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RESEARCH ARTICLES

**Randall F. Beer · Julius P. A. Dewald ·
Michelle L. Dawson · W. Zev Rymer**

Target-dependent differences between free and constrained arm movements in chronic hemiparesis

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Abstract This study compares the kinematic and kinetic characteristics of constrained and free upper limb movements in eight subjects with chronic hemiparesis. Movements of the dominant and nondominant limbs were also examined in five control subjects. Rapid movements were performed in the horizontal plane from a central starting point to five targets located to require various combinations of flexion/extension rotations at the elbow and shoulder. Support of the upper limb against gravity loading was provided either by a low-friction air-bearing apparatus (constrained condition) or by voluntary generation of abduction and external rotation torques at the shoulder (free condition). Data analysis focused on the peak joint torques generated during the acceleratory phase of movement, and on the net change in joint angles at the elbow and shoulder. We found that movement parameters were broadly invariant with support condition for either limb of control subjects, as well as for the nonparetic limb of hemiparetic subjects. In contrast, support condition had a target-dependent effect on movements of the paretic limb. Relative to the constrained condition, peak torques for free arm movements were significantly reduced for distal targets requiring elbow extension and/or shoulder flexion torques. However, peak elbow flexion and shoulder extension joint torques for proximal targets were relatively unaffected by support condition. Of perhaps more functional importance, free movements were characterized by a target-dependent restriction in the hand's work area that reflected a reduced range of active elbow extension, relative to constrained movements. The target-dependent effects of support condition on movements of the paretic limb are consistent with the existence of abnormal constraints on muscle activation patterns in subjects with chronic hemiparesis, namely an abnormal linkage between activation of the elbow flexors and shoulder extensors, abductors, and external rotators.

Keywords Stroke · Kinematics · Joint torque · Synergy · Reaching

R. F. Beer (✉) · J. P. A. Dewald · M. L. Dawson · W. Z. Rymer
Sensory–Motor Performance Program, Room 1406,
Rehabilitation Institute of Chicago,
345 East Superior Street,
Chicago, IL 60611, USA
e-mail: rbeer@casbah.acns.nwu.edu
Tel.: +1-312-2381408
Fax: +1-312-2382208

R. F. Beer · J. P. A. Dewald · W. Z. Rymer
Department of Physical Medicine and Rehabilitation,
Northwestern University,
Chicago, Illinois, USA

J. P. A. Dewald
Department of Physical Therapy and Human Movement Science, Northwestern University,
Chicago, Illinois, USA

J. P. A. Dewald · W. Z. Rymer
Department of Biomedical Engineering, Northwestern University,
Chicago, Illinois, USA

Introduction

Synergic relationships between the activations of shoulder and elbow muscles are normally not fixed, but are modulated by the central nervous system in response to task conditions such as load (Buchanan et al. 1986; Flanders and Soechting 1990) or movement (Gottlieb et al. 1997; Karst and Hasan 1991; Wadman et al. 1980) direction. In contrast, the recovery of upper extremity function following hemiparetic stroke is characterized by the emergence of stereotypic multijoint movement patterns that reflect a loss of independent joint control (Brunnstrom 1970; Twitchell 1951). With respect to movements of the paretic upper limb, these so-called limb synergies involve a tight coupling of elbow flexion and extension with shoulder abduction–extension–exorotation and adduction–flexion–endorotation, respectively (Brunnstrom 1970). The pathological limb synergies represent a manifestation of abnormal constraints on elbow and shoulder muscle activation patterns during the acute phase of stroke, presumably due to the destruction of corticospinal and corticobulbar fibers. However, given subsequent reorganization of the central nervous system (Chen et al. 2002; Nudo and Friel 1999), it remains unclear whether similar constraints contribute to disturbances of voluntary arm movements in *chronic* stroke.

Recent studies of reaching performance in chronic stroke subjects have generally concluded that the observed kinematic disturbances were not related to the limb synergies (Beer et al. 2000; Levin 1996; Reinkensmeyer et al. 2002; Trombly 1992; Wing et al. 1990). Rather, movement deficits have been variously attributed to agonist muscle paresis (El-Abd et al. 1993; Fellows et al. 1994; Gowland et al. 1992), reflex hyperactivity (Mizrahi and Angel 1979), changes in passive tissue properties (Dietz et al. 1991; Reinkensmeyer et al. 1999a), and/or disturbances of central planning (Beer et al. 2000; Kusoffsky et al. 2001; Levin 1996; McLellan et al. 1985; Trombly 1992). In contrast, quantitative studies of the muscle activation and joint torque patterns associated with isometric force production in subjects with chronic hemiparesis provide clear evidence that selective or independent activation of muscles remains compromised in the paretic upper limb (Bourbonnais et al. 1989; Dewald and Beer 2001; Dewald et al. 1995). The last two studies support the existence of abnormal synergies between elbow and shoulder muscles in the paretic upper limb, in particular between elbow flexors and shoulder abductors and between elbow extensors and shoulder adductors. Similarly, during arm movements that are mechanically constrained to a parasagittal plane, chronic stroke subjects generate abnormal out-of-plane forces consistent with these synergies (Reinkensmeyer et al. 1999b). That is, shoulder adduction and internal rotation torques increase during reaching and abduction and external rotation torques increase during retrieval.

We have previously shown under isometric conditions that the apparent weakness of the paretic elbow flexors and extensors is strongly dependent on the magnitude and direction of torques generated concurrently at the shoulder (Beer et al. 1999). Specifically, as the abduction torque generated by the subject is increased, the generation of elbow flexion torque is facilitated, while the ability to generate elbow extension torque degrades dramatically. This task-dependent weakness is consistent with a limited ability of subjects with chronic hemiparesis to activate elbow and shoulder muscles outside of the abnormal patterns described above. The present study extends this line of investigation to conditions of voluntary movement. We compare arm movements performed in the horizontal plane under two conditions of arm support, with the arm either supported against gravity loading on a low-friction air bearing (constrained movement) or actively supported by the subject (free movement). Thus, during constrained movements the air bearing resisted adduction and internal rotation torques associated with gravity loads on the limb or abnormal out of plane forces, while during free movements activation of the shoulder abductors and external rotators was required for postural stabilization.

We found that, relative to the constrained condition, free movements of the paretic arm were characterized by significant reductions in the peak elbow extension and shoulder flexion torques associated with movement initiation and a directionally dependent restriction in the planar work area that reflected a reduced range of active elbow extension but not flexion. The constrained condition provided a control for the effects of agonist muscle paresis, disturbances of central planning, and changes in passive tissue compliance. Therefore, we hypothesize that the primary mechanism underlying our findings is a residual linkage between the activations of elbow flexors and shoulder abductors, extensors, and external rotators in the paretic limb of subjects with chronic hemiparesis, with a potential secondary contribution from hyperexcitable stretch reflexes.

Materials and methods

Subjects

Eight subjects with chronic hemiparesis (mean age 56 years, range 46–69 years) and five control subjects (three males and two females; mean age 59 years, range 45–78 years) participated in this study. Demographic data for the hemiparetic group are summarized in Table 1. All subjects were right hand dominant. Hemiparetic

Table 1 Clinical data for hemiparetic subjects. (*F* flexion, *E* extension)

Subject	Gender	Age	Lesion site	Years since onset	Functional evaluation[a]	Spasticity F/E[b]
1	M	65	Right internal capsule, basal ganglia, and external capsule	3	53	2/1
2	M	52	Right internal capsule and basal ganglia	15	50	3/2
3	F	51	Right frontal cortex	5	48	2/2
4	F	55	Left frontal cortex	5	41	1/1
5	M	69	Left internal capsule	5	40	2/0
6	M	46	Right frontal and parietal cortex	13	27	3/3
7	M	50	Right frontal cortex	20	18	3/2
8	M	63	Left frontal and parietal cortex	4	15	2/1

[a]Based on Fugl–Meyer scale (maximum score=66)

[b]Modified Ashworth score for the elbow (0=normal function, 5=severe spasticity)

subjects admitted to the study fulfilled the following selection criteria: (1) hemiparesis resulting from a unilateral lesion of the cortex or subcortical white matter with an onset at least 1 year prior to data collection, (2) absence of notable sensory deficits in the paretic upper limb, (3) absence of severe cognitive or affective dysfunction, (4) absence of severe concurrent medical problems, (5) absence of severe atrophy or contracture of the paretic limb, and (6) capacity to complete the experimental protocol. All subjects provided informed consent in accordance with the Declaration of Helsinki prior to participation in this study, which was approved by the Institutional Review Board of Northwestern University.

Clinical evaluation

Motor function of the paretic upper extremity was evaluated using the Fugl-Meyer Motor Function Test (Fugl-Meyer et al. 1975). This assessment included the evaluation of tendon reflexes and voluntary movements performed within and out of the pathologic limb synergies (Brunnstrom 1970; Twitchell 1951). Possible scores range from 0 to a maximum of 66, which indicates no observable deficit. Muscle tone at the elbow was evaluated using a six-point scale (0=normal tone; 5=severe spasticity) based on the modified Ashworth criteria (Ashworth 1964). The results of these clinical evaluations are summarized in Table 1. Based on the Fugl-Meyer (FM) score, six of the subjects were moderately impaired (FM between 20 and 55) and two were severely impaired (FM<20).

Proprioceptive function was assessed using two protocols, both of which required the subject to sit with eyes closed. During the first protocol the subject used the nonparetic limb to duplicate a series of postures imposed on the paretic elbow, shoulder and wrist by the examiner (Brunnstrom 1970). The second protocol, developed by Leo and Soderberg (1981), required the subject to touch, with the index finger of the nonparetic limb, a piece of tape affixed to the back of the wrist of the paretic limb after it had been manipulated into each of six configurations involving different combinations of elbow and shoulder rotations.

Experimental setup

A schematic of the experimental setup is shown in Fig. 1. The subject was seated in a chair in front of a large table with the trunk immobilized by a set of straps and the wrist and finger joints immobilized using a fiberglass cast. A lightweight platform, which functioned as an air bearing, was attached to the forearm to allow virtually friction-free motion of the limb across the table surface during constrained movements.

Movement recording

Kinematic data were collected using the Optotrak/3010 motion analysis system (Northern Digital, Waterloo, Ontario, Canada). Infrared light emitting diodes (IREDS) were placed at the following positions: above the acromial process of the scapula, in-line with the flexion/extension axis of rotation of the elbow (Shiba et al. 1988), and on the cast above the tip of the ring finger. The position of each IRED was sampled at 300 Hz.

Target array

Movements were performed in the horizontal plane (90° shoulder abduction angle) from a common starting position to each of five targets as shown in Fig. 1. The starting position was aligned with the midsagittal plane of the subject and located at a distance from the body that yielded an elbow angle of 90°. Four of the targets were located to require 30° of rotation at the elbow (extension for the EE and Reach targets, flexion for the EF and Retrieval targets). The EE and EF targets were located such that they could be acquired without motion at the shoulder, while acquisition of the Reach and Retrieval targets required 20° of shoulder flexion or extension, respectively. The SF target was located to require flexion (20°) of the shoulder only.

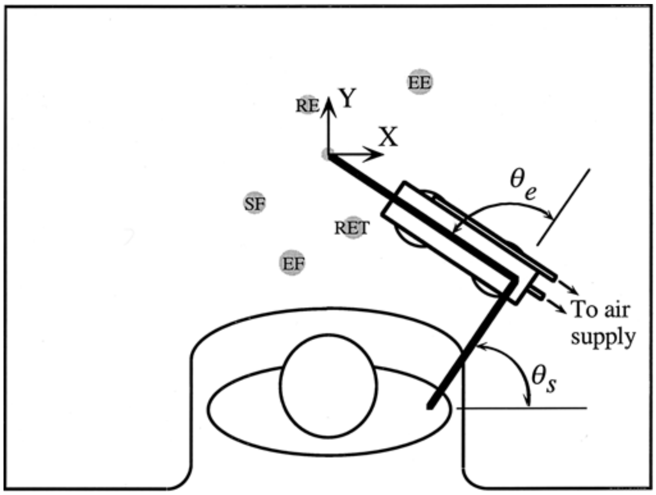

Fig. 1 Schematic of the experimental setup. Arm movements were performed in the horizontal plane from a central starting point to a set of five targets with the arm either supported on a lightweight air bearing device (constrained movement) or actively supported by the shoulder musculature (free movement). Targets were located to require various combinations of elbow and shoulder flexion/extension rotations for acquisition: *EE* 30° elbow extension, *RE* (reach) 30° elbow extension + 20° shoulder flexion, *SF* 20° shoulder flexion, *EF* 30° elbow flexion, *RET* (retrieval) 30° elbow flexion + 20° shoulder extension. The positions of the hand, elbow, and shoulder were measured in Cartesian coordinates (*X*, *Y*) using an optoelectric system and converted off-line into the corresponding shoulder (θ_s) and elbow angles (θ_e)

Circles designating the starting position and target were displayed on a computer monitor and projected onto the table surface using a liquid crystal display, projector, and mirror. Custom software allowed the size and location of the circles to be varied as desired. The target diameter was set equal to 20% of the movement amplitude (10–26 cm depending on target location and subject) to emphasize open-loop control of the trajectory (Wallace and Newell 1983).

Protocol

A short training session was provided prior to data collection to familiarize the subject with the apparatus and procedures. Constrained (by the table surface) and free (actively supported) movements were performed to each target. For free movements, the support platform remained attached to the forearm to preserve mass properties across support conditions and the chair height was increased by 3 cm. Combinations of target location and support condition were performed in random order. Ten consecutive trials were performed for each combination. Trials in the free condition were repeated if the arm contacted the table during the movement.

At the beginning of each trial the subject aligned the distal IRED over the starting position. The appearance of the target circle served as a cue for the initiation of movement. The subject was instructed to move the distal marker to the target as rapidly as possible and to maintain the final position until disappearance of the target, which indicated the end of data collection. It was stressed in the instructions that the subject was not required to react to the appearance of the target but could begin the movement at his/her discretion as long as it was completed before the end of data acquisition.

Subjects completed the protocol with both limbs in separate sessions spaced approximately one week apart, beginning with the nonparetic (hemiparetic subjects) or dominant (controls) limb.

Assessment of proximal weakness

In conjunction with a parallel study, maximum voluntary shoulder abduction and external rotation torques for the paretic limb were measured in seven of the eight subjects included in the present study (subject 3 excepted). These torques were measured under isometric conditions with the limb in the same posture from which movements were initiated here. Details of the methodology have been reported elsewhere (Dewald and Beer 2001). Based on estimated mass properties for the arm, cast, and air bearing, postural support of the paretic limb against gravity loading required abduction and external rotation torques representing, on average, 33% and 30% of voluntary maximums, respectively. Results for individual subjects ranged from 20% to 61% for shoulder abduction and from12% to 60% for external rotation. Note that the external rotation torque required for postural support decreased as the elbow was flexed or extended from the starting angle of 90°, while the required abduction torque increased approximately 20% with extension of the elbow to 60°, and decreased approximately 20% with flexion of the elbow to 120°.

Data analysis

Kinematics and kinetics

The Cartesian positional data were digitally filtered using a fourth-order Butterworth filter with a forward and reverse pass to eliminate phase delays. Cutoff frequencies (typically 15–25 Hz) were determined using a residual analysis (Winter 1990). To facilitate comparisons of left and right limbs, the sign of the x component of the positional data was reversed for movements performed with the left limb. Elbow (θ_e)and shoulder (θ_s) joint angles (see Fig. 1) were determined from the filtered Cartesian data using inverse kinematics. As a check, the elbow angle was also determined based on the dot product of vectors defined by the IREDs on the limb. Velocities and accelerations in Cartesian and joint coordinates were obtained using numerical three-point differentiation.

Joint torques (N.m, flexion positive) at the shoulder (T_s) and elbow (T_e) were estimated from the kinematic data using the inverse dynamics equations for a two-link system:

$$\begin{aligned} T_s = & \left(I_l + I_u + m_l l_u^2 + 2 m_l r_l l_u \cos\theta_e\right)\ddot{\theta}_s \\ & + \left(I_l + m_l r_l l_u \cos\theta_e\right)\ddot{\theta}_e \\ & - 2 m_l r_l l_u \sin\theta_e \dot{\theta}_s \dot{\theta}_e - m_l r_l l_u \sin\theta_e \dot{\theta}_e^2 \\ & - \left((m_l l_u + m_u r_u)\sin\theta_s + m_l r_l \sin(\theta_s + \theta_e)\right)\ddot{x}_s \\ & + \left((m_l l_u + m_u r_u)\cos\theta_s + m_l r_l \cos(\theta_s + \theta_e)\right)\ddot{y}_s \end{aligned} \quad (1)$$

$$\begin{aligned} T_e = & I_l \ddot{\theta}_e + \left(I_l + m_l r_l l_u \cos\theta_e\right)\ddot{\theta}_s + m_l r_l l_u \sin\theta_e \dot{\theta}_s^2 \\ & - m_l r_l \sin(\theta_s + \theta_e)\ddot{x}_s + m_l r_l \cos(\theta_s + \theta_e)\ddot{y}_s \end{aligned} \quad (2)$$

where m_u, m_l are the masses (kg), I_u, I_l are the mass moment of inertias (kg.m^2) about the proximal joint, and r_u, r_l are the distances (m) from the proximal joint to the center of mass, for the upper and lower segments, respectively, and $\ddot{x}_s$, $\ddot{y}_s$ are the shoulder joint linear accelerations (m/s^2). Mass properties for each segment were estimated using the regression equations developed by Zatsiorsky and Seluyanov (1985). Use of this method required various length, width, and circumferential measurements of the hand, forearm, and upper arm and allowed us to account for the specific morphology of

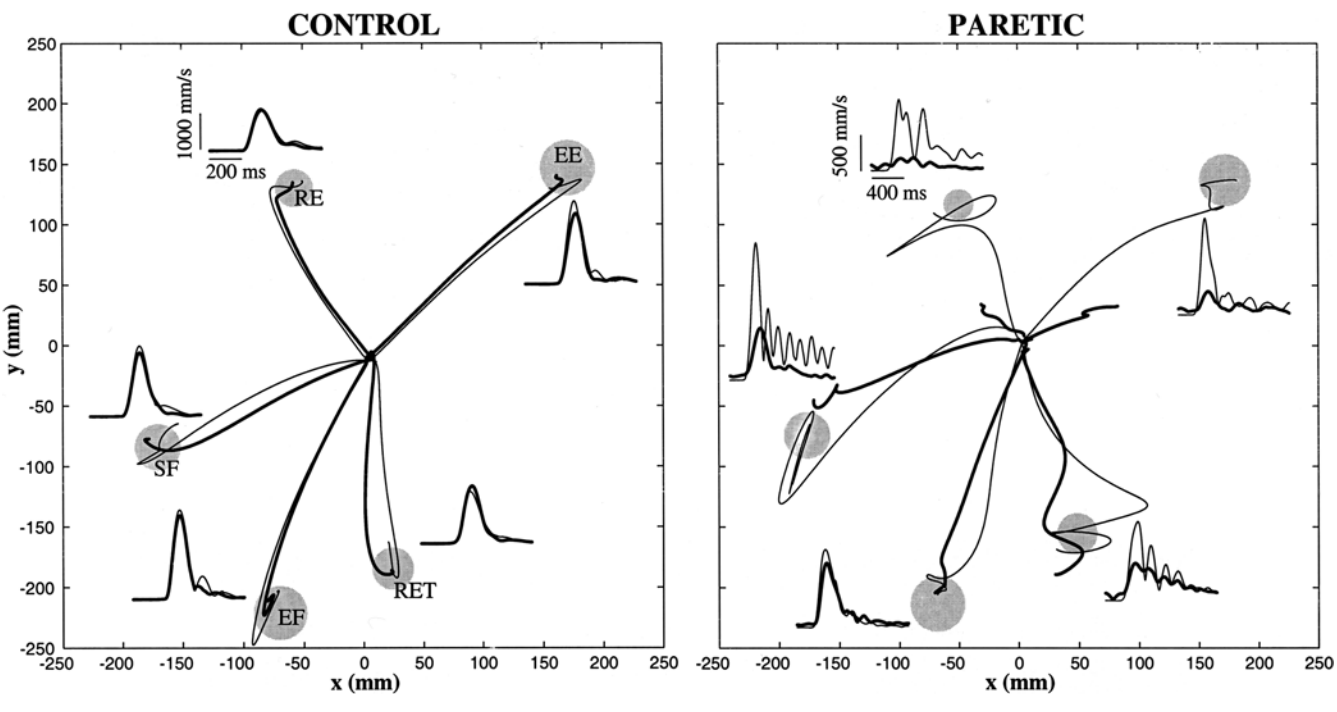

Fig. 2 Comparison of mean hand paths and tangential velocities for free (*thick lines*) and constrained (*thin lines*) arm movements. Trajectories are shown for the dominant limb of a 76-year-old control subject (*left panel*) and the paretic (dominant) limb of a moderately impaired subject (subject 4 in Table 1) with hemiparesis (*right panel*). Trials were aligned at movement onset for averaging. Targets, indicated to scale by the *shaded circles*, were located to require various combinations of elbow and shoulder flexion/extension rotations for acquisition: *EE* 30° elbow extension, *RE* (reach) 30° elbow extension + 20° shoulder flexion, *SF* 20° shoulder flexion, *EF* 30° elbow flexion, *RET* (retrieval) 30° elbow flexion + 20° shoulder extension

each subject. Mass properties of the lower (forearm and hand) segment were adjusted for the mass properties of the air bearing and cast.

For each trial, key kinematic (movement onset, initial direction of movement, peak endpoint acceleration and velocity, peak elbow and shoulder angular acceleration and velocity, initial and final joint angles) and kinetic (peak joint torques during the acceleration phase) features were identified using custom interactive software. Movement onset was defined using a threshold equal to 5% of the trial peak endpoint acceleration. The initial direction of movement was defined as the direction of the vector between the measured starting position and the position on the hand path at a distance of one-quarter of the required movement amplitude from the starting point.

Statistics

Statistical analysis of group trends focused on three dependent variables for the shoulder and elbow flexion/extension degrees of freedom: peak angular acceleration, peak joint torque, and angular excursion (difference between final and initial joint angles, flexion positive). The analysis was confined to the targets for which the joint exhibited substantial motion (i.e., for the elbow the four targets requiring 30° rotations; for the shoulder the three targets requiring 20° rotations).

Univariate analyses of variance (SPSS ANOVA) were performed for the hemiparetic and control groups to analyze the dependence of each variable on Limb, Support Condition, and Target. A three-factor design with repeated measures on all factors was used. A logarithmic transformation of torque magnitude was used to improve the sphericity of the data. The analysis of angular excursion was also based on absolute values (i.e., excursion magnitude). If a three-factor ANOVA indicated a significant interaction involving the factor Limb, separate two-factor (Support Condition, Target) ANOVAs were performed for each limb. The sphericity of each transformed dependent variable was evaluated using Mauchly's test. The Huynh-Feldt method was used to adjust the degrees of freedom used for tests of significance if the sphericity requirement appeared to be violated. The significance level was set at $P<0.05$ for all statistical analyses.

Results

Hand trajectories

Hand trajectories for either limb of control subjects and the nonparetic limb of hemiparetic subjects were found to be

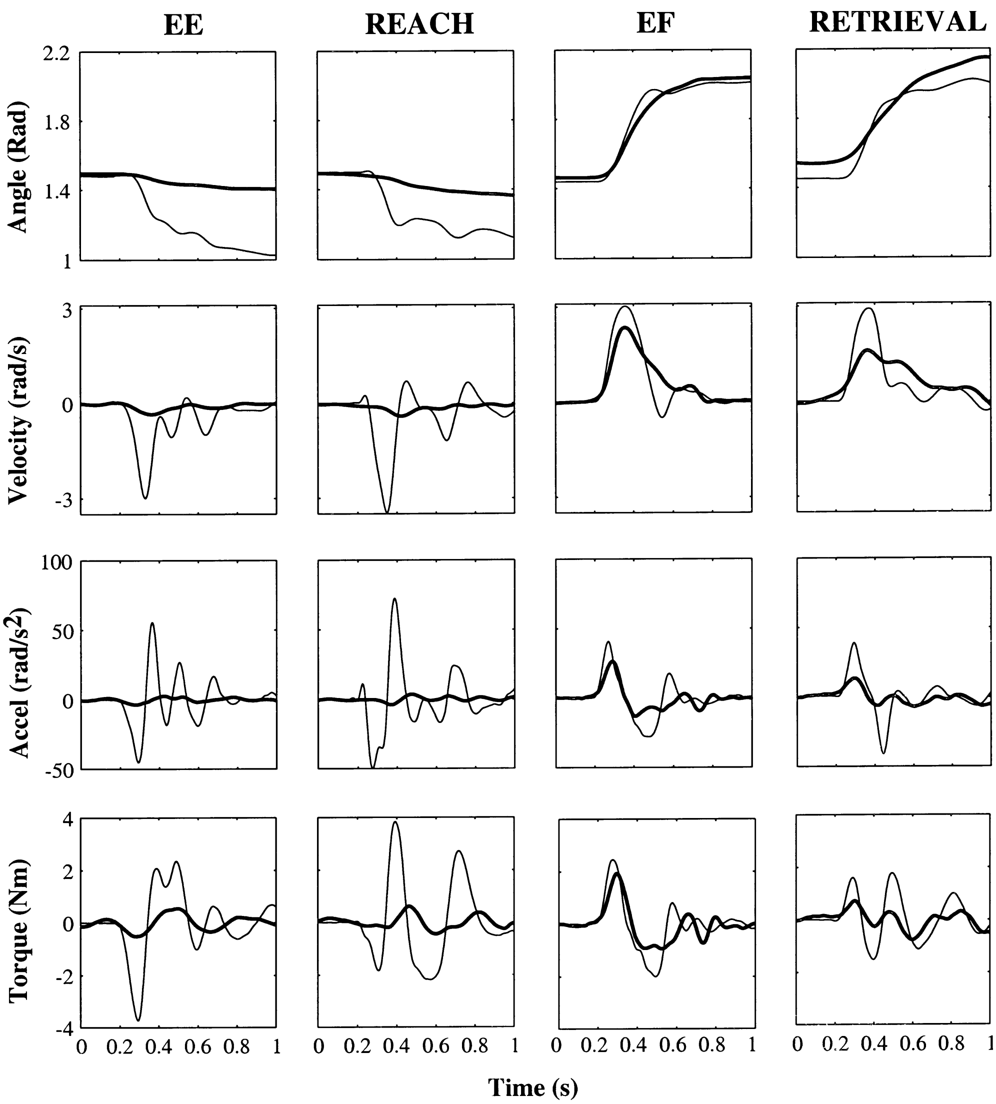

Fig. 3 Comparison of elbow kinematics and kinetics for free (*thick lines*) and constrained (*thin lines*) movements of the paretic limb for the four targets requiring a 30° elbow excursion. Mean joint angle (*first row*), angular velocity (*second row*), angular acceleration (*third row*), and joint torque (*fourth row*) profiles are shown. Trials were aligned at movement onset (at 0.2 s in each panel) for averaging. Positive ordinates in *second to fourth rows* correspond to flexion. Data are for same hemiparetic subject shown in Fig. 2

broadly invariant with support condition (Fig. 2). Limb movements were characterized by gently curved paths and smooth bell-shaped velocity profiles consistent with the findings of previous studies of rapid point-to-point hand movements performed by normal subjects (Accornero et al. 1984; Morasso 1981; Uno et al. 1989; Wadman et al. 1980). Although minor differences in the initial direction of movement were sometimes evident between constrained and free movements (for example, Fig. 2 *left panel*, SF and RET targets), no systematic directional differences were evident on a group basis, and in many cases, the hand paths were virtually identical for the two support conditions. Similarly, as illustrated by Fig. 2, support condition had no systematic effect on the peak tangential velocity of the hand.

In contrast to the aforementioned findings, endpoint kinematics for the paretic limb exhibited a marked dependence on support condition (Fig. 2). In the constrained condition, each target was acquired by the majority of subjects (albeit with subject-specific abnormalities in hand path) and all subjects were able to initiate movements in the general direction of each target. The terminal phase of movement was often characterized by a veering off of the hand away from the target (Fig. 2) that was associated with stoppage of the elbow movement while motion at the shoulder continued. The premature stoppage of elbow rotation suggests the excessive activation of antagonist muscles due perhaps to stretch reflex hyperexcitability or abnormalities in the descending command governing movement deceleration. Examination of hand tangential velocity profiles revealed preservation of a smooth, bell-shaped velocity profile over a substantial fraction of the trajectory, with evidence of a disturbance and/or corrective action later in the movement (Fig. 2).

Active support of the paretic limb resulted in a target-dependent degradation in movement kinematics, relative to the constrained condition (see Fig. 2). While acquisition of proximal targets was generally preserved across support conditions, six of the eight subjects were no longer able to acquire one or more of the distal targets (EE, Reach) while actively supporting the limb. Furthermore, for these targets, mean (across trials) peak tangential hand velocity was reduced for all subjects. Less severe reductions in

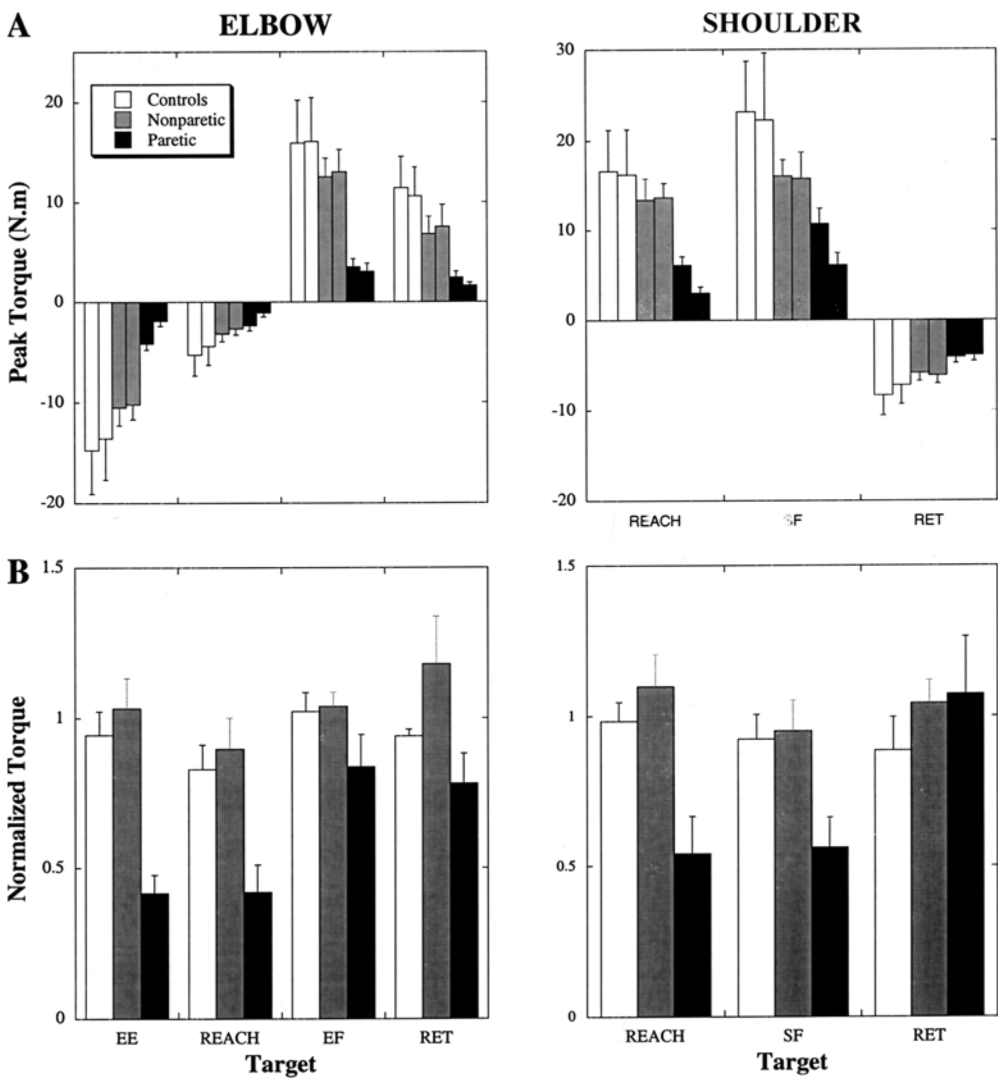

Fig. 4 A Modulation of mean (with SEM) peak joint torques with task and support condition for the control (*n*=5) and hemiparetic (*n*=8) groups. Adjacent bars of the same color represent the constrained (*left bar*) and free (*right bar*) support conditions. To highlight the impact of support condition on movement kinetics, the ratio of peak torques in the free and constrained conditions is shown in **B**. For the control group, pooled data for the dominant and nondominant limbs are shown

peak velocity were also evident for the proximal targets in the majority of subjects.

Quantitative analysis of joint kinematics and kinetics

To provide more insight into support-dependent changes in the hand's work area and trajectory we focused on quantitative analysis of the kinematics and kinetics of the underlying elbow and shoulder flexion/extension motions. Representative elbow kinematics and kinetics for the paretic limb are shown in Fig. 3 for the four targets requiring a 30° elbow excursion.

Our statistical analysis of group trends focused on the effects of support condition on three dependent variables for the shoulder and elbow: peak joint torque, peak angular acceleration, and angular excursion. Group results for these variables are summarized in Figs. 4, 5, and 6. Statistical (three-factor ANOVA) results for each dependent variable are summarized in Table 2 and discussed in more detail below.

Peak joint torque and angular/acceleration

Peak torques and angular accelerations (flexion positive) for the elbow and shoulder are summarized in Figs. 4 and 5, respectively. Despite the complex relationship between joint accelerations and torques for multijoint movements (see Eqs. 1, 2), similar trends were apparent in the group results for each variable (see Table 2; Figs. 4, 5). Accordingly, we will focus our presentation on peak joint torques, which reflect the net output of the neuromusculoskeletal system. As suggested by the error bars in Fig. 4A, large between-subject and/or between-limb differences were apparent in torque magnitudes. For statistical analysis we used a logarithmic transformation of the torque magnitude to enhance the sphericity of the data. Accordingly, our analysis was sensitive to the relative, rather than absolute, changes in joint torques associated with the independent variables. To highlight the effects of support condition, Fig. 4B summarizes the ratio of torques measured in the free and constrained movement conditions, such that an ordinate of 1 represents identical performance in the two conditions.

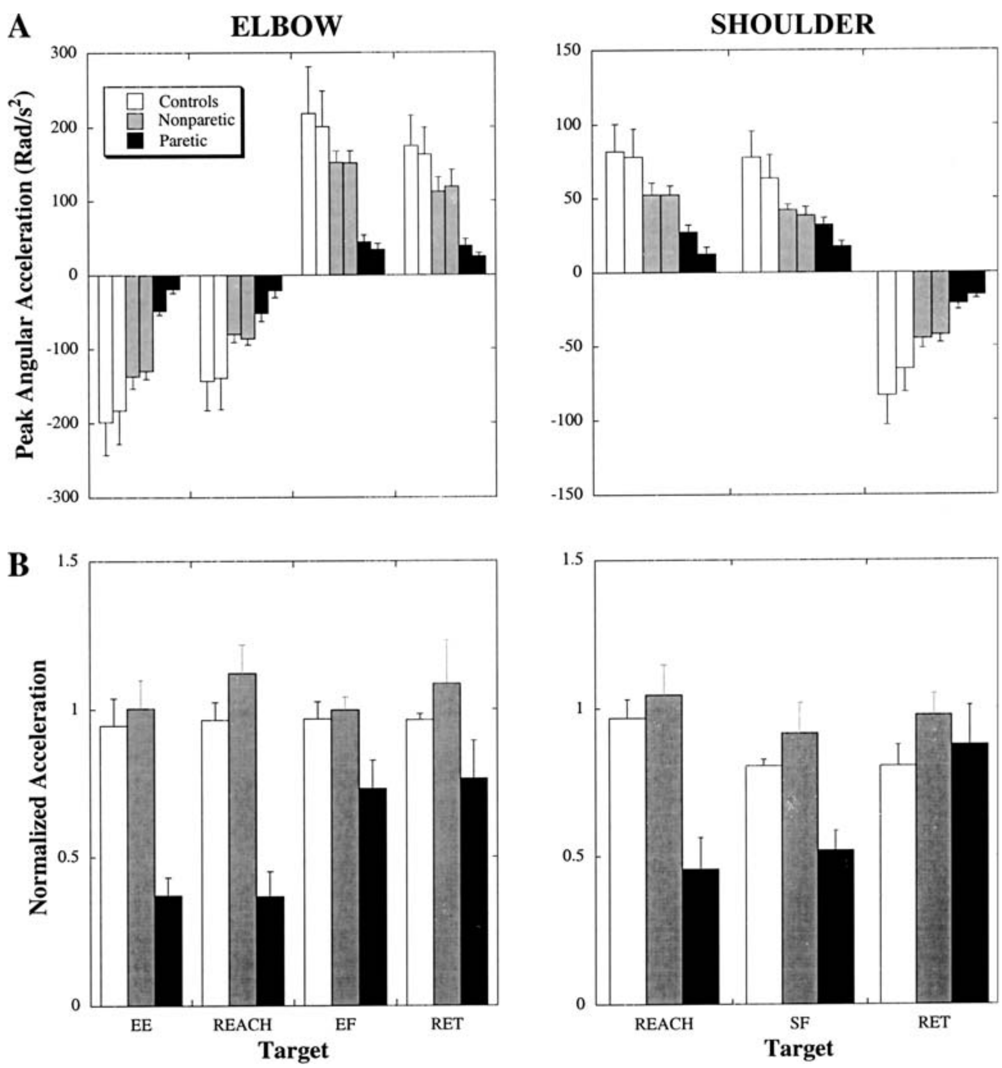

Fig. 5 A Mean (with SEM) peak angular accelerations for the control and hemiparetic groups. Adjacent bars of the same color represent the constrained (*left bar*) and free (*right bar*) support conditions. The ratio of peak angular accelerations in the free and constrained conditions is shown in **B**. Pooled data for the dominant and nondominant limbs are shown for the control group

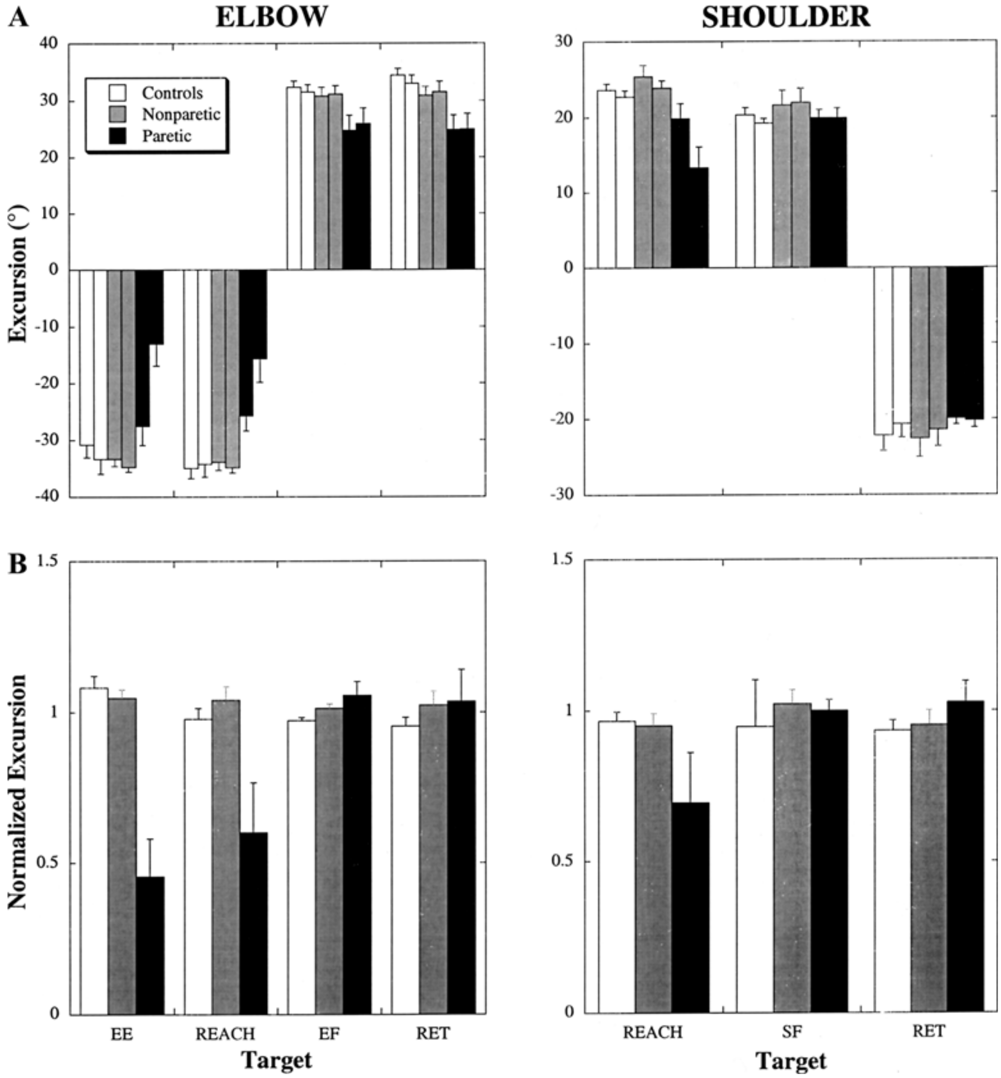

Fig. 6 A Variation of group mean (with SEM) joint excursions with task and support condition. Adjacent bars of the same color represent the constrained (*left bar*) and free (*right bar*) support conditions. The ratio of joint excursions in the free and constrained conditions is shown in **B**. Pooled data for the dominant and nondominant arms are shown for the control group

Table 2 Summary of ANOVA results

	Limb	Support	Target	Limb × Support	Limb × Target	Support × Target	Limb × Support × Target
Control group, elbow							
Peak torque	*	*	****	–	–	–	–
Peak acceleration	–	–	**	–	–	–	–
Excursion	±	–	–	–	–	**	–
Control group, shoulder							
Peak torque	–	–	**	–	–	–	–
Peak acceleration	–	–	–	–	–	–	–
Excursion	–	–	–	–	–	–	–
Patient group, elbow							
Peak torque	****	***	****	***	±	**	*
Peak acceleration	****	***	*	***	–	**	**
Excursion	**	±	–	**	*	*	*
Patient group, shoulder							
Peak torque	**	**	****	*	*	–	–
Peak acceleration	**	**	–	*	*	–	–
Excursion	*	–	–	–	–	*	–

– Not significant
± $P \leq 0.1$; * $P \leq 0.05$; ** $P \leq 0.01$; *** $P \leq 0.001$; **** $P \leq 0.0001$

For the control group, no limb-dependent differences were apparent in the effect of support condition on peak joint torques at the shoulder or elbow (see Table 2). Accordingly, to simplify the presentation, pooled results for the dominant and nondominant limbs are shown in Figs. 4 and 5. Relative to the constrained condition, free limb movements were characterized by a relatively minor but significant reduction (mean=12%) in peak elbow torque (Support, $F_{(1,4)}$=8.00, P=0.05) but no significant changes in peak torques at the shoulder. It should be noted that peak elbow torques for the nondominant limb were, on average, 27% greater than for the dominant limb (Limb, $F_{(1,4)}$=10.51, P=0.03). Although the Limb × Target interaction did not reach significance, the largest increase (mean=45%) was associated with the reaching task, and is consistent with previous reports of interlimb differences in the control of movement dynamics in normal subjects (Beer et al. 2000; Sainburg 2002; Sainburg and Kalakanis 2000).

Analysis of data for the hemiparetic group indicated that the effects of support condition on peak torques at the elbow and shoulder were limb dependent (see interaction terms, Table 2). Accordingly, two-factor (Support, Target) ANOVAs were performed to determine the effect of support condition on torques (and joint accelerations) for each limb.

For the nonparetic limb, no significant differences were found between peak joint torques for actively and passively supported movements. With reference to Fig. 4, grand means for the two support conditions differed by less than 5% at both joints.

In marked contrast to the behavior exhibited by the control group and the nonparetic limb, active support of the paretic limb resulted in substantial reductions in peak torques at the elbow and shoulder, relative to the constrained condition. At the elbow these reductions were strongly task-dependent (Elbow: Support × Target interaction, $F_{(3,21)}$=52.98, P=0.0002). On a group basis, significant and substantial (>50%) reductions were evident in the extension torques associated with the EE and Reach tasks (LSD test, P<0.0001 for both tasks), while the smaller reductions in group mean elbow flexion torques did not achieve significance (see Fig. 4B). On an individual basis, these reductions ranged from 32% to 85% for the EE task and from 21% to 88% for the Reach task. Reductions exceeding 20% were also evident for three (of eight) subjects for the EF task and in four subjects for the retrieval movement.

Statistical analysis of shoulder torques for the paretic limb also indicated a significant main effect of support condition ($F_{(1,7)}$=18.80, P=0.003) and a marginally significant ($F_{(2,14)}$=3.29, P=0.07) interaction of Support and Target. These results reflected reductions in shoulder flexion group mean torques in excess of 50% for both the Reach and SF tasks, while the group mean shoulder extension torque required for the Retrieval movement was little affected by support condition (Fig. 4B). On an individual basis, active limb support was associated with reductions in mean shoulder flexion torque in seven of eight subjects for the Reach task (range 12–82%), and for all subjects for the SF task (range 1–74%). However, for the Retrieval task, five of eight subjects exhibited *increased* shoulder extension torque with active support of the limb.

In summary, our results indicate a minor effect of limb support condition on peak torques at the elbow and shoulder for control subjects and the nonparetic limb of hemiparetic subjects, irrespective of task. In contrast, for the paretic limb the effect of support condition on joint torques was substantial and task-dependent. Specifically, relative to the constrained condition, free movements of the paretic limb were characterized by marked reductions in shoulder flexion and elbow extension torques, while shoulder extension and elbow flexion torques were relatively unaffected.

Joint excursions

Joint excursions for the elbow and shoulder are summarized in Fig. 6A. Figure 6B summarizes the ratio of joint excursions measured in the free and constrained movement conditions. Again, results for the dominant and nondominant limbs of control subjects have been pooled since interlimb differences were minor and did not reach significance (see Table 2). For control subjects and the nonparetic limb of hemiparetic subjects, the joint excursion magnitudes were typically near the target values of 30° and 20° for the elbow and shoulder, respectively. The smaller joint excursions for the paretic limb reflect the inability of one or more subjects to acquire certain targets.

Joint excursions for the control group were not substantially different in the free and constrained conditions. Statistical analysis (see Table 2) indicated a marginally significant main effect of limb ($F_{(1,4)}$=5.87, P=0.07) on elbow excursion as well as a significant Support × Target interaction ($F_{(3,12)}$=8.70, P=0.002), however the magnitudes of these effects were less than 3°.

For the hemiparetic group, statistical analysis of the elbow excursion data revealed a significant three-way interaction between Limb, Support Condition, and Target ($F_{(1.5,10)}$=6.95, P=0.02). A two-factor (Support, Target) ANOVA for the nonparetic limb indicated that there were no significant differences between elbow excursions in the free and constrained conditions. However, a similar analysis for the paretic limb indicated a target-dependent effect of support condition on elbow excursion (Support × Target interaction, $F_{(3,21)}$=7.44, P=0.001). Relative to the constrained condition, elbow extension excursions were significantly reduced in the actively supported condition (LSD test, EE:14.5° reduction, P<0.0001; Reach: 10.1° reduction, P=0.002) while elbow flexion excursions were not. On an individual basis, average elbow excursions for free movements toward the distal targets were 5° or less for three of the more impaired subjects (5, 7, and 8, see Table 1), while in the constrained condition these subjects were able to produce elbow excursions of 14–33°.

At the shoulder, statistical analysis indicated that joint excursions were significantly reduced in the paretic limb relative to the nonparetic limb. The effect of support condition was target but not limb dependent (see Table 2). However, with reference to Fig. 6, these results largely reflect the reduced shoulder flexion excursions for the paretic limb for the free reaching task. As indicated in Fig. 6B, for the SF and Retrieval tasks, group mean excursions for the paretic shoulder were virtually identical across support conditions. This raises the possibility that shoulder flexion was limited during the free reaching task because in the absence of adequate elbow extension, it only served to move the hand farther from the target.

Discussion

The primary finding of this study was that active support of the paretic arm against gravity loading resulted in a target-dependent degradation in movement kinematics and kinetics, relative to performance in the constrained condition. Specifically, active support of the paretic limb resulted in significant reductions in peak elbow extension and shoulder flexion torques, while peak elbow flexion and shoulder extension torques were relatively unaffected.

Of perhaps more functional importance, active limb support was found to result in a directionally dependent restriction in the planar work area that reflected a reduced range of active elbow extension but not flexion, relative to the constrained condition. With respect to the restriction of elbow extension in the free movement condition, similar impairment was observed for the single-joint elbow extension and multijoint reaching tasks. This result is consistent with Kamper et al. (2002) who examined free reaching to an extensive array of targets and found only a modest dependence of active range of motion on target location. However, in contrast to Reinkensmeyer et al. (1999a), who concluded that workspace reductions in subjects with chronic hemiparesis were primarily due to increased passive tissue restraint at the shoulder and elbow, our results suggest the involvement of an active mechanism.

Potential mechanisms

The impaired voluntary movement of the paretic arm following stroke has been attributed to a variety of mechanisms including agonist muscle paresis (El-Abd et al. 1993; Fellows et al. 1994; Gowland et al. 1992), reflex hyperactivity (Mizrahi and Angel 1979), changes in passive tissue properties (Dietz et al. 1991; Reinkensmeyer et al. 1999b), and disturbances of central planning (Beer et al. 2000; Kusoffsky et al. 2001; Levin 1996; McLellan et al. 1985; Trombly 1992). While the aforementioned mechanisms may have contributed to movement abnormalities in our hemiparetic subjects, we suggest that the target-dependent impact of support condition on voluntary movements of the paretic arm is likely to be a manifestation of abnormal synergies involving shoulder and elbow muscles.

Our earlier studies of isometric force generation in subjects with chronic hemiparesis (Dewald and Beer 2001; Dewald et al. 1995) and clinical descriptions of the flexor limb synergy in acute patients (Brunnstrom 1970; Twitchell 1951) provide evidence for an abnormal coactivation of elbow flexors with shoulder abductors, extensors, external rotators, elevators, and retractors in the paretic limb. Consistent with such a linkage, under isometric conditions the apparent weakness of the paretic elbow flexors and extensors is strongly dependent on the magnitude and direction of torques generated concurrently at the shoulder (Beer et al. 1999). Specifically, as the level of abduction torque generated by the subject is increased, the capacity to generate elbow flexion torque with the paretic limb is enhanced, while maximum elbow extension torques decrease substantially. A similar task-dependent weakness under dynamic conditions would explain the impaired ability to generate elbow extension torque (and motion) when actively supporting the paretic limb against gravity loading, but relatively preserved ability to perform actively supported movements requiring elbow flexion torque. Furthermore, in the constrained condition, subjects were potentially able to generate shoulder adduction and internal rotation torques, which may have enhanced elbow extension in the paretic limb (in conjunction with the extensor limb synergy). Finally, similar to our findings, a greater impact of active support on shoulder flexion torque, as compared to shoulder extension torque, would be expected based on clinical descriptions of the flexor synergy.

Previous studies of reaching performance in chronic stroke subjects have generally concluded that the observed kinematic disturbances were not related to the limb synergies (Beer et al. 2000; Levin 1996; Reinkensmeyer et al. 2002; Trombly 1992; Wing et al. 1990). However, these studies have examined movements under either free or constrained conditions but not both, so the impact of the synergies on movement performance may not have been apparent. Passive support of the arm was provided in Wing et al. (1990) and subjects in the Levin study were allowed to slide the paretic arm over the surface of a table. Thus, although both of these studies examined movements performed within and outside of synergy with respect to the shoulder and elbow flexion/extension motions, it was not necessary for subjects to concurrently generate shoulder abduction and external rotation torques. In a previous study of passively supported movements performed in the horizontal plane (Beer et al. 2000), we also found that directional disturbances in moderately and mildly impaired subjects were not consistent with a mechanism related to the limb synergies. Reinkensmeyer et al. (2002) reported that abnormal synergies appeared to impact free reaching performance only in the most clinically impaired subjects. However, free movements in their study were self-paced and the data analysis was limited to the initial direction of movement. Thus, subjects were not required to maximally drive muscle activation and any impact of the flexor synergy on force-related measures such as joint acceleration and torques were not evaluated.

Support-dependent changes in muscle stretch reflex thresholds may also have contributed to our findings for the paretic limb. The contribution of stretch reflex dysfunction to disturbances of voluntary arm movements in subjects with hemiparesis remains controversial (cf. Fellows et al. 1994; Levin et al. 2000; McLellan et al. 1985; Mizrahi and Angel 1979; Sahrmann and Norton 1977) and quantitative studies have generally been limited to passively supported (constrained) single-joint movements. Although the primary stimuli for stretch reflex activation—stretch amplitude and velocity—were clearly reduced in the free movement condition, active support of the paretic arm would be expected to result in an increased tonic activation of the elbow musculature in association with the abnormal flexion synergy discussed above. Given the direct relationship between stretch reflex mediated muscle activation and the tonic level of voluntary activity in normal subjects (Matthews 1986; Smeets and Erkelens 1991; Stein et al 1995), abnormal restraint of movement by antagonist muscles may have increased during active support. Finally, within the context of this argument, the target-dependence of our findings for the paretic elbow could be explained by the generally more severe reflex dysfunction exhibited by physiological flexor muscles (see Table 1).

Potential neurophysiological substrates for abnormal synergies

The neurophysiological substrates underlying the development of abnormal movement synergies (Brunnstrom 1970; Twitchell 1951) during the acute phase of stroke remain unclear. Similar manifestations of these synergies are evident in subjects with cortical or subcortical (capsular) white matter lesions. A common denominator among these subjects is the likely destruction of corticospinal fibers (Shelton and Reding 2001).

Our results, and those of our earlier isometric studies (Beer et al. 1999; Dewald and Beer 2001; Dewald et al. 1995) indicate the residual presence of abnormal muscle synergies in subjects with chronic hemiparesis. This suggests that selective activation of human shoulder and elbow muscles may be critically dependent on the lateral corticospinal tract. Consistent with this interpretation, recent electrophysiological evidence indicates that the human biceps brachii (Petersen et al. 2002) and deltoid (Colebatch et al. 1990) muscles receive strong and direct excitation from corticospinal fibers, the excitation of the latter muscle being comparable to that of an intrinsic muscle of the hand.

The reduction of lateral corticospinal input to proximal arm muscles following hemiparetic stroke potentially results in an increased dependence on descending pathways originating in the brainstem (for example, vestibulo- and reticulospinal pathways) and on uncrossed ventral corticospinal projections. In contrast to the relatively focused projections of the lateral corticospinal pathway, the brainstem and the ventral corticospinal pathways exhibit more extensive branching, innervating neurons over many spinal segments (Kuypers 1981). Hence, the diminished range of muscle synergic relations following stroke may reflect the anatomical constraints inherent in residual descending pathways. A second possibility is that abnormal muscle synergies emerge as an obligatory and adverse consequence of the cortical reorganization that follows stroke. Functional and structural changes in the cerebral cortex during recovery from stroke in humans (Cao et al. 1998; Marshall et al. 2000; Weiller et al. 1993), or following an induced motor cortical lesion in the monkey (Frost et al. 2003; Nudo and Milliken 1996), have been shown to result in enlarged areas of contralateral and ipsilateral sensorimotor cortical activity during volitional hand movements. Thus an obligatory coactivation of muscles may develop as intact cortical regions assume control of muscles whose innervation has been damaged. Finally, the emergence of increased segmental control over the limb following stroke, as evidenced by the presence of normally latent reflexes such as the tonic neck reflexes, may limit the ability to selectively activate muscles voluntarily.

Clinical implications

Conceptually, the central programming of voluntary arm movement can be considered to consist of two phases, a planning phase which specifies the spatial characteristics of movement based on sensory information concerning target location and limb configuration, and an execution phase which establishes the spatiotemporal patterns of muscle activation in order to realize the motor plan. Within this framework, we would attribute the deterioration of free limb movements relative to the constrained condition to mechanisms related to movement execution, rather than planning.

Given the relatively preserved performance of the paretic limb in the constrained condition, amelioration of the mechanism(s) underlying the deterioration of free reaching is likely to result in considerable functional improvement. Our isometric studies indicate that subjects with chronic hemiparesis retain the ability, though limited, to generate torques in combinations “outside” of the abnormal synergy patterns (Beer et al. 1999). An effective therapeutic approach may be the development of paradigms that specifically exploit and enhance this residual capacity (see, for example, Ellis et al. 2002).

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