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Relationship between maximum isometric joint moment and functional task performance in patients with brachial plexus injury: A pilot study

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ABSTRACT

We evaluated whether subjects with brachial plexus injury (BPI) adapted their movements to reduce the mechanical demand on their impaired upper extremity. In 6 subjects with unilateral BPI with C5 and C6 involvement, we measured bilateral maximum isometric shoulder and elbow strength, and computed joint kinematics and net muscle-generated joint moments during 7 unimanual functional tasks. Compared to the unimpaired extremity, maximum strength in shoulder abduction, extension, and external rotation was 60% ($p = 0.02$), 49% ($p = 0.02$), and 75% ($p = 0.02$) lower, respectively, on the impaired side. Significant kinematic and kinetic differences were observed only when reaching to the back of the head. However, because of substantially reduced strength in their impaired upper extremities, subjects used a significantly higher percentage of their maximum strength during several tasks and along several directions of movement. The peak percentage of maximal strength subjects used across tasks was 32% ($p = 0.03$) and 29% ($p = 0.03$) more on their impaired side in shoulder extension and external rotation, respectively. Subjects had less reserve strength available for performing upper extremity tasks and, therefore, may be less adaptive to strength declines due to injury progression and normal aging. Quantitatively measuring maximal strength may help clinicians ensure that patients maintain sufficient upper extremity strength to preserve long-term functional ability.

1. Introduction

Traumatic brachial plexus injury (BPI) occurs in approximately 1.2% [1] of the 130,000 multi-trauma (injury severity score ≥ 16) cases in the US each year [2]. BPI with involvement of the C5 and C6 nerve roots impairs shoulder abduction and external rotation, and elbow flexion ability [3,4]. In many cases strength and function of the impaired extremity may remain substantially diminished even following intensive surgery and physiotherapy [5]. Manual muscle grades and active range of motion are common clinical measures of post-surgical outcomes [6,7]. However, interpretation of reported outcomes is challenging since different grading systems may be used among clinicians [8], and injury characteristics vary considerably among patients [9]. Additionally, it is unclear how clinical measures correspond to a patient's ability to perform functional tasks required for self-care and independent living, such as eating, bathing, and dressing.

Quantitative functional assessment techniques would permit a more comprehensive characterization of upper extremity functional ability in BPI patients. Maximum joint strength, quantified as maximum isometric joint moment (MIJM), has been measured at the shoulder and elbow in older adults [10] and patients with spinal cord injury [11]. Though shoulder strength was identified as an important factor in the ability to perform reaching and pulling tasks [10], quantitative joint strength measurements in patients with BPI have been limited to the elbow, wrist, and hand [4,5]. Strength and joint kinematics during functional tasks have

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been reported in children with brachial plexus birth palsy [12–14], but not for adults with BPI.

In general, movement ability is determined by whether an individual's maximum strength exceeds the joint moments that muscles must generate to perform tasks. Vandenberghe and colleagues investigated individual muscle contributions to upper extremity joint trajectories during functional tasks, but muscle contributions to joint moments were not reported [15]. Joint kinematics have been reported for numerous functional tasks, but the associated joint forces were not determined [16,17]. Upper extremity kinematics during basic functional tasks [12], as well as scapular kinematics for limited shoulder movements and postures [18], have been reported for children with brachial plexus birth palsy, but not for adults with BPI.

We conducted a pilot study to evaluate the relationship between MIJM and joint moments during 7 upper extremity functional tasks in adults with BPI. We hypothesized that joint strength at the shoulder and elbow would be lower in the impaired extremities than in the unimpaired contralateral extremities. Additionally, we expected that subjects with less maximal strength would have greater difficulty performing tasks as indicated by greater bilateral differences in joint angle extrema and the percentage of MIJM used during tasks.

2. Methods

2.1. Subject recruitment

We recruited six adults ages 23–75 with a history of unilateral traumatic BPI (Table 1). Subjects were included if they had a history of brachial plexus injury affecting the C5 and C6 roots of the brachial plexus but were able to move their shoulder, and excluded if they had a secondary upper extremity musculoskeletal disorder, such as osteoarthritis. The causes of injury were motor vehicle collisions ($n = 2$), motorcycle accidents ($n = 2$), an all-terrain vehicle accident, and a pedestrian struck by a car. All patients had previously undergone surgery which included neurolysis, direct nerve repair, nerve graft, and nerve transfer. Mean time since injury and surgery were 26.2 (SD = 8.3) and 21.2 (SD = 9.5) months, respectively.

2.2. Subject testing

The experimental protocol was approved by the Institutional Review Board for human subject research, and informed consent was obtained prior to each testing session. During a single testing session, we assessed the bilateral maximum joint strength and movement ability of each subject, with the unimpaired extremities serving as controls. Joint strength, as quantified by MIJM, was measured along 8 directions of movement (Table 2) using a Chatillon CSD300 hand-held dynamometer (AMETEK, Inc., Largo, FL). For each trial, subjects were positioned in the desired posture and verbally encouraged to press against the dynamometer with maximal effort for 5 s. The dynamometer was positioned to measure linear force orthogonal to both the joint axis of rotation and the subject's extremity. Two trials were performed for each direction of movement, and the maximum measured linear force was recorded. Arm, forearm, and total limb lengths were measured to determine the dynamometer's moment arm about the joint center of rotation for each direction of movement. MIJM was computed as the product of the maximum linear force and the dynamometer moment arm about the joint axis of rotation.

Marker kinematic data was collected for 7 unimanual tasks (task name in italics): shoulder *abduction* to 90° in the frontal plane, hand to contralateral *axilla*, hand to *face*, hand to back of *head*, hand to ipsilateral back *pocket*, hand to *shelf* at eye level, and hand to *table* top at waist level. Twenty-seven retro-reflective markers were placed on each subject to track the position of the torso, head, and right and left upper extremities during the movements. During the motion capture session, subjects were seated in an upright posture and instructed to begin and end each trial with the arm relaxed at the side. Subjects performed each task 3 times with each extremity at a self-selected speed, and were allowed to rest each side for 60 s between trials. Subjects were encouraged to move the hand as close to the desired endpoint as possible. Marker trajectories were measured and recorded at 200 Hz using a 7-camera Hawk infrared motion capture system (Motion Analysis, Santa Rosa, CA). One of the 3 trials for each extremity was chosen for post-processing in Cortex (Motion Analysis, Santa Rosa, CA) based on the quality of the recorded marker trajectories.

Table 1
Subject demographics and clinical summary.

Subject	Age	Sex	Height (cm)	Body mass (kg)	Level of injury	Cause	Nerve surgery	Concomitant injuries at time of BPI	Affected limb	Dominant limb
1	54	m	181.6	92.5	C5-C6	Motorcycle accident	**Neurolysis** of C5 and C6 nerve roots, upper trunk, left brachial plexus. **Excision** of neuroma. **Direct repair** of suprascapular nerve	Left clavicle and multiple rib fractures	L	R
2	75	m	177.8	104.8	C5-C6	Pedestrian struck by car	**Neurolysis** of supraclavicular plexus. **Direct repair** of brachial plexus, axillary nerve. **Extensive mobilization** of radial nerve.	C3 transverse process fracture, lacerations above left eye	L	R
3	24	m	177.8	98.0	C5-C6	motor vehicle crash	**Neurolysis** of supraclavicular plexus. **Direct repair** brachial plexus.	Mild TBI	L	R
4	31	m	180.3	94.1	C5-T1	motorcycle accident	**Neurolysis** of supraclavicular and infraclavicular plexus. **Repair** of brachial plexus with greater than 4 cm left sural nerve graft.	Left proximal radial head fracture	L	R
5	51	m	177.8	86.2	C5-C6	ATV accident	**Neurolysis** of supraclavicular plexus, suprascapular nerve and branches.	left mid-shaft humerus fracture	L	R
6	23	f	162.6	57.2	C5-T1	motor vehicle crash	**Neurolysis** of C5 nerve root and suprascapular nerve branch, C6 nerve root and branches, C7 nerve root and middle trunk, C8 nerve root and the lower trunk, and T1 nerve root.	Right thoracic outlet syndrome	R	R

Table 2
Postures in which maximum isometric joint moment (MIJM) were measured for each direction of movement.

Direction of movement	Posture
Shoulder abduction and adduction	Subject supine, elbow extended, shoulder abducted to 45°
Shoulder flexion and extension	Subject seated upright, elbow extended, shoulder abducted to 30°
Shoulder internal and external rotation	Subject supine, elbow flexed to 90°, shoulder abducted to 30°
Elbow flexion and extension	Subject supine, elbow flexed to 90°, shoulder abducted to 30°

A generic adult upper extremity musculoskeletal model [19,20] implemented in OpenSim [21] was simplified to include five degrees of freedom: shoulder elevation, shoulder elevation plane, shoulder rotation, elbow flexion, and forearm pronation/supination. Shoulder degrees of freedom, including shoulder elevation (thoracohumeral angle) and shoulder elevation plane (rotation of the arm from the frontal plane, where 0° is pure abduction and 90° is forward flexion) were defined according to recommendations by the International Society of Biomechanics [22]. Muscles were replaced by linear torque actuators along the five degrees of freedom. The upper extremity model was scaled to match each subject's size using marker data recorded while the subject maintained a static pose. Using the processed marker trajectories, an inverse kinematics analysis was performed to compute the joint kinematics during each task. The joint kinematic data was filtered at 5 Hz using a 3rd order low pass IIR Butterworth digital filter. An inverse dynamics analysis was performed to compute task joint moments produced by the model's linear torque actuators during the tasks. Task joint moments (M_t) produced by the linear torque actuators represent the net joint moments that muscles crossing the shoulder would have to generate to complete each task. Once computed, task joint moments were filtered using a simple moving average filter with a 50-sample window, with each sample being equally weighted.

To permit comparison between MIJM and task joint moments, task joint moments about the shoulder were converted from the Euler reference frame used in the model to an anatomical reference frame. Shoulder abduction/adduction moment, generated about the anterior–posterior anatomical axis, was computed as:

$$M_{\text{abduction}} = M_{\text{SE}}\cos(EA) \quad (1)$$

and shoulder flexion/extension moment, generated about an axis parallel to the frontal plane, was computed as:

$$M_{\text{flexion}} = \text{sign}(M_{\text{EA}})\sqrt{M_{\text{EA}}^2 + [M_{\text{SE}}\sin(\text{EA})]^2}. \quad (2)$$

In Eqs. (1) and (2), M_{SE} and M_{EA} are the moments about the shoulder elevation and elevation plane axes, respectively, and EA is the elevation plane angle.

2.3. Data analysis

For this pilot study, one-tailed paired sample Wilcoxon signed rank tests were performed to determine if within-subject MIJM was significantly lower on the impaired side than on the unimpaired side. The percentage of MIJM that subjects used to perform the tasks (%MIJM) was computed for each extremity by dividing the peak task joint moment ($M_{\text{t,peak}}$) for each task by MIJM. We performed two-tailed paired sample Wilcoxon signed rank tests to determine whether, during the seven upper extremity tasks, extremum joint angles, $M_{\text{t,peak}}$, and %MIJM differed between the impaired and unimpaired extremities. Additionally, the peak %MIJM for each subject across all tasks was compared between extremities using one-tailed paired sample Wilcoxon signed rank tests. Statistical comparisons were significant for $p < 0.05$. Due the pilot nature of this study, no corrections were made for performing multiple statistical tests.

3. Results

Subjects had significantly lower maximum isometric joint moment (MIJM) in the impaired extremities than in the unimpaired extremities in all 8 tested directions of shoulder and elbow movement (Fig. 1). Bilateral differences in MIJM as a percentage of unimpaired limb MIJM were most pronounced in abduction (60%, $p = 0.02$), extension (49%, $p = 0.02$), and external rotation (75%, $p = 0.02$). Subject 2 had no measurable shoulder abduction and external rotation strength in the tested postures. Likewise, subject 4 had no measurable elbow flexion or extension strength in the tested postures.

Maximum and minimum joint angles differed between subjects' impaired and unimpaired extremities for some of the tested unimanual tasks (Table 3 and supplementary data). When performing the head task with the impaired limb, subjects achieved 23.1° ($p = 0.03$) lower peak posterior elevation plane angle; 15.2° greater peak internal shoulder rotation angle ($p = 0.04$); 16.2° ($p = 0.03$) lower peak external shoulder rotation angle; and 24.4° ($p = 0.04$) lower peak elbow flexion angle, on average, than when using the unimpaired limb. In other words, subjects' impaired extremities were in a slightly more anterior, internally rotated posture when touching the back of the head with respect to the defined joint angle reference frame. As a result of severe weakness, only subjects 2 and 4 could not move the hand of their impaired extremity to the desired endpoint for all 7 tasks. Subject 2 could only successfully complete the pocket and table tasks, while subject 4 could only complete the abduction, shelf, and table tasks.

Shoulder extension and shoulder adduction $M_{\text{t,peak}}$ were 29% ($p = 0.03$) and 38% ($p = 0.01$) lower on the impaired side during the head task as a result of between-side kinematic differences during this task. The task that required the highest $M_{\text{t,peak}}$ varied among subjects and between sides, but was consistent with the limb movement needed to perform the task (Table 4). For example, subjects generated the highest shoulder abduction $M_{\text{t,peak}}$ with their unimpaired limbs during the head, abduction, and shelf tasks. These tasks required subjects to elevate their arm approximately to the level of the shoulder given the endpoint constraints of the tasks.

Due to lower MIJM on the impaired side, $M_{\text{t,peak}}$ accounted for a higher percentage of subjects' maximum strength for tasks performed with the impaired upper extremities. %MIJM was significantly higher on the impaired side for all 7 tasks in shoulder

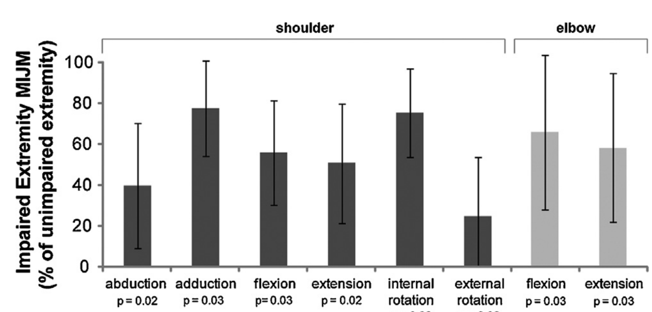

Fig. 1. Mean (± standard deviation) of MIJM measured in subjects' impaired extremities as a percentage of MIJM measured in the unimpaired extremities. MIJM was significantly lower on the impaired side than on the unimpaired side for all directions of movement.

Table 3
Bilateral differences in maximum (A) and minimum (B) joint angle (unimpaired – impaired). Angles were positive for shoulder elevation, anterior elevation plane angle, internal shoulder rotation, and elbow flexion.

Task	Shoulder elevation		Elevation plane		Shoulder rotation		Elbow flexion	
	Mean	(SD)	Mean	(SD)	Mean	(SD)	Mean	(SD)
(A)								
Abduction	11.9	(23.1)	−19.8	(18.6)	−3.9	(9.3)	3.3	(8.4)
Axilla	2.9	(4.9)	8.3	(11.8)	0.1	(6.5)	10.9	(30.7)
Face	−4.7	(17.5)	1.1	(8.0)	−6.1	(18.0)	9.8	(17.3)
Head	19.3	(25.8)	−11.8	(15.1)	−15.2	(17.0)*	24.4	(33.9)*
Pocket	10.7	(17.4)	−25.3	(34.8)	−0.6	(15.2)	9.6	(17.8)
Shelf	−0.2	(30.3)	−2.0	(5.2)	−12.5	(18.3)	10.4	(24.7)
Table	−5.6	(18.6)	−15.1	(23.1)	−5.8	(11.5)	11.1	(24.3)
(B)								
Abduction	2.7	(2.6)	−13.7	(26.5)	−9.8	(18.9)	1.8	(8.2)
Axilla	1.5	(2.5)	−0.3	(35.1)	−3.1	(11.7)	7.4	(10.4)
Face	3.2	(2.4)	−12.4	(24.8)	−2.5	(13.7)	3.8	(6.6)
Head	2.0	(2.7)	−23.1	(16.1)*	−16.2	(16.5)*	4.0	(6.9)
Pocket	2.7	(2.6)*	−4.4	(13.4)	2.7	(19.1)	7.8	(9.0)
Shelf	2.3	(2.2)	−10.4	(40.8)	−6.5	(9.0)	7.7	(9.0)
Table	2.4	(2.5)	−7.5	(25.2)	2.4	(8.7)	6.8	(9.0)

* $p < 0.05$.

Table 4
Tasks for which the highest peak task joint moment ($M_{t,peak}$) was generated for each subject and side.

Subject	Side	Direction of movement							
		Shoulder abduction	Shoulder adduction	Shoulder flexion	Shoulder extension	Shoulder internal rotation	Shoulder external rotation	Elbow flexion	Elbow extension
1	unimp	head	head	axilla	face	abd	axilla	axilla	head
	imp	head	head	shelf	axilla	abd	axilla	face	head
2	unimp	head	abd	shelf	shelf	head	axilla	shelf	head
	imp[a]	face	shelf	shelf	shelf	abd	axilla	shelf	pocket
3	unimp	head	head	shelf	axilla	abd	axilla	head	head
	imp	head	head	shelf	shelf	abd	axilla	shelf	head
4	unimp	abd	head	table	face	face	axilla	axilla	head
	imp[b]	axilla	abd	shelf	shelf	abd	face	head	shelf
5	unimp	head	head	head	face	abd	axilla	head	head
	imp	head	head	shelf	axilla	abd	axilla	axilla	head
6	unimp	shelf	head	table	table	abd	axilla	head	head
	imp	shelf	table	table	table	shelf	axilla	shelf	head

[a] Subject 2 had no measurable shoulder abduction and external shoulder rotation strength in tested postures.
[b] Subject 4 had no measurable elbow flexion or elbow extension strength in tested postures.

external rotation, 3 of 7 tasks in shoulder abduction, 2 of 7 tasks in elbow flexion, and 1 of 7 tasks in shoulder adduction, shoulder flexion, shoulder extension, and elbow extension (Fig. 2). %MIJM was only significantly lower on the impaired side in shoulder adduction during the head task. The peak %MIJM that subjects used across all tasks was significantly higher on the impaired side in shoulder extension (32%, $p = 0.03$) and shoulder external rotation (29%, $p = 0.03$) directions of movement (Fig. 3).

4. Discussion

Despite great advances in the clinical management of patients with BPI over the past few decades, restoring muscle strength remains a challenge. One center reported that, of 176 patients with lost shoulder function, only half recovered the ability to abduct the shoulder more than 45° and externally rotate the shoulder more than 20° [9]. Similarly, we observed that subjects were significantly weaker on the affected side for all directions of movement tested, despite all having undergone extensive surgery and physiotherapy.

The results of this study generally did not support our hypothesis that subjects with substantially lower maximal strength change their movement strategy enough to significantly reduce net muscle-generated joint moments during upper extremity tasks. The few significant bilateral kinematic differences observed during trials resulted only in significantly lower shoulder extension and shoulder adduction $M_{t,peak}$ on the impaired side during the head task. Consequently, subjects used a significantly higher percentage of maximal strength, especially in shoulder external rotation, to perform several tasks (Fig. 2). Possible strategies to reduce acute mechanical demand could be to perform tasks more slowly or elevate the arm away from the body less during tasks. Future studies are needed to identify specific ways in which individuals may employ these or other kinematic compensation strategies to overcome strength limitations.

Quantitatively measuring maximum joint strength may help clinicians more precisely monitor and preserve function in patients with upper extremity musculoskeletal disorders. Currently, patient function is evaluated by assigning manual muscle grades [6,7], observing patients performing tasks [3], measuring active range of motion [9], or tracking responses to task-based questionnaires [23]. However, we observed that the ability to perform basic functional tasks was not an indicator of joint strength, since 4 of the 6 subjects were able to complete all 7 tasks despite large bilateral differences in MIJM. Quantitative strength measurements provide context to functional ability by allowing clinicians to estimate how close patients are to being unable to perform tasks.

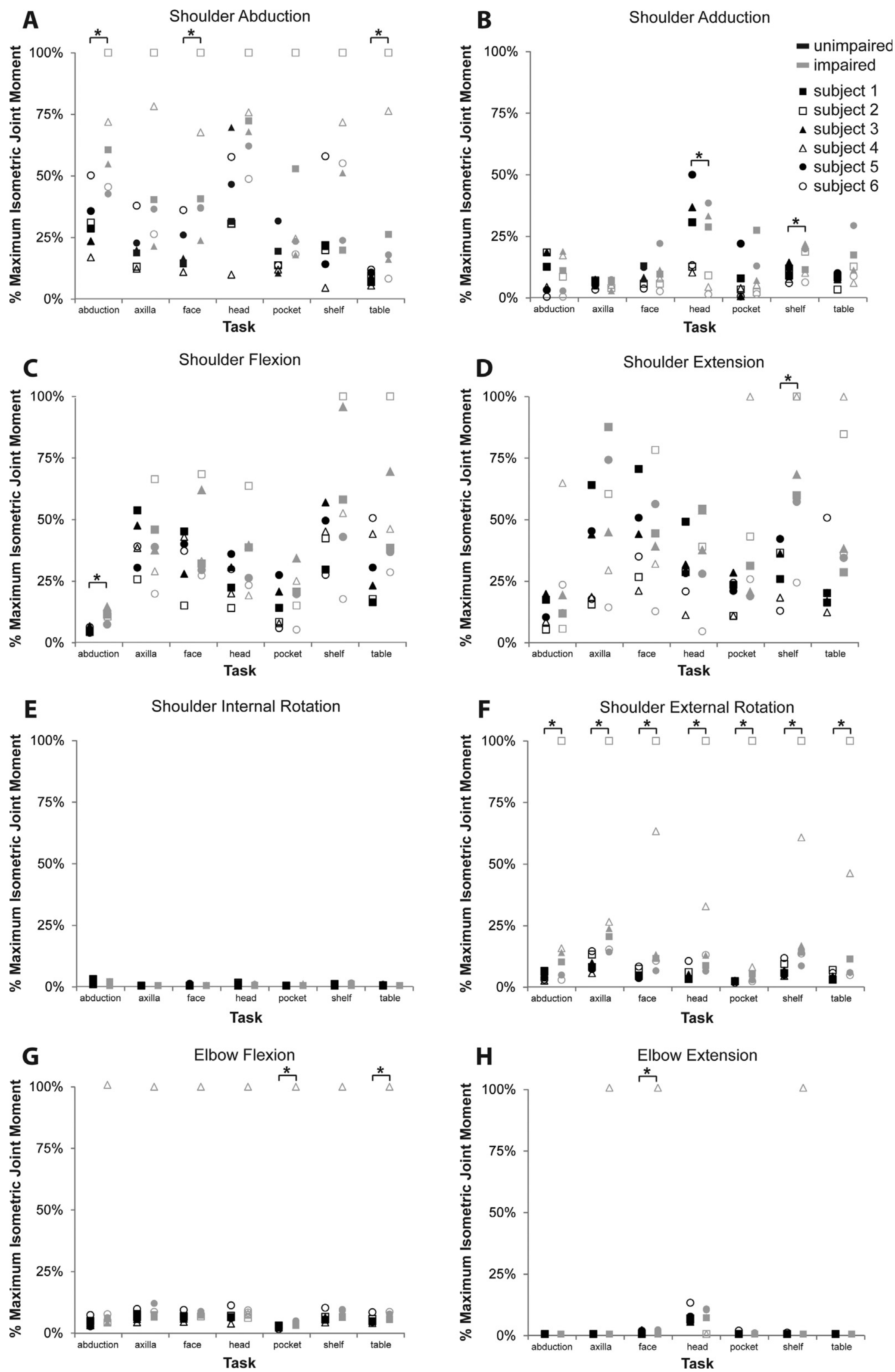

Fig. 2. %MIJM during tasks in eight directions of movement: (A) shoulder abduction, (B) shoulder adduction, (C) shoulder flexion, (D) shoulder extension, (E) shoulder internal rotation, (F) shoulder external rotation, (G) elbow flexion, and (H) elbow extension. %MIJM was significantly higher on the impaired side for several tasks and directions of movement (*$p < 0.05$).

Hand-held dynamometry [24], as used in this study, is practical to implement in clinical settings and provides a more accurate and high-resolution measure of strength than manual muscle grades. Additionally, hand-held dynamometers have been used to measure upper extremity strength in children with brachial plexus birth palsy [14]. Given the idiosyncratic clinical presentation of BPI in our subjects and in reported clinical outcomes, it may be most beneficial and practical to quantify strength along directions of movement in which patients perform poorly during traditional qualitative exams. Additionally, strength training may

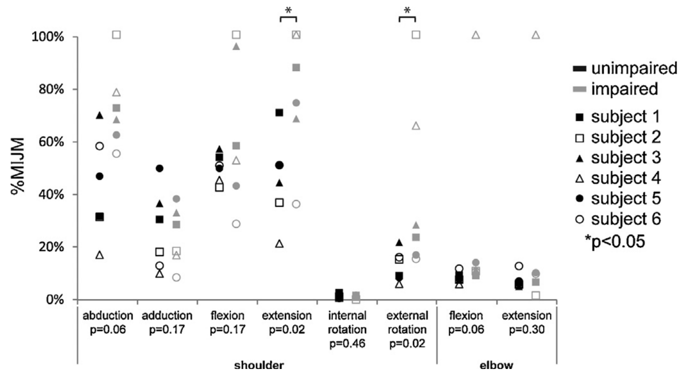

Fig. 3. The maximum percentage of MIJM (%MIJM) used by subjects across all tasks. Paired differences in %MIJM between subjects' impaired and unimpaired extremities were significant along the shoulder extension ($p = 0.02$) and shoulder external rotation ($p = 0.02$) directions of movement. Subjects 2 and 4 required 100% of their MIJM to perform at least one of the tasks.

improve functional ability as observed for other strength-compromised conditions such as rotator cuff injuries [25] and advanced age [10].

%MIJM is one possible effective indicator for clinical strength training interventions. Because it represents the margin between a patient's maximum strength and the strength required to perform tasks, individuals using a higher %MIJM to perform tasks may be less adaptive to long-term strength decline due to injury progression [26] or normal aging [10]. While strength decline may be interrupted with targeted training and rehabilitation [27], the %MIJM threshold for clinical intervention remains to be defined. Future studies should establish the rate of strength decline in patients with BPI and other upper extremity disorders to define critical intervention time points. Additionally, the strength required to perform a variety of upper extremity tasks should be established to standardize estimates of %MIJM.

Previous studies have shown that both strength and upper extremity kinematics can be impaired following BPI, but the relationship between the two have not been explored in the same subjects. Following treatment, elbow flexion strength in the impaired extremity of adult patients with C5–C6 injury ranged from 27% to 59% of that of the unimpaired contralateral side [4]. Likewise, children with brachial plexus birth palsy can exhibit significantly reduced strength at the shoulder and elbow [14]. Kinematic data from children suggest a reduced ability to abduct and externally rotate the shoulder during tasks, and higher scapulothoracic motion relative to glenohumeral motion during shoulder elevation [12,13,18,28]. We observed fewer bilateral kinematic differences during tasks in our adult cohort than those reported for children with brachial plexus birth palsy, possibly due to between-population differences in injury severity, neuromuscular recovery, and treatment strategies, or the development of shoulder deformity in children. Additionally, we did not measure scapular kinematics during tasks to determine if they differed between sides.

When considering treatment for patients with BPI involving the C5 and C6 nerve roots, some clinicians prioritize restoring elbow function [29], while others assert that restoring shoulder strength is most important as it supports movement distally at the elbow, wrist, and hand [30]. Based on the task performance of subjects 2 and 4, severe weakness at either the shoulder or elbow may render individuals unable to perform many of the most basic functional tasks required for independent living. However, we observed that greater strength is required at the shoulder than at the elbow to perform such tasks, which is consistent with previous findings [10]. Therefore, treatments should restore both shoulder and elbow function, with greater emphasis on recovering shoulder strength.

There were several limitations of our study. First, though all included subjects had involvement of the C5 and C6 nerve roots, the extent and severity of injury and treatments received varied considerably among subjects. Biomechanical evaluation of patients with BPI is challenging given the heterogeneity of their clinical presentation. Limiting inclusion criteria (involvement of C5 and C6 nerve roots) and assessing strength and function bilaterally improved our statistical testing. Consequently, we identified functional ability trends that motivate the development of more focused studies with larger numbers of subjects, potentially drawn from multiple medical centers.

Another limitation of the study was that, for each direction of movement at the shoulder and elbow, we compared MIJM measured in a single posture to joint moments produced in many different postures during each task. However, MIJM varies with joint posture, as it is a function of the posture-dependent length and moment arm of each contributing muscle. We also measured MIJM using a hand-held dynamometer, which does not provide a direct measure of joint moment as other full-body dynamometers do (e.g., Biodex, New York, USA). Variation in $M_{t,peak}$ across subjects, tasks, and sides may have been due to subject-specific factors such as self-selected movement speed.

In conclusion, adult subjects with unilateral BPI did not significantly alter their impaired extremity kinematics and dynamics despite having significantly lower strength on their impaired side. Therefore, subjects used a significantly higher percentage of their impaired side maximal strength for several tasks and directions of movement. Future studies should evaluate how quantitative strength relates to semi-quantitative strength measures (e.g. manual muscle grades) and patient self-reported function. Additionally, longitudinal studies to monitor strength and functional declines over time would help establish clinical intervention thresholds. Quantitatively measuring joint strength, in addition to movement ability, during standard clinical exams may more discriminately identify patients who could most benefit from timely interventions to preserve their long-term strength and functional ability.

Conflicts of interest

There are no conflicts of interest.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.gaitpost.2015.12.038.

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