Dynamic Three-Dimensional Ultrasound to Evaluate Scapular Movement Among Manual Wheelchair Users and Healthy Controls

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Background: A large percentage of individuals with spinal cord injury (SCI) report shoulder pain that can limit independence and quality of life. The pain is likely related to the demands placed on the shoulder by transfers and propulsion. Shoulder pathology has been linked to altered scapular mechanics; however, current methods to evaluate scapular movement are invasive, require ionizing radiation, are subject to skin-based motion artifacts, or require static postures. **Objective:** To investigate the feasibility of applying 3-dimensional ultrasound methods, previously used to look at scapular position in static postures, to evaluate dynamic scapular movement. **Method:** This study evaluated the feasibility of the novel application of a method combining 2-dimensional ultrasound and a motion capture system to determine 3-dimensional scapular position during dynamic arm elevation in the scapular plane with and without loading. **Results:** Incremental increases in scapular rotations were noted for extracted angles of 30°, 45°, 60°, and 75° of humeral elevation. Group differences were evaluated between a group of 16 manual wheelchair users (MWUs) and a group of age- and gender-matched able-bodied controls. MWUs had greater scapular external rotation and baseline pathology on clinical exam. MWUs also had greater anterior tilting, with this difference further accentuated during loading. The relationship between demographics and scapular positioning was also investigated, revealing that increased age, pathology on clinical exam, years since injury, and body mass index were correlated with scapular rotations associated with impingement (internal rotation, downward rotation, and anterior tilting). **Conclusion:** Individuals with SCI, as well as other populations who are susceptible to shoulder pathology, may benefit from the application of this imaging modality to quantitatively evaluate scapular positioning and effectively target therapeutic interventions. **Key words:** kinematics, scapula, ultrasound, wheelchair user

The shoulder is a common site of injury across many populations. Because it is the most mobile joint in the body, the high prevalence of disorders is not surprising. Individuals are at increased risk for shoulder pathology when exposed to high forces, sustained postures, and repetitive movements.¹ Wheelchair users are exposed to all of these factors in activities of daily living. Among manual wheelchair users (MWUs), 35% to 67% report shoulder pain.²⁻⁷ In this population, the presence of shoulder dysfunction significantly affects function and decreases quality of life.^{8,9} With altered scapular kinematics being linked to a multitude of shoulder problems, the identification of changes in kinematics may allow for earlier detection of pathology and targeting of appropriate interventions.¹⁰⁻²⁵ However, evaluation

of dynamic scapular movement is a challenging task, as the scapula rotates about 3 axes while also gliding underneath overlying tissue. Direct visualization of the bone is ideal but is often limited by cost, availability, and exposure to radiation, and skin-based systems are prone to error.²⁶⁻³³

The overall goal of this study was to investigate the feasibility of applying 3-dimensional ultrasound methods, previously used to look at scapular position in static postures, to evaluate dynamic scapular movement.³⁴ The specific goals were as follows:

1. Evaluate intermediate angles of functional elevation during dynamic movement (30°, 45°, 60°, and 75°). We hypothesize that we will see incremental increases in external rotation, upward rotation, and posterior tipping

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Top Spinal Cord Inj Rehabil 2015;21(4):303-312
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www.thomasland.com

doi: 10.1310/sci2104-303

- throughout the movement to maintain the distance between the acromion and humerus.
2. Compare dynamic scapular movement between MWUs and able-bodied controls (ABs). We anticipate that the nature of wheelchair propulsion and demands of activities of daily living will elucidate differences between this population and ABs with comparably lower daily demands on the shoulder.
 3. Evaluate the effect of loading on scapular movement, as other studies have suggested that differences in kinematics are clearer in the presence of loading.^{10,35,36}
 4. Investigate the relationship between shoulder pathology, age, years since injury, and body mass index (BMI) and scapular positioning.

Methods

Participants

In this institutional review board–approved study, subjects were recruited through flyers and word of mouth at the University of Pittsburgh as well as the 2012 National Veteran's Wheelchair Games in Richmond, Virginia (MWUs only). Subjects were eligible to participate in this study if they were over the age of 18, spoke English, and were able to raise their arms above their head. Subjects were excluded from this study if they had a history of fractures or dislocations in the shoulder from which they had not fully recovered; had upper extremity impairment, weakness, or spasticity that prevented smooth movement; or if they could not complete reach tasks while seated with support straps around the trunk. For MWUs, there was an additional inclusion criterion that a manual wheelchair was their primary means of mobility (≥ 40 hours/week). Control subjects were gender- and age-matched within 5 years to MWUs.

Questionnaires and clinical exam

Participants were asked to complete basic intake forms that asked about age, height, and weight. Among MWUs, we also asked questions about type of injury or diagnosis and date of injury or diagnosis, and we administered the Wheelchair User's

Shoulder Pain Index (WUSPI), which measures shoulder pain associated with the functional activities of wheelchair users.³⁷ Ultrasound exam of the dominant upper extremity was completed to determine whether the participant had shoulder pathology. The exam (Ultrasound Shoulder Pathology Rating Scale [USPRS]) has been previously described; it includes static evaluation of bony surfaces and tendons of the rotator cuff as well as dynamic evaluation of impingement.⁶ The USPRS ranges from 0 (normal tendon fibrillar patterns, smooth cortical surface, and no evidence of impingement) to 20 (fuller thickness tendon tears, marked cortical irregularity, and marked impingement).

Testing

A custom testing chair was designed to isolate scapular movement and provide repeatable movements of the participant's dominant arm in space. This chair (**Figure 1**) has an adjustable height backrest, a pad and strap to secure the contralateral shoulder, and a trunk strap to isolate scapular movement for the shoulder being tested. An angle adjustable guide bar was used to ensure consistent movement in the scapular plane across trials, with a stop marker placed at 90° arm elevation as measured by a goniometer. Participants wore a tank top or removed their shirts to allow for placement of Vicon markers (Vicon Motion Systems, Centennial, CO) on the trunk and dominant arm, consistent with our methods from previous studies.³⁸ Vicon markers were used to determine humeral elevation and trunk position and were imaged with 10 Vicon cameras at a sampling frequency of 120 Hz using Vicon Nexus 1.8 software.

During testing, participants were instructed to keep their dominant hand against the guide bar with the thumb pointed upwards. Participants completed 20 raise and lower cycles to and from the stop marker. During each cycle, participants raised their arm to a visual countdown over a period of 5 seconds, held for 2 seconds in the elevated position, and lowered their arm over a period of 5 seconds. They were given a 10-second rest period between repetitions to prevent fatigue. Participants were permitted to practice prior to

Figure 1. Custom testing chair with contralateral shoulder pad (A), contralateral shoulder strap (B), trunk strap (C), and guide bar (C).

testing to attain a smooth movement pattern. A loaded trial was completed in the same manner with the participants holding a 3-, 4-, or 5-lbs hand weight as determined by their body weight (<133 lbs, 134-155 lbs, and >155 lbs, respectively). A 2-minute rest period was provided between unloaded and loaded trials to prevent fatigue.

Ultrasound imaging of the scapula

One operator performed all imaging using a Philips HD11XE ultrasound machine equipped with a 5 to 12 MHz linear transducer (Philips Medical Systems, Bothell, WA). The probe was fitted with an orthogonal marker system to allow for tracking during imaging and subsequent 3-dimensional reconstruction.³⁴ The imaging depth was set to 4 cm for all participants. During

each raise and lower cycle, the ultrasound probe was moved to a new location along the spine ($n = 10$) and medial border ($n = 10$) of the scapula. During each cycle, the probe was held in contact with the skin and moved slightly to maintain visibility of the bony architecture throughout the pattern of movement. Video collection of ultrasound images used an Epiphan Frame Grabber (Epiphan Systems; Ottawa, Ontario, Canada) and 10 Hz sampling frequency.

Data processing

Ultrasound videos were segmented to individual frames and the scapular border was manually identified as an x-y coordinate in the image. The scapular border consisted of the spine of the scapula and medial border. We have previously found

high inter- and intrarater reliability for this method of manual detection (0.975-0.99).³⁸ Vicon data were smoothed using a 4th order zero-lag Butterworth filter with a cutoff frequency of 5 Hz and were down-sampled to match the sampling frequency of the ultrasound video. A series of transformations was applied to the 2-dimensional x-y coordinates of the scapular border in ultrasound images (P_{beam}) based on the static calibration of the ultrasound beam to the orthogonal attachment ($T_{\text{beamS,attachS}}$), location of the attachment ($T_{\text{attachD,global}}$) and trunk ($T_{\text{global,trunkD}}$) during the trial, and static calibration of the trunk local coordinate system ($T_{\text{trunkS,global}}$) to achieve the 3-dimensional point (P_{global}):

$$P_{\text{global}} = [T_{\text{trunkS,global}}] [T_{\text{global,trunkD}}] [T_{\text{attachD,global}}] [T_{\text{beams,attachS}}] * P_{\text{beam}}$$

The resulting pooled 3-dimensional data set displayed the location of the scapular border throughout all rest periods and raise and lower cycles of the trial (**Figure 2A**). To determine scapular position at the arm elevation angles of interest, we time normalized and spline fit our humeral elevation angle data with a 3rd order polynomial for each raise cycle, determined the percentage of that cycle when the arm was at the angle of interest (30°, 45°, 60°, and 75°), and extracted the corresponding reconstructed 3-dimensional ultrasound point (**Figure 2B**). As

not all participants consistently achieved 90° of elevation as measured kinematically, we did not include this angle in analysis.

A local coordinate system was fit to the pooled data for the desired angle of arm elevation to determine scapular position. As our methods differed and involved scanning the spine and medial border of the scapula, we established a local coordinate system to mirror methods used by the International Society of Biomechanics (ISB).³⁸ We determined our z-axis as a linear regression of the points making up the spine of the scapula border, the x-axis as perpendicular to a plane fit to all of the points in our scapular point cloud, and the y-axis as their cross-product.³⁸ A YXZ rotation sequence was used for matrix decomposition to determine scapular rotations in the following order: internal/external rotation (IR/ER), upward/downward rotation (UR/DR), and anterior/posterior tilting (AT/PT). With this coordinate system, positive rotations included IR, DR, and PT. ISB recommendations were followed for determining trunk and humeral local coordinate systems.

Statistical analysis

An independent *t* test was used to compare demographics across groups. A 3-way repeated measures analysis of variance was used to compare

Figure 2. (A) Pooled 3-dimensional data set throughout all raise/lower cycles for one participant in the frontal plane and (B) corresponding scapular border points at intermediate angles of arm elevation.

each of the scapular rotations with a between-group factor of MWU or AB and within-group factors of loading and arm elevation angle. Planned comparisons were made across elevation angles using a repeated contrast. If the assumption of sphericity was violated, the F value was corrected using the Greenhouse-Geisser correction when the estimate of sphericity was <0.75 and the Huynh-Feldt correction otherwise. Additionally, Pearson correlation was used to evaluate the relationship between scapular position during early (30°) and late (75°) humeral elevation and demographic variables of age, years since injury (MWU group only), BMI, and USPRS score.

Results

Sixteen MWUs and 16 ABs were recruited for this study and provided written informed consent. Each group contained 6 women and 10 men. Demographics can be found in **Table 1**. There were no significant differences across groups, except MWUs had significantly higher USPRS scores ($P = .003$). The median WUSPI score among MWUs was 2.4, with an interquartile range (IQR) of 0 to 17.8.

Scapular rotations for both groups in both loading conditions are shown in **Figure 3**. There was a significant main effect of elevation across all 3 scapular rotations [IR/ER, $F(1, 29) = 5.639$, $P = .024$; UR/DR, $F(3, 27) = 15.776$, $P < .001$; AT/PT, $F(3, 27) = 5.342$, $P = .005$]. Planned

comparisons of sequential angles of arm elevation revealed significant increases ($P < .05$) in from 30° to 45° (IR, UR, PT), 45° to 60° (IR, UR), and 60° to 75° (IR, UR, PT). The AB group had greater IR and PT than the MWU group [$F(1, 29) = 5.639$, $P = .024$, and $F(1, 28) = 3.486$, $P = .042$, respectively]. No differences were found in scapular rotations based on loading. There was a significant interaction between elevation and group for IR/ER [$F(3, 27) = 3.814$, $P = .021$], with planned comparisons by level of arm elevation indicating that MWUs decreased IR during early elevation while ABs increased. An interaction was also found between loading and group for AT/PT with the AB group demonstrating less AT than the MWU group in the unloaded condition as compared to the loaded condition when there was less of a difference between groups. Results of the correlational analysis between scapular rotations and demographics for loaded and unloaded conditions can be found in **Table 2** for early (30°) and late (75°) humeral elevations.

Discussion

We found incremental increases in scapular IR, UR, and PT with humeral elevation. McClure et al³⁹ used bone pins to evaluate dynamic scapular movement and found increases in UR and PT throughout the range of motion that were linear in nature. We found similar steady increases across our participants. In the same study, they found

Table 1. Demographics for manual wheelchair users (MWUs) and able-bodied controls (ABs)

Demographics	MWUs	ABs
Age, years	51.7 $\pm$ 11.3	51.1 $\pm$ 10.1
BMI, kg/m ²	23.8 $\pm$ 1.2	23.8 $\pm$ 2.8
USPRS	6.9 $\pm$ 3.8	3.2 $\pm$ 2.5
WUSPI	9.3 $\pm$ 13.3	N/A
Years since injury	16.1 $\pm$ 10.3	N/A
Diagnosis	Paraplegia ($n=8$)	N/A
	Quadriplegia ($n=3$)	
	Bilateral amputee ($n=1$)	
	Traumatic brain injury ($n=1$)	
	Spinal cerebellar degeneration ($n=1$)	
	Guillan Barre syndrome ($n=1$)	
	Bilateral tibia/fibular fractures ($n=1$)	

Note: Values are provided as mean $\pm$ SD. BMI = body mass index; N/A = not applicable; USPRS = Ultrasound Shoulder Pathology Rating Scale; WUSPI = Wheelchair User's Shoulder Pain Index.

Figure 3. Scapular rotations by group (able-bodied [AB], manual wheelchair user [MWU]) and loading condition (unloaded, loaded) presented throughout the range of arm elevation. IR/ER = internal/external rotation; UR/DR = upward/downward rotation; AT/PT = anterior/posterior tilting.

Table 2. Correlations between scapular rotations in different arm elevation conditions and body mass index (BMI), years since injury (YSI), and Ultrasound Pathology Rating Scale Score (USPRS)

Arm elevation condition	Internal rotation	Downward rotation	Anterior tilting
Unloaded	30°	—	USPRS: $R=0.372$, $P=.036$ Age: $R=0.384$, $P=.030$
	75°	—	USPRS: $R=0.371$, $P=.037$ Age: $R=0.427$, $P=.017$
Loaded	30°	YSI: $R=0.600$, $P=.014$	BMI: $R=0.399$, $P=.024$ USPRS: $R=0.388$, $P=.031$ Age: $R=0.419$, $P=.017$
	75°	USPRS: $R=0.377$, $P=.033$	USPRS: $R=0.397$, $P=.024$ Age: $R=0.355$, $P=.046$

more gradual changes in IR/ER that showed greater increase with overhead elevation ($>90^\circ$). We found similar smaller grade changes in IR/ER that were less consistent throughout the range of motion and increased in IR with elevation. It is possible that at higher levels of arm elevation, like those in the

study by McClure et al, we may have seen greater changes in IR/ER. The increase in IR in our study may have been a result of participants maintaining contact with the guide bar and being pulled into a more IR position or from a difference in coordinate systems. Future studies should expand the range of

motion to include overhead elevation, as changes in scapular IR/ER appear to be more pronounced at $>90^\circ$ arm elevation in other studies of scapular movement.³⁹ Future studies should build upon this proof of concept to determine the repeatability and validity of this method.

We found differences between groups, with MWUs demonstrating decreased IR and increased AT compared to ABs. Scapular positioning studies specific to MWUs are lacking, but studies have been completed comparing individuals with and without impingement syndrome.^{10,15,40} Unlike our study, these studies did not find differences between groups in IR/ER. It is possible that the increased ER we saw in MWUs is a compensatory mechanism to preserve subacromial space secondary to pain or pathology. Previous MRI studies have found that increased IR decreases the subacromial space.⁴¹ We expected to find a difference between groups with UR/DR as a lack of UR is associated with shoulder pathology, but we found no significant differences. This may be explained in part by the low level of reported shoulder pain among MWUs in our study as evidenced by the WUSPI scores. For a similar average age and years of wheelchair use, previous studies have found that individuals had an average WUSPI score between 25 and 30, which is greater than the first quartile among participants in our study.³⁷ MWUs had higher USPRS scores than AB controls, however these scores were also low compared to previous studies with individuals who had untreated shoulder pain (16.2-40.7).⁶ As such, the participants in our study may not have had sufficient shoulder pathology for us to be able to elucidate differences such as those seen in other studies secondary to impingement.

Disagreement exists across previous studies about whether UR and AT are increased^{15,42} or decreased¹⁰ or whether there is no difference at all⁴⁰ among individuals with impingement during humeral elevation in the scapular plane. Although not statistically significant, the average UR was greater for ABs at higher levels of elevation. The increased AT among MWUs in our study may be associated with a seated posture that features rounded shoulders and thoracic kyphosis.⁴³⁻⁴⁵ Previous studies have related this posture to muscle imbalance and shoulder pain.^{46,47} A more AT scapula orients the acromion closer to the

head of the humerus, decreasing the subacromial space and potentially compressing its contents.⁴¹ Increased AT is consistent with previous studies of individuals with impingement.^{15,18,48}

No differences were found based on loading despite the anticipated outcome that differences would be based on the need for greater muscle activation. Myers et al⁴⁹ performed a study in which AB participants were loaded to 25% of their maximum voluntary contraction at 30° , 60° , 90° , and 120° arm elevation. Our results have agreement with the pattern of movement, showing increases in UR, IR, and PT. Although the loaded condition did not result in significant differences in scapular positioning, this condition revealed a greater number of significant associations with participants' demographics. The loaded condition revealed that postures associated with shoulder pathology (increased IR, DR, AT) were correlated with greater BMI and years since injury (MWU group only). Such scapular positions can be detrimental, as they may put the shoulder in an impinged position.¹⁰ Weight management may be an important factor in preventing shoulder pathology. Among MWUs this is particularly important, as increased BMI is equivalent to increased weight to transport during propulsion and transfers. Independent of loading, increased AT was associated with greater age and shoulder pathology as determined by the USPRS. Previous studies have found that increased pathology is related to less posterior tilting with humeral elevation.^{10,40} Among the general population, 35% of persons over the age of 65 years report shoulder problems.⁵⁰ As individuals with SCI age, the incidence of shoulder pathology increases.⁵¹ Similar to how the difference between groups may be related to posture, the increase in AT with age may also be related to the tendency toward a kyphotic posture with aging. This draws emphasis to the importance of preventative exercise and appropriate seating and positioning of the scapular stabilizers and stretching of anterior chest musculature. USPRS scores were also associated with IR and DR in the loaded condition during late elevation (75°). Later elevation may better mirror the higher stresses that the shoulder is exposed to during overhead activities of daily living. Increased age was related to AT/PT across groups.

The significant interaction between loading and group showed that in early elevation, MWUs briefly became more ER, potentially as a mechanism to gain clearance in the subacromial space, whereas ABs tended toward IR throughout the entire range of motion evaluated. An interaction was also found between loading and group that showed ABs had less AT compared to MWUs with no loading as compared to the loading condition where there was less of a difference between groups. This interaction may lend support to the claim that strengthening of the scapular stabilizers is important to maintain proper alignment. The loading condition provides a greater demand on the shoulder musculature that may cue these stabilizers to kick in. Proper scapular positioning is just as important when no load is present, as any increases in AT may lead to decreased subacromial space and potential impingement.

Limitations

The reliability and validity of this method to evaluate scapular movement need to be established. Future studies should include repeated trials as well as comparison to a gold standard. Reliability studies will help to determine the effect of variation in motion across cycles. The scapula local coordinate system was determined through regression and plane fitting of the points that made up the scapula border. The magnitude of scapular rotations during dynamic movement differed from a previous study that applied this technique to the evaluation of static postures.³⁸ This is likely the result of the decreased number of points composing the scapular border, one per raise and lower cycle, in dynamic trials. The decreased number of points for dynamic trials was a function of the limited sampling frequency of the ultrasound machine used for this study. Future studies with increased sampling frequencies will provide increased data for intermediate levels of elevation and may reduce the number of repeated cycles of raising and lowering that are required. The high number of repetitions used limits the clinical applicability of this method. Reducing the number of repetitions of movement will also decrease the burden of testing time and need for repeated elevation in a population subject to

shoulder pathology. Use of a gold standard such as dynamic fluoroscopy would allow for visualization of the scapular surface and would make it possible to investigate how the modified coordinate system used in this study affects the calculation of scapular rotations.

The seating system of the wheelchair provides important postural support for MWUs. A custom testing chair set-up was used for this study to provide a consistent seating system across all participants, isolate shoulder movement, and guide the plane and height of arm movement. However, it is worthwhile to note that this set-up may have differed with respect to seat dump, backrest height, and a number of other factors from the set-up of the wheelchairs of MWUs, which may have led participants to assume different seating postures and affected scapular kinematics. Our study included a diverse group of diagnoses among MWUs and reported less shoulder pathology than in previous studies of wheelchair users. Because of this diverse sample, we did not categorize individuals with SCI according to the American Spinal Cord Injury Association Impairment Scale, we only noted level of injury. Therefore, we are unable to determine whether all participants had fully innervated upper extremities and scapular stabilizers. The range of arm elevation did not consistently reach 90° across participants, which limits the ability to compare our study to other studies of overhead reaching. Future studies may benefit from a more homogeneous population, inclusion criteria of shoulder pain and pathology, and higher levels of arm elevation to elucidate between-group differences.

Conclusion

This study demonstrates the feasibility of applying freehand 3-dimensional ultrasound to evaluate dynamic scapular movement. Although the validity and reliability of this method still need to be established, this study demonstrates the feasibility of using this method to evaluate scapular movement. The magnitude of dynamic scapular positions in this study differs from studies using similar methods on static postures,³⁸ but proof of concept is demonstrated by incremental increases in scapular rotations with arm elevation,

differences between groups, and correlation to demographic factors associated with differences in scapular position consistent with previous studies. Future studies should utilize ultrasound machines with higher sampling rates to increase the available data at intermediate levels of elevation; this may increase the reliability of this method in analyzing dynamic movement. Individuals with SCI as well as other populations who are susceptible to shoulder pathology may benefit from a noninvasive imaging modality to quantitatively evaluate scapular positioning. IR and AT were correlated with greater pathology on ultrasound exam. Strengthening of the scapular stabilizers and stretching of the anterior chest musculature is recommended to ensure proper

scapular movement and address potentially kyphotic postures. Scapular positioning was also related to age and years since injury; individuals should be aware of these changes through the lifespan. Further, it is recommended that MWUs maintain their body weight, as it may have negative implications on scapular movement.

Acknowledgments

The authors have no conflicts of interest to disclose. This material is based upon work supported by VA Center for Excellence for Wheelchairs and Associated Rehabilitation Engineering (grant #B6789C) and a National Science Foundation Graduate Research Fellowship.

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