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ORIGINAL ARTICLE

Comparative shoulder kinematics during free standing, standing depression lifts and daily functional activities in persons with paraplegia: considerations for shoulder health

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Study design: Case series; nonparametric repeated-measures analysis of variance.

Objective: To compare and contrast three-dimensional shoulder kinematics during frequently utilized upper extremity weight-bearing activities (standing depression lifts used in brace walking, weight-relief raises, transfers) and postures (sitting rest, standing in a frame) in spinal cord injury (SCI).

Setting: Movement Analysis Laboratory, Department of Physical Therapy, Ithaca College, Rochester, NY, USA.

Methods: Three female and two male subjects (39.2 ± 6.1 years old) at least 12 months post-SCI (14.6 ± 6.7 years old), SCI distal to T2 and with an ASIA score of A. The Flock of Birds magnetic tracking device was used to measure three-dimensional positions of the scapula, humerus and thorax during various activities.

Results: Standing in a frame resulted in significantly less scapular anterior tilt (AT) and greater glenohumeral external rotation (GHER) than standing depression lifts and weight-relief raises.

Conclusions: Standing frame posture offers the most favorable shoulder joint positions (less scapular AT and greater GHER) when compared to sitting rest posture, weight-relief raises, transfers and standing depression lifts. Knowledge of kinematic patterns associated with each activity is an essential first step to understanding the potential impact on shoulder health. Choosing specific activities or modifying techniques within functional activities that promote favorable shoulder positions may preserve long-term shoulder health.

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Introduction

The shoulder is the most common site of upper extremity (UE) pain, and this pain may interfere with function including wheelchair mobility, ambulation, transfers and pressure relief in individuals with spinal cord injury (SCI).[1] Each year, 7800 new SCIs occur in the United States and at any one time, 250 000–400 000 people live with an SCI.[2] Secondary complications are numerous and include shoulder pain, reported to range between 38 and 75% in wheelchair users.[1,3,4]

Following SCI, the role of the UE is changed from primarily prehensile activity to activities requiring loading and repetitive movements. The shoulder complex is particularly at risk as it is exposed to repetitive functional activities, including weight-relief raises, transfers and wheelchair propulsion. Additional demands may be placed on the shoulder when activities such as supported standing in a frame and brace walking are incorporated into rehabilitation programs. While standing and brace walking are often the goals for persons following SCI, the rationale behind these goals primarily lies in the perceived benefits of standing, including improvements in quality of life, range of motion, bowel regularity, skin integrity and fewer urinary tract infections.[5,6] However, the risks for increased shoulder pain and impingement associated with repetitive stresses from lifting one's entire body, as may occur during brace walking or seated depression lifts, are not well understood.

In persons without SCI, shoulder pain and impingement have been linked to alterations in scapulothoracic and glenohumeral movement patterns.[7,8] Scapular patterns

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resulting in less scapular upward rotation (UR), greater anterior tilt (AT) and internal rotation (IR) were found in subjects with impingement performing arm elevation tasks, compared with a non-painful control group.[7,8] These kinematic alterations are of concern due to the potential compromise of the subacromial space. Even small changes in scapular position have been shown to result in loss of subacromial space.[9] Scapular changes of as little as 7° can result in a decrease of approximately 25% of subacromial space.[9] Thus, scapular positions that may negatively influence subacromial space may lead to increased shoulder pain secondary to compression and irritation of subacromial soft tissues. In addition to scapular patterns affecting subacromial space, greater glenohumeral internal rotation (GHIR) may also negatively influence clearance of the rotator cuff tendons in this space.[10]

More recently, kinematic patterns have been described in able-bodied subjects during UE weight-bearing (WB) activities simulating weight-relief raises and transfers.[10] Although demonstrated in persons without SCI, the directions of shoulder joint movements during WB were similar to those found in able-bodied subjects with subacromial impingement while performing arm elevation activities. It is likely that depression lifts performed during brace walking would result in similar shoulder kinematic patterns as found during weight-relief raises and transfers. Although the consequences of abnormal shoulder kinematics may be a loss of mobility and function, comparative scapular and glenohumeral kinematics for these activities have not been described in persons with paraplegia.

Given the demands placed on the shoulder over the lifetime, maintaining healthy upper extremities is critical for maintaining functional independence. Knowledge of kinematic patterns associated with each WB activity is an essential first step to understanding the potential impact on shoulder health. Given this information, rehabilitation professionals and individuals with SCI can choose between activities, or modify techniques within functional activities that promote favorable shoulder positions and preserve long-term shoulder health.

The purpose of this study was to evaluate shoulder kinematics during UE WB activities requiring a depression lift (weight-relief raises, transfers and standing depression lift) in persons with SCI. Scapular and glenohumeral kinematic patterns were compared to shoulder positions achieved during upright standing in a frame. We chose unloaded standing as the comparison position, as we hypothesized it to be the preferred shoulder position from which to compare how other positions and functional activities relate. Specifically, we hypothesized that kinematic changes during standing would result in more favorable scapular patterns (greater UR, less AT and IR) and glenohumeral patterns (greater glenohumeral external rotation (GHER)) when compared to other UE WB activities or sitting postures.

Materials and methods

Subjects
Five subjects between the ages of 18 and 65 were recruited through the National Spinal Cord Injury Association local chapter in Rochester, New York (Table 1). All subjects sustained an SCI from trauma, vascular or orthopedic pathology, resulting in paraplegia below the second thoracic neurological level. Subjects were at least 1 year post-SCI and used a manual wheelchair as their primary means of mobility. They were able to perform a weight-relief raise and wheelchair transfer independently, stand with knee-ankle foot orthoses and perform standing depression lifts independently or with minimal assistance. All subjects had experience with a standing frame and brace walking. At the time of this study, three subjects used a standing frame at least weekly, but no subjects were brace walking.

Subjects were excluded if reporting a current history of shoulder pain localized to the proximal anterolateral shoulder region or pain with clinical impingement testing.[11] Subjects were also excluded if they experienced pain during transfers, weight-relief raises or wheelchair propulsion.

Phone screening was performed to assess the level of SCI, time since onset of injury, shoulder pain history and functional status. Appropriate individuals were referred to the Movement Analysis Laboratory at Ithaca College, Rochester Center. Participants reviewed and signed university-approved informed consent documents for human subjects prior to participation. All applicable institutional and governmental regulations concerning the ethical use of human volunteers were followed during the course of this research.

Table 1 Subject demographics

Subject	Gender	Age mean (s.d.)	ASIA level	Height mean (s.d.)	Weight mean (s.d.)	Years since injury	Hours in wheelchair/day	Transfers/day
1	Female	37	A T4–5	167.6 cm	65.8 kg	23	16	16
2	Female	40	A T5–6	157.5 cm	57.2 kg	15	17	18
3	Female	30	A L1–2	165.1 cm	65.8 kg	5	12	20
4	Male	44	A T11–12	175.3 cm	77.1 kg	18	16	15
5	Male	45	A T10–11	182.9 cm	91.6 kg	12	18	20
Total	Female = 3 Male = 2	39.2 (6.1)		169.7 (9.7)	71.5 (13.3)	14.6 ± 6.7	15.8 ± 2.3	17.7 ± 2.4

In the ASIA level column, ASIA A is from the ASIA Impairment Scale and is defined as a person with no motor or sensory function preserved in the sacral (S) segments S4–S5. The 'T' stands for thoracic and 'L' for lumbar followed by the lowest spinal segmental levels that test as normal.

Instrumentation

The Flock of Birds electromagnetic tracking system (mini-BIRD model 800, Ascension Technology Corporation, VT, USA) was used to track three-dimensional position and orientation of the thorax, scapula and humerus during all activities. Sensors were attached to the skin overlying the respective segments via adhesive tape. These surface sensor placements have been shown to closely track underlying bone motion in previous studies of shoulder motion.[12,13] The reliability and validity of the electromagnetic tracking systems have been well documented in shoulder biomechanics research.[7,8,10,12,14]

Design and procedure

The dominant arm was tested on subjects in their custom wheelchair. Sensors were attached to the thorax (sternum), scapula and humerus as described previously.[7,10] The transmitter was aligned ensuring movement capture within the range of the transmitter during all activities. Anatomical landmarks on each segment were digitized to allow transformation of sensor data to local anatomical coordinate systems. Landmarks followed the International Society of Biomechanics-recommended standard for shoulder kinematics, except that the original recommended landmark of the posterior acromioclavicular joint was used rather than the posterolateral acromion.[15]

Activities were tested during one session in the following order: sitting rest posture, weight-relief raise, transfer to and from their wheelchair, supported standing in a frame and standing depression lifts with knee-ankle foot orthoses. Each activity was verbally described to the subjects, and they were given rest as needed between trials and activities. The weight-relief raise was performed with the subject's hands placed as he or she typically performed this task. Positioning on the wheel, hand rims or armrests were all acceptable. Verbal instructions included (1) begin with hands in your lap, (2) on command of 'go' move your hands to the desired lifting location, perform a depression lift by lifting body as high as possible, (3) hold position for 3 s and (4) lower body and return to the start position.

Sit-pivot transfers were performed toward the side of the dominant extremity. This was referred to as the 'lead arm transfer' from wheelchair to mat. When returning back to the wheelchair, the dominant arm became the trailing arm and was referred to as the 'trail arm transfer'. The chair was positioned in close proximity to the mat at an angle determined as typical for each subject and equal in height to the wheelchair seat. The armrest closest to the mat was removed and the leg rests were removed at the subject's discretion. Verbal instructions provided to the subject included as the following: (1) slide forward to a 'ready position' on the front edge of the chair with hands in the lap; (2) on command of 'go', transfer to the mat; return hands to the lap when activity is completed. A similar procedure was followed while returning from mat to wheelchair.

Following transfers, subjects donned knee-ankle foot orthoses with knees locked in full extension and ankles in slight dorsiflexion. A standing frame was custom-built and
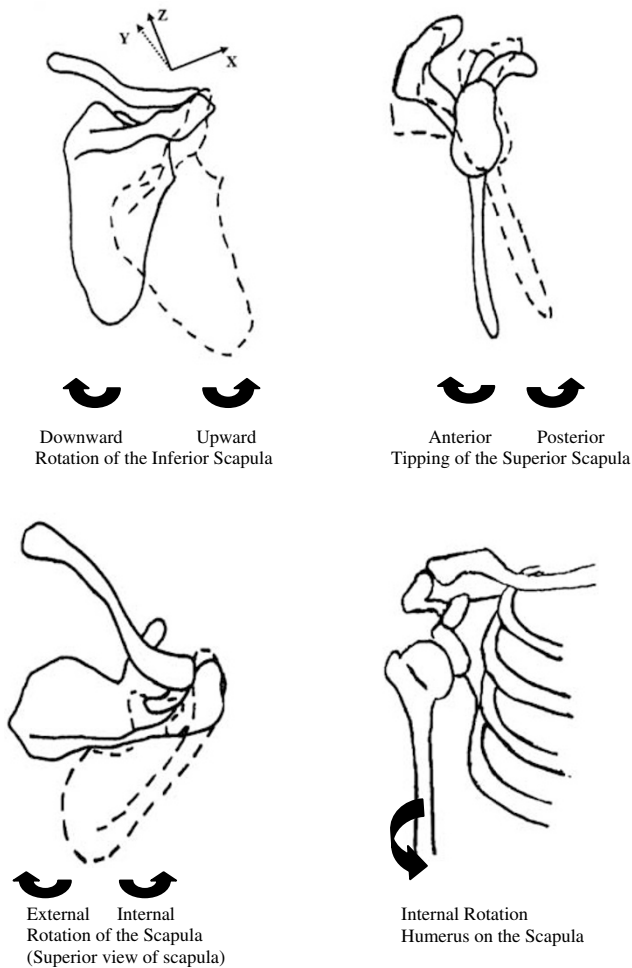

Figure 1 Supported standing posture in a custom-built standing frame with the elbows flexed to 90° and the forearms resting comfortably on the table. The knee-ankle foot orthoses maintained knee extension and a pelvis/hip strap was used to keep the hips extended once manually assisted into a standing position.

subjects were manually assisted into standing. The knee-ankle foot orthoses maintained knee extension and a pelvis/hip strap was secured to the standing frame to keep the hips extended. The standing frame was adjusted to allow each subject to stand with elbows flexed to 90° and the forearms to rest comfortably on the table (Figure 1). Upright standing posture was defined as the position when the upper trunk was vertical with respect to the room (laboratory reference frame). Trunk position was validated using a digital inclinometer aligned parallel to the upper thoracic spine. Standing data were collected for 10 s.

The subject then performed the depression lift using a standard walker. Commands for this activity were similar to those for the weight-relief raise except that the subject began the activity with arms at their side: (1) begin with hands by your side; (2) on command of 'go' move hands to the walker, perform a depression lift by lifting body as high as possible; (3) hold position for 3 s; and (4) lower body and return to the start position.

Data reduction and analysis

Data reduction summarized here was consistent with previous work.[10] Right-handed orthogonal coordinate systems

Downward   Upward
Rotation of the Inferior Scapula

Anterior   Posterior
Tipping of the Superior Scapula

External   Internal
Rotation of the Scapula
(Superior view of scapula)

Internal Rotation
Humerus on the Scapula

Figure 2 Scapular and glenohumeral motions. For the scapula, x is directed laterally from the root of the scapular spine to the acromioclavicular joint, y is directed anteriorly perpendicular to the plane of the scapula and z is directed superiorly perpendicular to x and y. Similar axis orientation was defined for the humerus such that positive z is upward. Scapular motions: downward/upward rotation, posterior tilt/anterior tilt and internal rotation/external rotation. Glenohumeral motion: internal rotation of the humerus on the scapula.

were determined for each segment using the respective digitized anatomic landmarks. With the subject in the anatomical position, orientation of x, y and z axes approximated the right, forward and upward directions, respectively[7,8,10] (Figure 2). Scapular orientation relative to the thorax (z, y', x'' Cardan angles) was described as internal/external rotation (IR/ER) about the z_s axis, downward/upward rotation (DR/UR) about the y'_s axis and posterior/anterior tilting (PT/AT) around the x_s'' axis. For glenohumeral orientation relative to the scapula (y, x', z'' Cardan angles), GHIR/GHER occurred around the z_h axis.[7,10,15]

Each activity except standing and sitting rest postures was divided into three phases: start of humeral motion (phase 1); beginning of vertical trunk displacement (initial UE loading, phase 2) and peak trunk displacement (assumed maximum loading, phase 3) (Figures 3a and b). These phases were consistently reproducible among subjects. Only phases 2 and

3 were statistically analyzed as they indicate initial and maximal loading of the upper extremities.[16]

Means, medians and variability of the three trials for all conditions and subjects were completed and median trial data used for further analyses. Comparisons across conditions were analyzed using a Friedman's nonparametric repeated measures analysis of variance for each dependent variable and phase. There were six conditions (standing, sitting, weight-relief raise, lead arm transfer, trail arm transfer and standing depression lift) and two phases (initial and maximum loading). Dependent variables included scapular IR/ER, DR/UR and PT/AT, and GHIR/GHER. In the presence of significant overall condition effects, Wilcoxin-signed rank pairwise follow-ups were completed between each condition and the standing condition. The overall alpha was $P < 0.05$.

Results

Data (medians, s.e.) for the dependent variables are presented in Figures 4a–d. For scapular IR and UR, there were no significant differences across conditions for either phase. For scapular tilting, there was a significant condition effect for phase 2 (initial UE loading), but not for phase 3 (assumed maximum loading). Significantly greater AT was found during weight-relief raises and standing depression lifts in phase 2 (Figure 4b). Individual subject data are presented in Figure 5 for this dependent measure. For glenohumeral rotation, significant condition effects were present for both phases. Less GHER was demonstrated for rest, weight-relief raises and standing depression lifts in phase 2. Significantly less GHER was demonstrated for all activities in phase 3 (Figure 4d). Both the weight-relief raise and the standing depression lift resulted in more GHIR with respect to the scapula in phase 3.

Discussion

Historically, standing in a frame or brace walking has been a routine part of rehabilitation for patients following SCI due to perceived and mainly self-reported psychological and physiological benefits. Based on questionnaire data, patients with SCI using standing devices reported improved quality of life, bowel regularity, and ability to straighten their legs and fewer bedsores and bladder infections, as compared with those who stood less.[5] However, quantitative evidence regarding actual physiological benefits of standing is notably limited. A case study reported that the use of a standing table increased frequency of bowel movements and decreased bowel care time.[17] Tilt-table standing has demonstrated a small effect on ankle mobility, but little or no effect on femur bone mineral density.[18] Additionally, for many patients, walking is often considered the 'ultimate goal' and some form of walking or standing is routinely implemented into rehabilitation programs. In addition to limited data regarding the physiological benefits of standing and brace walking, the implications of these activities on shoulder health is often overlooked in the rehabilitation program.

Figure 3 (**a**) Weight-relief raise. Beginning of vertical trunk displacement corresponding to initial upper extremity loading, phase 2. (**b**) Weight-relief raise. Peak trunk displacement corresponding to assumed maximum loading, phase 3. (**c**) Weight-relief raise. Posterior view of phase 2. (**d**) Weight-relief raise. Posterior view of phase 3.

To our knowledge, this is the first study comparing shoulder kinematics during static postures of standing and sitting as well as functional UE WB activities that require depression lifts, including depression lifts that are used in brace walking. Standing in a frame resulted in shoulder kinematics presumed most favorable for shoulder function (that is less AT and greater GHER) and served as the reference for follow-up comparisons to the other conditions. This scapular orientation during standing was comparable to scapular positions described for able-bodied subjects during standing rest postures in previous investigations.[7]

Of increased concern may be the kinematic patterns associated with weight-relief raises and standing depression lifts. Compared to standing, weight-relief raises resulted in

significantly greater AT and GHIR during the phases where presumed maximal loading occurs (Figures 3b, d and 4). In persons without SCI, these kinematic patterns have been linked to shoulder impingement.[7] It is unknown whether these same patterns are present in persons with SCI and impingement. However, these findings may provide guidance for clinical recommendations. For example, common practice is to recommend weight-relief raises every 15 min while in the wheelchair to prevent pressure sores. In this case, should a forward lean be recommended instead of

depression lifts to achieve the same goal? Whether or not alternative movement strategies should be considered to minimize detrimental shoulder postures certainly warrants further investigation.

Similar to findings for weight-relief raises, standing depression lifts resulted in increased AT and GHIR. Inclusion of supported standing in a frame and brace walking into rehabilitation programs have uncertain implications for the shoulder. From a clinical perspective, rehabilitation professionals need to help patients make informed choices
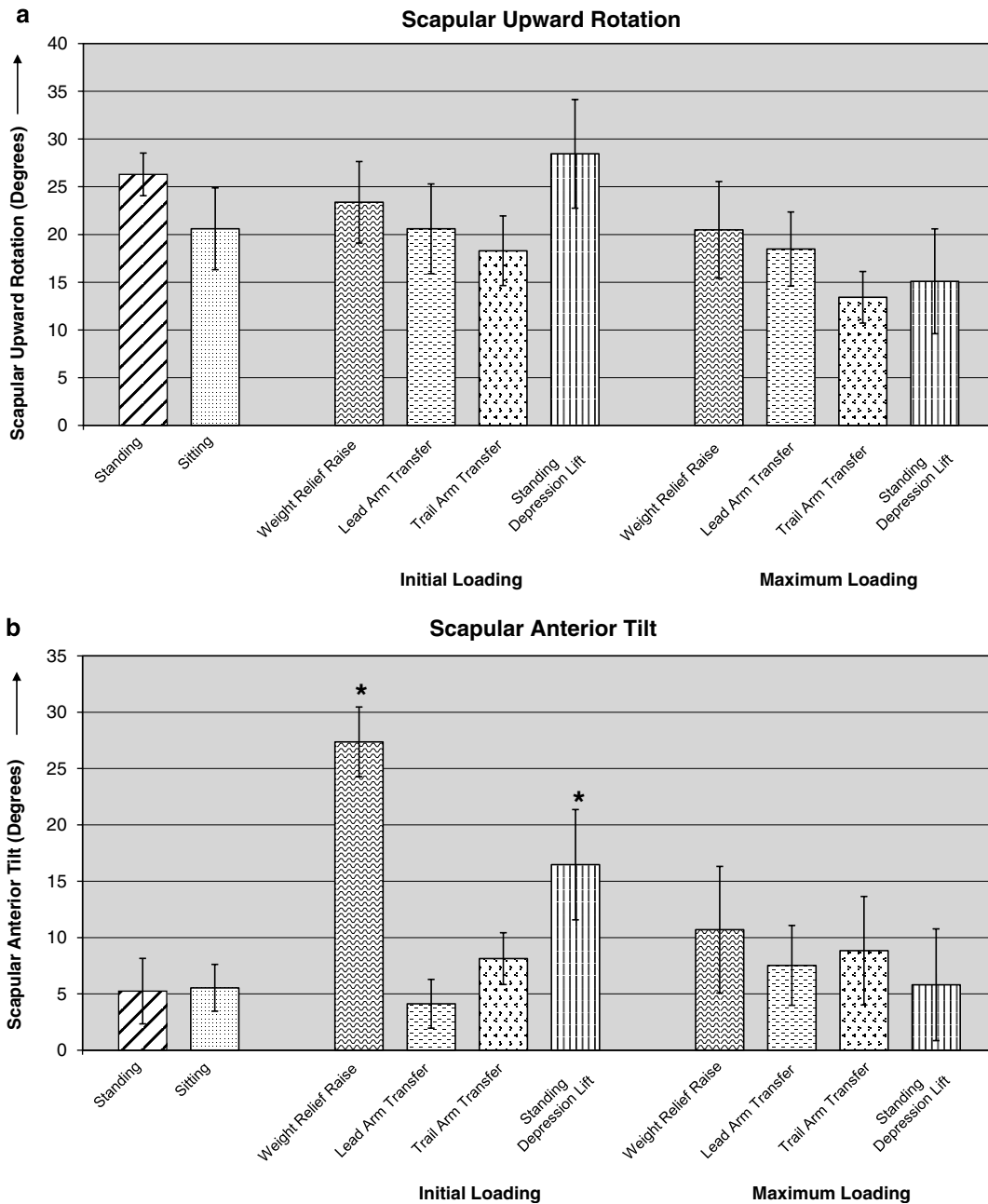
Figure 4 (a) Medians and s.e. for scapular upper extremity. (b) Medians and s.e. for scapular anterior tilt. *Significant differences from standing posture P<0.05. (c) Medians and s.e. for scapular internal rotation. (d) Medians and s.e. for greater glenohumeral internal rotation/greater glenohumeral external rotation. *Significant differences from standing posture P<0.05.

c

Scapular Internal Rotation

d

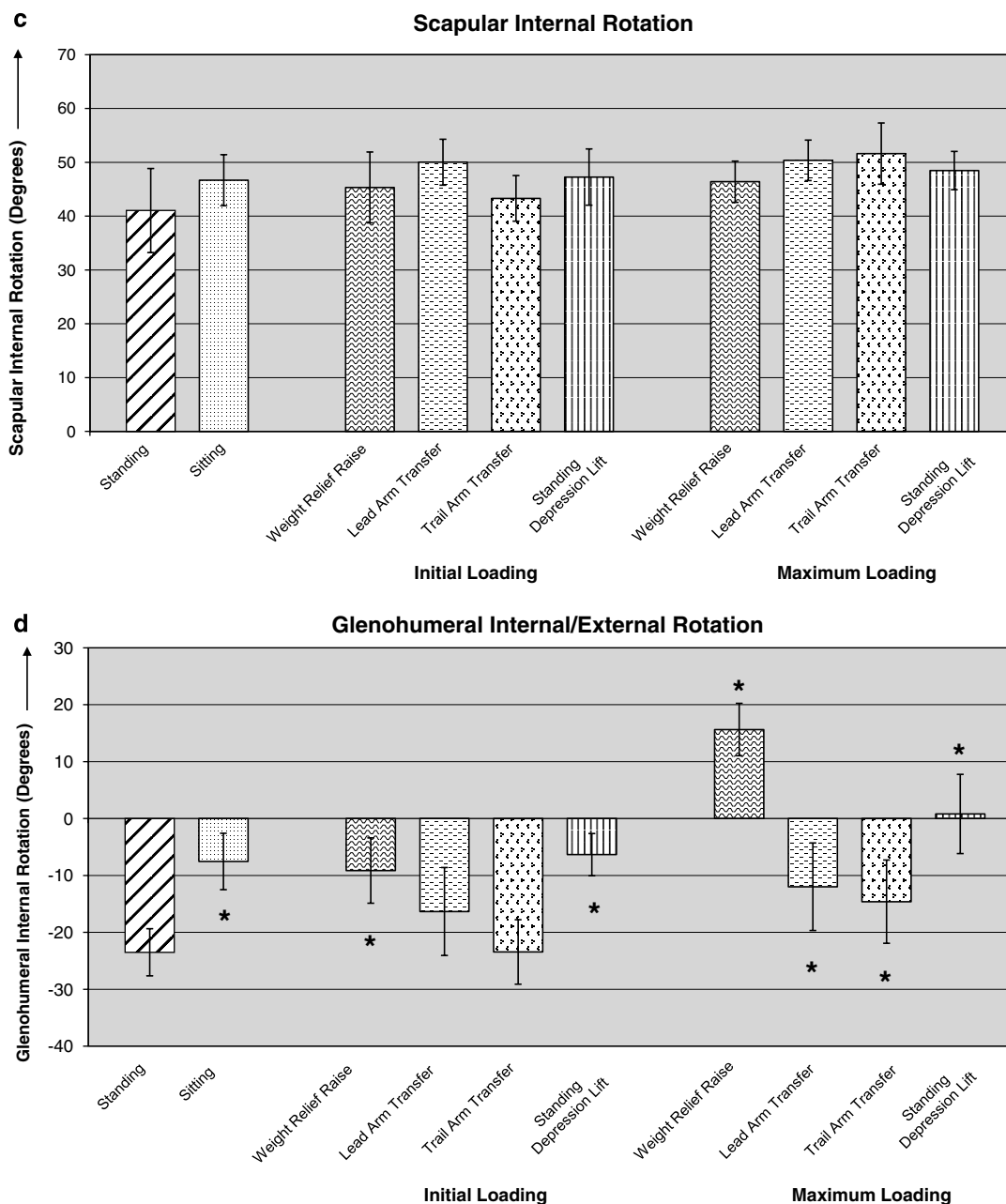## Glenohumeral Internal/External Rotation

Figure 4 Continued.

regarding brace walking. If brace walking is important psychologically, but possibly causes greater shoulder impingement risk, then protective strategies might be employed with supplemental use of a standing frame or by limiting the amount of time brace walking. A greater understanding of how shoulder kinematic patterns and positions impact the subacromial space and rotator cuff soft tissues is needed.

Standing frame postures were also compared to sitting in a wheelchair. Sitting demonstrated significantly less GHER. This position may be of particular concern since sitting is often maintained for 12–14 h daily[19] and, in addition to less GHER, this posture is associated with a flexed trunk. From a

functional perspective, poor vertical postural alignment with wheelchair sitting results in less reach in subjects with SCI.[20] Additionally, increased thoracic kyphosis also results in restrictions of shoulder elevation and may place the shoulder at earlier risk for impingement.[14] Whether these sitting postures contribute to more detrimental kinematics and impaired shoulder function during subsequent UE loading activities are not known. However, the findings of this study have immediate applications for seating evaluation/wheelchair prescription aimed at improving both shoulder and upright thoracic postures.

A limitation of the work is the small sample of healthy subjects with paraplegia. Additionally, loading of the UE was
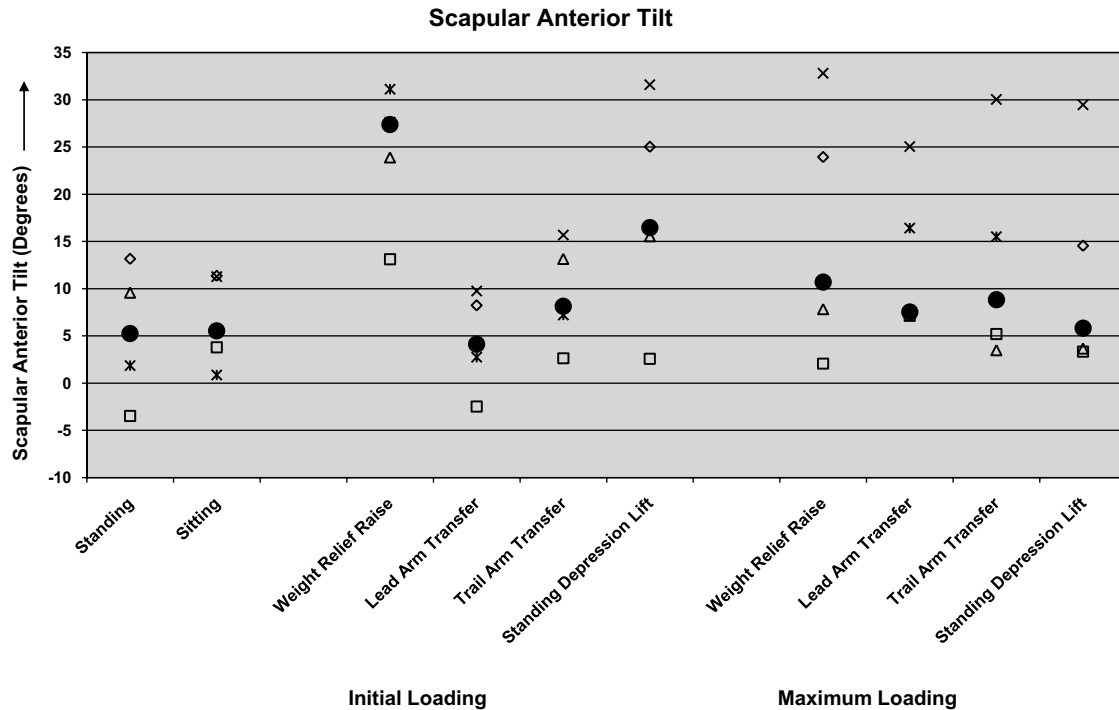
Figure 5 Individual (medians) subject data for scapular anterior tilt.

not measured, but inferred from previous investigations of shoulder function in persons with SCI.[16] The interactive contributions of differing thoracic postures and UE loading to the altered shoulder kinematics demonstrated in this study are important to further investigate as potential mechanisms contributing to shoulder pain in SCI. With a better understanding of the magnitude and direction of differences from the 'optimal' position as provided by this investigation, further studies can begin to test strategies to modify functional activities in an attempt to reduce shoulder pathology.

Conclusions

Standing frame posture offers the most favorable shoulder joint positions (less AT and greater GHER) when compared to sitting rest posture, weight-relief raises, transfers and standing depression lifts. Knowledge of kinematic patterns associated with each activity is an essential first step to understanding the potential impact on shoulder health. Choosing specific activities or modifying techniques within functional activities that promote favorable shoulder positions may preserve long-term shoulder health. Future studies should address alternative movement strategies for UE WB that may minimize harmful shoulder postures and impingement risk in persons with SCI.

Acknowledgements

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