotation (4.5°) for the downward press (lower range) (Tab. 2, Fig. 3). The modified position also resulted in increased glenohumeral external rotation (18.2°) for the overhead pulldown (upper range) (Tab. 2, Fig. 4). However, the traditional hand position would be more biomechanically favorable when performing the overhead press with increased scapular external rotation (5.5°) and glenohumeral external rotation (9.1°) at lower-range humerothoracic elevation angles (Tab. 2, Fig. 3). The hand position selections (traditional or modified) are simple variations that can be selected by the user during CRT exercise execution and may influence impingement potential.

The downward press machine is one of the most commonly used strengthening machines in SCI centers and is intended to strengthen the muscles used during functional tasks such as the weight-relief raise. The downward press exercise incorporates shoulder movements that are similar to those used in the weight-relief raise. A prior investigation compared 3D shoulder kinematics during daily upper extremity weight-bearing activities in individuals with paraplegia.47 The findings of that study showed increased scapular anterior tilt during initial upper extremity loading of a weight-relief raise and increased glenohumeral internal rotation during both initial upper extremity loading and maximal loading phases of a weight-relief raise.47 In the current study, at the lower range of humerothoracic elevation, the downward press exercise performed in the traditional hand position was highlighted as the exercise of most concern, as it had the greatest amount of scapular anterior tilt and internal rotation and the least amount of glenohumeral external rotation and scapular upward rotation.

Mimicking the motion of a weight-relief raise,47 the current study showed the kinematic similarities between the downward press and the weight-relief raise, especially with regard to the degree of scapular anterior tilt at 23.8 degrees and 27 degrees, respectively. If the downward press is necessary to target a specific muscle group, the findings from the current study point to the need for the therapist and individual with SCI to consider alternate movement strategies that may minimize harmful shoulder postures while strengthening the muscle groups necessary for successful function. Changes in hand positions may be one strategy that can be considered during the exercise. For example, simple hand placement modifications during the downward press were able to achieve a 5-degree increase in glenohumeral external rotation and a 4-degree increase in scapular external rotation.

To our knowledge, this is the first project to determine whether shoulder kinematics can be favorably modified during CRT exercises by altering hand position and to ultimately develop specific positioning recommendations for CRT exercises that emphasize healthy shoulder mechanics (Appendix). Considering the impact of shoulder impingement on function and quality of life following paraplegia, exercise recommendations must thoughtfully include a rationale that encompasses healthy biomechanics. Hand modifications are just one modification that may influence shoulder biomechanics and ultimately reduce impingement risk.

Modifications of trunk position through wheelchair and seating alterations or CRT equipment design also may influence shoulder biomechanics and reduce impingement risk. Participants in this study were allowed to sit in their own custom-designed wheelchairs to mimic the natural environment. Additionally, accessibility issues are the reality of what individuals with SCI encounter on a regular basis when participating in an exercise program. Although Cybex Total Access equipment (Cybex International Inc, Medway, Massachusetts) was used during this study, it was determined that not all of the upper extremity equipment provided “total access” for all manual wheelchairs. For example, the horizontal bar on the solid back of rigid wheelchairs prevented some wheelchairs from being able to fully access the equipment. These accessibility issues may have contributed to detrimental positioning for some participants and ultimately kinematics that increased impingement risk. Improved accessibility may have the potential to improve scapular and glenohumeral kinematics and ultimately decrease shoulder impingement risk during CRT.

There are limitations to this study. The current literature regarding kinematics and impingement does not imply causal inference. For instance, it is unknown whether faulty kinematics cause impingement or whether pre-existing impingement causes altered kinematics. Furthermore, it is presumed that more “favorable” kinematics will increase the subacromial space. However, without 3D modeling, it is not possible to verify the impact of multiplanar scapular and glenohumeral motion on subacromial space during the execution of CRT. Also, kinematics were assessed with electromagnetic surface markers overlaying bony prominences, which creates the possibility of skin motion artifact, especially at ranges exceeding 120 degrees of humerothoracic elevation. For this reason, the analysis was conducted below 120 degrees of humerothoracic elevation, which reduces the impact of skin motion artifact.45 Finally, variable wheelchair seat heights may influence shoulder positions. However, allowing participants to sit in their own custom-designed wheelchairs was purposefully selected to mimic the natural environment.

This study provides the foundation for future studies, including a clinical trial for individuals with impingement and application to other strengthening programs. Future research is needed to investigate shoulder kinematics with other brands of CRT equipment, beyond Cybex Total Access. Future research also is needed to assess the effect of modifi-
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Dr Riek, Dr Ludewig, and Dr Nawoczenski provided concept/idea/research design. Dr Riek and Dr Nawoczenski provided writing and project management. Dr Riek and Mr Tome provided data collection. Dr Riek, Dr Nawoczenski, Mr Tome, and Dr Ludewig provided data analysis. Dr Riek and Dr Nawoczenski provided project management. Dr Nawoczenski provided facilities/equipment and institutional liaisons. Dr Ludewig and Dr Nawoczenski provided consultation (including review of manuscript before submission).

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References


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Appendix.


<table>
<thead>
<tr>
<th>Overhead Press</th>
<th>Traditional Hand Position</th>
<th>Modified Hand Position</th>
<th>Recommended Hand Position</th>
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</thead>
<tbody>
<tr>
<td>Start</td>
<td>End</td>
<td>Start</td>
<td>End</td>
</tr>
<tr>
<td>Traditional</td>
<td></td>
<td></td>
<td>Traditional</td>
</tr>
<tr>
<td>Instructions:</td>
<td>Grasp horizontal handles</td>
<td>Instructions:</td>
<td>Grasp perpendicular</td>
</tr>
<tr>
<td></td>
<td>and press straight up.</td>
<td></td>
<td>handles and press straight up.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Chest Press</th>
<th>Traditional Hand Position</th>
<th>Modified Hand Position</th>
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<tbody>
<tr>
<td>Start</td>
<td>End</td>
<td>Start</td>
<td>End</td>
</tr>
<tr>
<td>Either</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Instructions: Adjust handle position so that, when grasped, upper arms are straight to side. Grasp horizontal handles. Keep elbows out to the side, level with handles. Extend elbows.</td>
<td>Instructions: Adjust handle position so that, when grasped, elbows are at the side. Grasp vertical handles. Keep elbows at side. Extend elbows.</td>
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</tbody>
</table>

(Continued)
## Shoulder Kinematics in Individuals With Paraplegia

### Appendix.

Continued

<table>
<thead>
<tr>
<th>Overhead Pulldown</th>
<th>Traditional Hand Position</th>
<th>Modified Hand Position</th>
<th>Recommended Hand Position</th>
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<tbody>
<tr>
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<td>Start</td>
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<td>Start</td>
</tr>
<tr>
<td><img src="image1" alt="Instruction" /></td>
<td>Instructions: Set handle position height and adjust thigh pads for stabilization. Grasp bar outside shoulder width with palm down, lean back at hips, and pinch shoulder blades down and back. Bend arms, bringing bar down in front of face, and return elbows to side of body.</td>
<td></td>
<td></td>
</tr>
<tr>
<td><img src="image2" alt="Instruction" /></td>
<td>Instructions: Set handle position height and adjust thigh pads for stabilization. Grasp bar outside shoulder width with palm up, lean back at hips, and pinch shoulder blades down and back. Bend arms, bringing bar down in front of face, and return elbows to side of body.</td>
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</table>

<table>
<thead>
<tr>
<th>Horizontal Row</th>
<th>Traditional Hand Position</th>
<th>Modified Hand Position</th>
<th>Recommended Hand Position</th>
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<tbody>
<tr>
<td><img src="image3" alt="Instruction" /></td>
<td>Instructions: Adjust chest pad to allow grasp of handle with arms fully extended. Feet on footrest. Grasp horizontal handles. Pinch shoulder blades throughout and contact chest pad. Bend arms and bring elbows beside body with elbows up.</td>
<td></td>
<td></td>
</tr>
<tr>
<td><img src="image4" alt="Instruction" /></td>
<td>Instructions: Adjust chest pad to allow grasp of handle with arms fully extended. Feet on footrest. Grasp vertical handles. Pinch shoulder blades throughout and contact chest pad. Bend arms and bring elbows beside body.</td>
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<table>
<thead>
<tr>
<th>Downward Press</th>
<th>Traditional Hand Position</th>
<th>Modified Hand Position</th>
<th>Recommended Hand Position</th>
</tr>
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<tbody>
<tr>
<td><img src="image5" alt="Instruction" /></td>
<td>Instructions: Center machine with handles between greater trochanters and lateral femoral condyles. With thumbs pointing forward, grasp forward-facing handles. Lean forward off backrest with head centered over mid-thighs. Press straight toward the floor with elbow extension and shoulder depression.</td>
<td></td>
<td></td>
</tr>
<tr>
<td><img src="image6" alt="Instruction" /></td>
<td>Instructions: Center machine with handles between greater trochanters and lateral femoral condyles. With thumbs pointing forward, grasp lateral-facing handles. Lean forward off backrest with head centered over mid-thighs. Press straight toward the floor with elbow extension and shoulder depression.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>