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Electromyographic and kinematic analysis of the shoulder during four activities of daily living in men with C6 tetraplegia

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Abstract—The pattern of motor paralysis that commonly follows C6 tetraplegia creates an increased demand on upper limb function. The present investigation documented shoulder motion and muscular activity during planar motions and four activities of daily living (ADLs) in 15 men with spinal cord injuries (SCI) resulting in C6 tetraplegia. Three-dimensional (3-D) shoulder motion was recorded using a VIÇON motion system, and intramuscular electrodes recorded electromyographic (EMG) activity of 12 shoulder muscles. Active flexion and abduction required greater EMG than control subjects lifting a 2-kg weight. Relative EMG was similar for most muscles during hair combing, drinking, and reaching forward, although increased humeral elevation commonly resulted in a greater relative muscular effort. Hair combing had the most humeral elevation (90°) with moderate to high levels of activation (32% to 63% maximum) recorded in the anterior deltoid, supraspinatus, infraspinatus, and scapular muscles. During reaching for the perineum, posterior deltoid and subscapularis activity dominated.

Key words: *activities of daily living, electromyography, kinematics, shoulder, spinal cord injury, tetraplegia.*

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INTRODUCTION

To perform the basic activities of daily living (ADLs), one must reach forward, backward, overhead, and sideways in several planes. Spinal cord injury (SCI) in the region of the neck reduces the ability to meet these demands in proportion to the resulting pattern of arm and hand weakness. Strength can vary from normal to absent as the muscles of the upper limb are innervated by more than one spinal segment and their neural supply extends from the second cervical (C2) to the first thoracic (T1) nerves (1). Presently, the most common classification system for determining the level of motor paralysis involves manual muscle testing (MMT) of key muscle groups (2).

The pattern of motor paralysis that commonly follows C6 tetraplegia allows a significant functional ability in some areas, yet creates major limitations in others (3,4). Individuals with C6 tetraplegia have at least 3/5 strength wrist extensors, grade 4/5 elbow flexors and a complex pattern of muscle strength controlling the shoulder. The high levels of innervation for the trapezius (C2–4), rhomboid (C4–5), rotator cuff (C4–6), and deltoid (C5,6) allow effective arm elevation in all directions, though the partial innervation of the serratus anterior (C6–7) can limit the final range. Upper limb weight-bearing activities for pressure relief and transfers are significantly restricted by weakness of the humeral depressors (latissimus dorsi and pectoralis major) and elbow extensors (5). Reach length also is limited by impairment of the serratus anterior and elbow extensors. Loss of function in the long finger flexors, extensors, and the hand intrinsic muscles necessitates the use of a tenodesis grasp for hand function.

With some level of residual function in each of the major upper limb joints, independence is frequently achieved in grooming, hygiene, eating, and dressing (4). Partial paralysis at the distal joints, however, requires postural adaptations by the shoulder to adequately position the hand. As movement patterns change, so do the demands on various muscles of the upper limb. Weakness also results in a relative increase in the muscular demand required for common activities (6–8).

While the high incidence of shoulder pathology in persons disabled with tetraplegia (9,10) has been attributed to weight-bearing activities such as weight shifting, pressure relief, and transfers (9–11), the basic movement patterns used for various non-weight-bearing ADLs also could add strain to an overworked system. Therefore, the purpose of this study was to identify the patterns of shoulder motion and level of musclar activity required by individuals with C6 tetraplegia to move the unweighted arm during basic ADLs. Four ADLs using motion patterns characteristic of many upper limb tasks, while avoiding equipment that would obstruct camera documentation of movement patterns, were selected for study.

METHODS

Subjects

Fifteen adult men participated in this study. All previously had suffered traumatic injury to the cervical spinal cord and were subsequently classified as having complete C6 motor paralysis according to the guidelines proposed by the American Spinal Injury Association (2). All subjects denied a past or present history of shoulder pain or dysfunction. The mean age of participants was 33 years (SD 7, range 22–44 years), with a mean time since injury of 9 years (SD 7, range 3–21 years). Mean subject weight was 72 kg (SD 13, range 47–95 kg).

Procedure

Shoulder motion was recorded with a VICON motion analysis system (Oxford Metrics Ltd., Oxford, England). This system utilized 6 infrared cameras to track 13 reflective markers placed on the subject's trunk and upper limb (manubrium, xiphoid, C7 spinous process, greater tubercle of humerus, mid-humerus, lateral epicondyle, medial epicondyle, proximal ulna, distal ulna, ulnar styloid process, radial styloid process, lateral border of head of fifth metacarpal, and head of third metacarpal). Motion data were acquired on a DEC PDP 11/23 computer (all DEC machines from Digital Equipment Corporation, Maynard, MA).

To determine the total range of humeral elevation available to the subject, the maximum passive shoulder flexion and abduction range were recorded. During this test, the investigator stabilized the elbow to accommodate for the lack of active elbow extensors. Maximum active shoulder flexion and abduction identified the functional range available to the subject when no external elbow stabilization was provided.

Electromyographic (EMG) activity was recorded from 12 muscles of the shoulder: the upper and lower trapezius, rhomboid major, lower serratus anterior, supraspinatus, infraspinatus, subscapularis, clavicular head of the pectoralis major, long head of the biceps brachii, and the anterior, middle, and posterior heads of the deltoid. Following skin preparation, a pair of 50-micron wire electrodes (with the distal two millimeters stripped of nylon insulation) were inserted into each muscle with a 25-gauge needle. To secure the electrode in the muscle tissue, the subject's upper limb was moved passively through its entire range of motion several times, and the subject then actively performed contractions of the appropriate muscle groups. The free end of each wire electrode was stripped of insulation and attached to screws mounted in small plastic junction blocks taped to the subject's posterior thorax. Each block accepted two electrode pairs, had a quilted stainless steel ground plate back, and a switch to toggle between electrodes. Shielded, 32-gauge cables connected the junction blocks to a belt-worn transmitter package.

EMG signals were transmitted to a data acquisition system (DEC PDP 11/73+) via FM-FM telemetry (Model 2600, Biosentry Telemetry Inc., Torrance, CA). The signals were bandpass filtered through an analog filter (150–1,000 Hz), and were sampled and digitized at a 2,500 Hz rate. The high pass cut-off of 150 Hz was used to avoid cross-talk from adjacent muscles. The overall signal gain was 1,000.

Prior to any testing, electrode placement in the designated muscle was confirmed by palpating the tendon and muscle belly during mild electrical stimulation through the inserted wires. EMG recordings were made during three levels of activity: resting, MMT, and functional testing. With the subject's arm supported, a 5-s sample of resting EMG was recorded in order to provide a baseline threshold for the detection of myoelectric activity. A maximal effort MMT then was performed for each of the 12 muscles while the subject was seated in his wheelchair, his trunk secured to the chair back for stabilization. Muscles typically tested in the sitting position (upper trapezius, serratus anterior, biceps brachii, and the three heads of the deltoid) were tested as defined by Kendall (1). For muscles normally tested prone (lower trapezius, rhomboid major, infraspinatus, and subscapularis) or supine (clavicular pectoralis major) the same upper limb position relative to the trunk and direction of resistance were applied in the seated posture. The supraspinatus was tested by resisted abduction with the humerus in 45° abduction and internally rotated so that the thumb was pointed toward the floor (12–14).

Testing of the basic functions consisted of active shoulder flexion and abduction and four selected ADLs. Both EMG and VICON motion data were collected for each task. For the active arm elevation tests, the subjects were asked to maximally raise and lower their arm without any assistance, completing three successive cycles in both the flexion and abduction planes. Next, four ADLs were tested: 1) drinking from an empty cup, 2) flipping a lightswitch (positioned 76 cm anterior and 13 cm lateral to the shoulder joint at 142 cm vertical height), 3) hair combing, and 4) reaching for the perineum. Subjects were instructed to perform each activity a total of three consecutive times at their self-selected speed. Two of the activities (hair combing and reaching toward the perineum) began with the hand resting on the lap. For the other two activities (drinking from a cup and flipping a light switch) the test began with the hand resting on a table. A hand-held event timer switch was used by the investigator to mark the beginning and end of the reaching phase for all activities. The event timer generated an electronic signal that was collected simultaneously with the EMG data. Because EMG data acquisition was limited to a maximum of six muscles at any given time, it was necessary for subjects to perform two trials of each activity to acquire data from all 12 muscles. Motion data were recorded for both trials of a task.

All tests were videotaped (30 frames/s) in a sagittal plane view with a solid-state color video camera. A second camera and a split screen effects generator were used to include the oscilloscopic EMG and event marker tracings with the video image of each data collection trial.

Finally, using a LIDO Active dynamometer (Loredan Biomedical Inc., Davis, CA), maximum isometric torques were measured for shoulder external rotation (ER), internal rotation (IR), and elevation in the scapular plane (scaption). For the two tests of rotation, the subject's arm was placed in a device that allowed him to remain seated in his wheelchair while having his humerus supported in 90° of elevation in the frontal plane with 0° of rotation (15). Elevation in the scapular plane was tested with the shoulder in a plane 30° anterior to the sagittal plane and 30° of elevation. A long arm splint was used to prevent elbow flexion during the test. Trunk stabilization was provided with a strap that secured the subject to the backrest of the wheelchair.

Data Analysis

For each activity, EMG and motion data were divided into a lift (or reach) and return phase, based on motion data and the timing of the event marker. The videotape recordings were viewed by a second investigator to determine the accuracy of the event marker. When discrepancies were observed, video frame counts were used for corrections of event marker timings. Only the lift phase of movement was used in the analysis. The average rate of humeral elevation during the lift phase was used to determine the speed of movement.

Processing and analysis of the data were performed on a DEC Micro VAX 3200 workstation. EMG signals were full-wave rectified and integrated over intervals of 0.02 s. A moving window was used to identify the greatest 1 s of the EMG signal recorded during a 5-s MMT. From this maximum 1 s, the average 0.02 s interval was calculated and served as a normalization value of 100 percent (%MMT) for comparison with EMG signals recorded during all functional tests. Relative EMG intensities recorded during ADL activities were categorized as high (>50 %MMT), moderate (25 to 50 %MMT), and low (<25 %MMT). Analysis of upper limb kinematics was restricted to the motion of the shoulder. Data from the second of the three repetitions of each task were analyzed unless motion data were incomplete. If this occurred, data from either the first or third repetition were analyzed.

Motion at the shoulder joint (relative to the thorax) was defined according to a three-dimensional (3-D) global coordinate system described by An et al. (16) and Pearl et al. (17) for clinical interpretation of 3-D kinematics. In this system, the glenohumeral joint was considered to be the center of an imaginary globe. The radius of the globe was the long axis of the humerus (identified as a line between the center of the glenohumeral joint and the center of the elbow joint). Arm position was defined by the angle of elevation (latitude) and the plane in which the elevation occurred (longitude). Glenohumeral rotation, as usual, referred to motion about the long axis of the humerus.

For the global coordinate system, the neutral arm position of zero elevation, plane, and rotation (0,0,0) identified the position of the humerus with the arm at the side (mid axillary line) and the elbow flexed 90° so the forearm was horizontal and parallel to the sagittal plane. Each shoulder position has three coordinates (elevation, plane, and rotation). Plane was defined as anterior (positive values) or posterior (negative values), with the frontal plane of the trunk as the reference. Similarly, rotation was specified as IR (positive values) or ER (negative values).

Mean humeral position at the onset of motion and at the time of peak arm elevation was used to describe functional range of motion for each activity. For reaching the perineum, mean humeral position at the time of peak IR also was used, because this position closely coincided with the end of the reaching phase.

Relative EMG intensities recorded during active arm elevation and ADL testing were screened for normality of distribution using the Wilk's-Shapiro W statistic. These data were found to be predominantly non-normally distributed, therefore non-parametric analyses were performed. Friedman's two-way analyses of variance (ANOVA) were used to compare the relative EMG intensity of each muscle across the four ADL tasks. Similar analyses were performed to compare relative EMG intensities of functionally similar muscles (humeral elevators, rotator cuff, scapular muscles) for each ADL task. For all statistical tests, a significance level of $p<0.05$ was used.

RESULTS

Strength and Functional Range of Motion

The mean isometric torque for scaption was 5.2 kg-m (SD 1.8 kg-m) or 67 percent of the capacity of age-matched controls (%CON), for IR 2.3 kg-m (SD 0.5 kg-m; 39 %CON) and for ER 2.8 kg-m (SD 0.8 kg-m; 58 %CON). Peak humeral elevation during passive shoulder flexion was 133° (SD 9°) and during passive shoulder abduction was 133° (SD 10°). Median rates of humeral elevation for active flexion and abduction were 42 and 54°/sec respectively. There were no significant correlations between the self-selected rates of elevation and EMG for any of the muscles. Active flexion resulted in an average elevation of 103° in the 48° anterior plane with 58° ER (**Table 1**). Active abduction showed similar mean arm elevation, but the plane was closer to the coronal plane of the trunk (102° elevation, 19° anterior plane, 41° ER).

Table 1.
Mean humeral position (standard deviation) in degrees at time of peak arm elevation in subjects with C6 tetraplegia (n=15).

	Angle	Plane[a]	Rotation[b]
Active flexion	103(15)	48(15)	-58(12)
Active abduction	102(16)	19(19)	-41(15)
Hair combing	90(18)	45(15)	-59(22)
Drinking from cup	65(12)	64(9)	-41(12)
Reaching: lightswitch	77(12)	46(16)	-56(14)
Reaching: perineum	63(12)	-42(16)	70(19)

Angle=elevation angle; [a]Plane of elevation: values are positive for planes anterior to the trunk and negative for those posterior to the trunk; [b]positive rotation values indicate internal rotation and negative values are external rotation.

During active flexion, the median EMG of the anterior deltoid and serratus anterior muscles was significantly higher than that registered during abduction (52 vs. 16 %MMT and 57 vs. 42 %MMT, respectively) (**Table 2**).

Table 2.
Active flexion and abduction. Median EMG intensity (interquartile range) expressed as a percentage of manual muscle test EMG (%MMT); n=15.

	Flexion	Abduction
Humeral elevators		
Anterior deltoid*	52(48-89)	16(14-46)
Middle deltoid**	41(21-47)	65(43-80)
Posterior deltoid**	2(0-9)	18(11-28)
Clavicular pectoralis	12(7-27)	3(1-10)
Biceps long head	5(3-8)	3(2-5)
Rotator cuff muscles		
Supraspinatus**	52(23-75)	64(52-84)
Infraspinatus	46(34-73)	35(29-69)
Subscapularis	19(6-35)	15(6-34)
Scapular muscles		
Upper trapezius	47(36-77)	49(40-114)
Lower trapezius	63(25-77)	56(35-74)
Serratus anterior*	57(42-76)	42(21-57)
Rhomboid major	42(23-64)	62(21-75)

*=EMG during flexion significantly greater than abduction ($p<0.05$); **=EMG during abduction significantly greater than flexion ($p<0.05$).

Conversely, the abduction synergy showed significantly increased middle deltoid (65 vs. 41 %MMT), posterior deltoid (18 vs. 2 %MMT) and supraspinatus (64 vs. 52 %MMT) intensities. The upper and lower trapezius and rhomboid muscles registered moderate to high levels of action during active abduction and flexion (median EMG from 42 to 63 %MMT). The average EMG intensity of the subscapularis and clavicular pectoralis major was less than 20 %MMT in both events, while that of the biceps brachii was less than 5 %MMT.

Activities of Daily Living

Of the self-selected rates of humeral elevation used in the performance of the four ADL activities, hair combing (37°/sec) and reaching for a lightswitch (26°/sec) were performed more rapidly than drinking (12°/sec) and reaching the perineum (17°/sec). As with flexion and abduction, the rate of humeral elevation was not significantly correlated with EMG for any of the muscles.

Motion

Hair combing used a 72° arc of arm elevation from the beginning position of the hand resting in the lap (mean initial humeral position: 18° ELEV, 32° ANT PLANE, and 6° ER). From this position, the arm was elevated, moved anteriorly, and was first externally rotated and then internally rotated as the hand was passed over the head (**Figure 1**). At the time of peak arm elevation, the mean humeral position was 90° ELEV, 45° ANT PLANE, and 59° ER (**Table 1**).

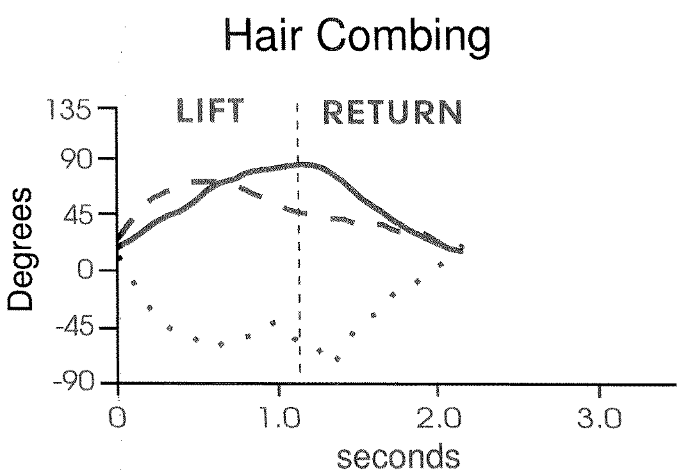

Figure 1.
Representative motion pattern from an individual subject during the HAIR COMBING task. The solid line represents the angle of humeral elevation, the dashed line represents the plane of humeral elevation with positive being anterior to the trunk, and the dotted line represents humeral rotation with positive being IR.

During the task of drinking from a cup the arm remained in an anterior plane as the cup was lifted from the table top to the lips and tipped for drinking by elevation and ER of the humerus (**Figure 2**). The mean peak arm elevation used for drinking was 65°, with the humerus in a 64° ANT PLANE and 41° ER (**Table 1**).

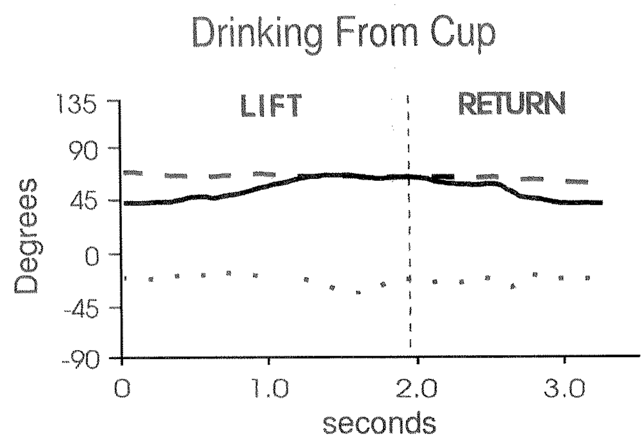

Figure 2.
Representative motion pattern from an individual subject during the DRINKING FROM CUP task. The solid line represents the angle of humeral elevation, the dashed line represents the plane of humeral elevation with positive being anterior to the trunk, and the dotted line represents humeral rotation with positive being IR.

Flipping the light switch involved elevation of the arm from the table top in a forward plane accompanied by prominent ER (**Figure 3**). Mean humeral position at the time of peak arm elevation was 77° ELEV, 46° ANT PLANE, and 56° ER (**Table 1**).

Reaching toward the perineum required arm elevation in a posterior plane accompanied by prominent IR (**Figure 4**). As the hand moved around the side of the trunk the humerus achieved peak elevation with a mean position of 63° ELEV, 42° POST PLANE, and 70° IR (**Table 1**). Peak IR occurred at the end of the reach phase of the activity, with the humerus now in a mean position of 48° ELEV, 61° POST PLANE and 96° IR.

Muscle Function

For ADLs, statistically significant differences ($p<0.05$) in EMG activity patterns most often were recorded in comparisons between tasks anterior to the trunk (i.e., drinking, combing, and flipping a switch) and reaching for the perineum. During the three activities of daily living which involved arm elevation in the anterior

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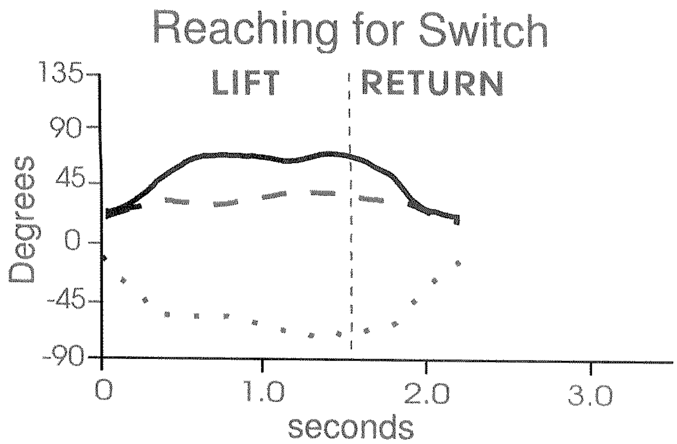

Figure 3.
Representative motion pattern from an individual subject during the DRINKING FOR SWITCH task. The solid line represents the angle of humeral elevation, the dashed line represents the plane of humeral elevation with positive being anterior to the trunk, and the dotted line represents humeral rotation with positive being IR.

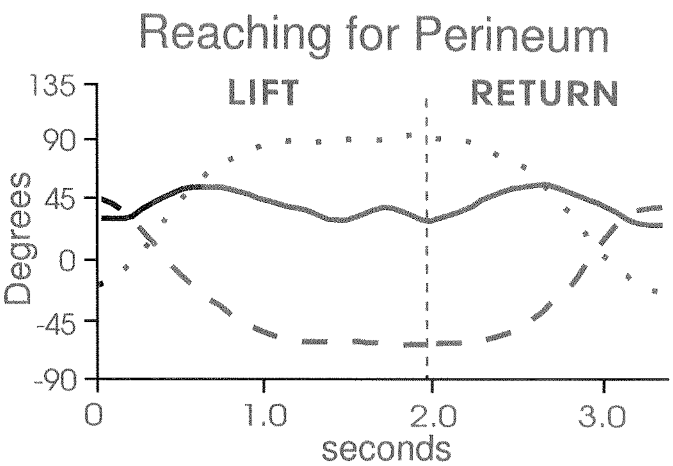

Figure 4.
Representative motion pattern from an individual subject during the REACHING FOR PERINEUM task. The solid line represents the angle of humeral elevation, the dashed line represents the plane of humeral elevation with positive being anterior to the trunk, and the dotted line represents humeral rotation with positive being IR.

Table 3.
Humeral elevators during ADLs: median relative EMG intensity (interquadrile range) during hair combing (COMB), drinking from cup (DRINK), reaching for a lightswitch (LIGHT), and reaching for perineum (PERINEUM); n=15.

	COMB	DRINK	LIGHT	PERINEUM
Anterior deltoid*	32	32	31	0
	(20-57)	(14-38)	(18-40)	(0-1)
Middle deltoid	19	2	22	17
	(7-27)	(0-6)	(9-26)	(12-32)
Posterior deltiod*	1	0	1	29
	(0-5)	(0-2)	(0-10)	(19-46)
Clavicular pectoralis	10	9	7	4
	(4-21)	(4-17)	(3-21)	(2-13)
Biceps long head**	20	4	4	1
	(10-25)	(3-14)	(3-7)	(0-1)

*=EMG during reaching for perineum significantly different from all other ADLs ($p<0.05$); **=EMG during hair combing significantly greater than reaching for lightswitch and reaching for perineum ($p<0.05$).

plane (drink, comb, switch), the most active humeral elevator muscle was the anterior deltoid with a median EMG of 31–32 %MMT (**Table 3**). The middle deltoid showed comparable activity in hair combing and flipping a light switch (EMG 19–22 %MMT). During the drinking task, however, middle deltoid action was not significant (2 %MMT). Neither the posterior deltoid (EMG 0–1 %MMT) nor the clavicular pectoralis major (EMG 7–10 %MMT) displayed more than minor activity. The biceps, with an EMG of 20 %MMT during hair combing, registered significantly greater activity than the 4 %MMT effort used when flipping the light switch. Larger intersubject variability obliterated the statistical difference between drinking from a cup and hair combing.

Reaching for the perineum showed a significantly different pattern of humeral muscle activity. The dominant deltoid was the posterior head (EMG 29 %MMT), assisted by the middle deltoid (EMG 17 %MMT). The anterior deltoid registered no EMG, and participation by the clavicular pectoralis major and biceps was minimal (EMG 4 and 1 %MMT, respectively).

Among the rotator cuff muscles, the intensity of supraspinatus activity was not significantly different between the forward and backward tasks (EMG 36–38 %MMT and 18 %MMT, respectively; see **Table 4**). The infraspinatus and subscapularis displayed opposing patterns of activity. Infraspinatus EMG was maximal during the combing and switch tasks (45 %MMT) and minimal during the perineum reach (1 %MMT). In contrast, the subscapularis was most active during the peroneal reach (EMG 50 %MMT) and otherwise registered low EMG. All of the rotator cuff muscles showed low EMG during the drinking task.

Among the scapular muscles, the two heads of the trapezius and the serratus anterior showed significantly greater EMG (23–63 %MMT) during the tasks using anterior plane elevation than during the backward reach to the perineum (4–12 %MMT; see **Table 5**). In addition, the hair combing task stimulated the highest EMG for each of these muscles. Drinking from a cup showed a sig-

Table 4.
Rotator cuff muscles during ADLs: median relative EMG intensity (interquadrile range) during hair combing (COMB), drinking from cup (DRINK), reaching for a lightswitch (LIGHT), and reaching for perineum (PERINEUM); n=15.

	COMB	DRINK	LIGHT	PERINEUM
Supraspinatus*	36	8	38	18
	(17-44)	(4-14)	(18-57)	(4-34)
Infraspinatus**	47	17	45	1
	(31-58)	(12-20)	(20-70)	(1-3)
Subscapularis***	9	5	10	50
	(1-22)	(0-13)	(4-25)	(30-55)

*=EMG during hair combing and reaching for lightswitch significantly greater than in drinking from cup ($p<0.05$); **=EMG during hair combing and reaching for lightswitch significantly greater than in drinking from cup and reaching for perineum ($p<0.05$); ***=EMG during reaching for perineum significantly greater than in drinking from cup ($p<0.05$).

Table 5.
Scapular muscles during ADLs: median relative EMG intensity (interquadrile range) during hair combing (COMB), drinking from cup (DRINK), reaching for a lightswitch (LIGHT), and reaching for perineum (PERINEUM); n=15.

	COMB	DRINK	LIGHT	PERINEUM
Upper trapezius*	46	33	32	12
	(27-69)	(21-60)	(18-78)	(4-33)
Lower trapezius**	63	43	42	5
	(26-86)	(23-54)	(13-60)	(4-19)
Serratus anterior***	32	17	23	4
	(21-50)	(9-32)	(11-47)	(1-14)
Rhomboid major	45	39	28	23
	(16-65)	(16-61)	(19-54)	(9-31)

*=EMG during hair combing significantly greater than in reaching for perineum ($p<0.05$); **=EMG during reaching for perineum significantly less than in all other ADLs ($p<0.05$); ***=EMG during hair combing and reaching for lightswitch significantly greater than in reaching for perineum ($p<0.05$); EMG during hair combing significantly greater than in drinking from cup ($p<0.05$).

nificantly lower level of serratus anterior activity. The rhomboid major displayed comparable EMG during all four tasks. Finally, for each task, the relative intensity of the scapular muscles was similar with the exception of statistically increased lower trapezius action compared to serratus anterior during drinking.

DISCUSSION

Despite considerable limitations, the subjects participating in this study had adequate strength and range of motion at the shoulder to complete all the activities tested. Maximum isometric strength for scaption (67 %CON) and ER (58 %CON; 15) were least affected and corresponded with a MMT grades of 4/5 to 5/5 (18). Decreased strength in these motions resulted from impaired innervation of three muscles groups; glenohumeral, scapular, and trunk. Direct control of the humerus is reduced by involvement of muscles supplied by the C6 innervation level such as the deltoid, supraspinatus, infraspinatus, and teres minor (C5,6; 1,18). Paralysis of the trunk muscles provides an unstable base for the arm even though the subjects were firmly strapped to their wheelchairs. IR strength was limited to 39 %CON (15) as a result of weakness of the sternal pectoralis major and latissimus dorsi muscles (C6,7,8).

Peak arm elevations during maximum active flexion and abduction were 30° less than the ranges obtained passively. In a similar investigation of functional shoulder motion Pearl evaluated 5 maximal reaches (including maximum elevation) and 4 tasks (including hair combing and reaching the perineum) in a control population. Compared to the active range of Pearl's control subjects, both active and passive ranges of shoulder elevation in our subjects were limited (70 and 90 %CON, respectively; 17). Mild weakness of the humeral elevators may have limited active elevation. However, a more likely scenario is that the lower position was purposely chosen to preserve passive elbow stability in the absence of triceps function.

The planes of elevation used were not those of "absolute" flexion or abduction. The plane selected for flexion (48° anterior) closely approximated that used by Pearl's control group during free arm elevation (55° anterior) which permitted the subject to select the plane of elevation. The implication of these actions was that a plane close to that of the scapula (30 to 45°) provides the optimum balance among the three heads of the deltoid and the supraspinatus to equalize the strain on the muscles. In the present investigation, median relative EMG intensity recorded from the middle deltoid (41 %MMT) approximated that of the anterior deltoid and supraspinatus (52 %MMT).

The relative EMG intensities used for active flexion were high compared to that reported for control populations. Using similar techniques for EMG data acquisition and processing, Kronberg et al. reported the peak relative EMG required for shoulder flexion and abduction while lifting a 2-kg weight in a control population. Average EMG for the lift phase derived from their graphs identifies that our subjects, without added weight, required slightly more anterior and middle deltoid action (8 to 10 %MMT) and twice the activation levels for supraspinatus (52 %MMT vs. 28 %MMT). Posterior deltoid, clavicular pectoralis major, infraspinatus, and subscapularis muscle activity was similar to that of the contorl subjects lifting 2 kg, yet our subjects lifted only the arm (19). Based on the anthropometric data of the subjects tested in Kronberg's study, the addition of the 2-kg weight at the hand doubled the external demand at the shoulder. Evaluating a series of shoulder rehabilitation exercises in control individuals, McCann et al. documented the increased demand of lifting a 2.25-kg weight (20). Their subjects required 22 to 47 percent higher activation levels of the three heads of the deltoid, a 42 percent increase in supraspinatus and 89 percent increase in infraspinatus activity with the weight compared to unweighted arm elevation. The reduced strength of the humeral elevators in our subjects likely necessitated a stronger relative effort to lift even the unweighted arm.

The plane used for abduction (19° anterior) more closely approximated the zero plane of true abduction. Significantly greater EMG in the posterior and middle deltoid and supraspinatus with decreased anterior deltoid activity reflects this difference in position. Similar to the pattern seen in flexion, our subjects required a greater relative effort during abduction from the middle deltoid (20 %MMT) and twice the intensity for supraspinatus (64 vs. 35 %MMT) to lift an unweighted arm than the control subjects lifting a 2-kg weight (19).

Of the three tasks performed anterior to the trunk, the highest angle of elevation occurred during the hair combing task (90°). This position was less than both the subject's maximum active range (103°) and the 112° of elevation during hair combing recorded in control subjects by Pearl (17). As a compensation for this decreased elevation, subjects flexed their necks in order to lower the head and complete the task. Reducing the magnitude of humeral elevation also decreased the median EMG intensity to 1/2 to 2/3 of the level for maximum active flexion. In addition to the lower angle of elevation, combing was performed with a flexed elbow which would reduce the external moment at the shoulder. Absent triceps function also may have contributed to limited arm elevation during hair combing by purposefully avoiding a posture that would cause the forearm to collapse into complete flexion.

Reaching for the lightswitch was similar to the hair combing task both in its pattern of motion and EMG with one exception, reduced biceps brachii activity. During hair combing, median EMG for the biceps was 20 %MMT, which could be related to active elbow flexion and/or forearm supination. In contrast, there was minimal biceps activity (EMG 4 %MMT) as the arm reached for the light switch or while drinking from a cup. The common difference observed was forearm pronation during these two tasks, as drinking from a cup also used elbow flexion. Hence, forearm supination may be the determinant of biceps brachii activation. These results support the finding in baseball pitching, that the long head of biceps brachii is not a contributor to shoulder flexion (21).

Drinking from a cup deviated from the other two forward reaching tasks in several aspects. A more anterior plane (64° ANT) was used, and the amount of humeral elevation was less (65°). As a result, the anterior deltoid was the only humeral elevator which had a relative intensity similar to the hair combing and lightswitch tasks (32 %MMT). Activity of the middle deltoid (EMG 2% vs. 19 and 22 %MMT) and supraspinatus (EMG 8% vs. 36 and 38 %MMT) were significantly reduced. This reflects the selective activation of the humeral elevators dictated by humeral positioning. Stronger participation by the middle deltoid and supraspinatus (both <10 %MMT) would tend to elevate the humerus in the plane of the scapula and result in failure to position the cup in the midline for drinking. There also was a significant decrease in the relative intensity of infraspinatus during drinking from the cup that reflected the change in the ER demands. Both hair combing and reaching for the lightswitch required approximately 60° of active ER during the activity, while drinking from the cup maintained a fairly constant posture of 40° to 45° of ER. The subjects in our study with C6 tetraplegia required twice the shoulder elevation to drink from a cup than the control subjects studied by Safaee-Rad et al. (22). The greater range of motion at the shoulder probably reflects the need to use a tenodesis grip to grasp the body of the cup rather than lifting the cup by the handle. Thus, our subjects were unable to use small arcs of forearm, wrist, and hand movement to position the cup for drinking. Instead, the forearm, hand, and cup became a single unit that required shoulder motion to both lift the cup to the mouth and tip it for drinking.

Reaching for the perineum, the one task studied which required posterior humeral elevation, showed a similar magnitude of motion (63°) but a different deltoid pattern composed of the posterior and middle heads (25 and 17 %MMT, respectively). With absence of latissimus dorsi function, posterior deltoid, and subscapularis, along with rhomboid major, were the prime movers for this task. For subjects with tetraplegia, peak IR (96°) was only slightly less than that reported by Pearl in control subjects (109°) (17). This marked IR stimulated strong subscapularis activity (EMG 50 %MMT) in contrast to its usual minor role for activities anterior to the trunk (EMG <10 %MMT). At the same time the more commonly active infraspinatus was inhibited (EMG 1 %MMT). Although the majority of persons with C6 tetraplegia require assistance during toileting because of limited elbow and hand control (23), the reaching for the perineum task represents an important movement pattern used in other ADLs (weight shifting, balance support for other reaching tasks, dressing, transfers).

For each higher level of arm elevation used during the tasks performed in the anterior plane (drink, switch, comb) the scapular muscles dedicated to upward rotation (upper and lower trapezius and serratus anterior) showed increasing median EMG intensity. Contrary to the normal synergy, the intensity of serratus anterior EMG was notably lower than that of the two trapezius muscles. Even with light switch flipping, when scapular protraction would be useful to increase reach, serratus demonstrated low level of relative activation (23 %MMT). Instead, the rhomboid decreased its intensity of action to allow scapular protraction. During normal elevation, regardless of the plane, the serratus anterior and upper trapezius showed a close synergy with comparable intensities, while lower trapezius activity is notably lower (24). In the subjects with tetraplegia there was a reversal of intensity with the serratus anterior relatively low and the lower trapezius relatively high. This suggests that they have developed a means of protecting the impaired serratus anterior from overuse by increasing the involvement of the lower trapezius. Rhomboid muscle activity also was greater than the normal pattern. The clinical implication is that specific attention should be directed toward strengthening the posterior scapular muscles during the rehabilitation program of persons with C6 tetraplegia.

Scapular muscle participation during posterior humeral elevation was low for all muscles tested. With the need of scapular adduction and downward rotation of the glenoid, the rhomboid muscle was the strongest participant (23 %MMT).

The relative intensity of muscle action, EMG as a percent of MMT, is significant for functional endurance. Muscle contraction increases intramuscular pressure, which in turn, reduces the availability of oxygen to the contracting muscle fibers. Edwards reported that muscle blood flow was arrested at just 20 percent maximum voluntary contraction (25). Continued oxygenation depends on the frequency of muscle relaxation intervals to replenish the stored oxygen supply. Monad previously reported that muscle fatigue was directly related to the relative intensity and duration of effort (26). As stored oxygen is diminished, the muscle turns to anaerobic energy, but this is only five percent as efficient as aerobic energy. Hence, fatigue soon follows. The moderate to high levels of EMG, combined with strength deficits, suggest that persons with C6 tetraplegia are susceptible to muscular fatigue when performing repetitive or prolonged nonweightbearing ADLs. For example, during the combing activity, with 90° of humeral elevation, the anterior deltoid, supraspinatus, infraspinatus, and all the scapular muscles functioned between 32 percent and 63 percent of their maximal activation level. Based on the graphs relating muscle contraction intensity to contraction endurance limits proposed by Monad, at this level of effort, fatigue would occur between 3.3 and 0.7 min (respectively) with continuous activity. Additionally, Hagberg (27) identified that the supraspinatus was less fatigue-resistant than the deltoid during overhead activities. Fatigue-reduced effort of supraspinatus requires increased activity from the deltoid to maintain force levels. Because the line of pull of the supraspinatus is predominantly horizontal and that of the deltoid is superior, continued deltoid activity with reduced effort from the supraspinatus could result in a greater upward shear force within the glenohumeral joint and subsequent compromise of subacromial structures.

CONCLUSIONS

Subjects with complete C6 tetraplegia required moderate levels of relative muscle action to elevate the arm less than 90°. Because they are starting from a seated position, more of the daily functional requirements of vocation and recreation must be performed at shoulder height and overhead to interact with the environment. Activities above 90° shoulder elevation yielded EMG greater than that reported for the humeral elevators (19) and the upward rotators of the scapula (24) in control subjects. Two causes of increased EMG activity have been identified. Decreased strength of the shoulder complex and altered shoulder motion patterns to substitute for loss of distal control of the elbow, wrist, and hand. The moderate to strong action of the upward rotators of the scapula with elevation at or above 90° emphasizes the need to include these muscles in the shoulder rehabilitation program for patients with C6 tetraplegia.

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