

Effect of Trunk Restraint on the Recovery of Reaching Movements in Hemiparetic Patients

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Background and Purpose—Reaching movements made with the affected arm in hemiparetic patients are often accompanied by compensatory trunk or shoulder girdle movements, which extend the reach of the arm. We investigated the effects of the suppression of these compensatory movements on reaching ability in hemiparetic individuals.

Methods—Eleven healthy and 11 hemiparetic individuals participated. Three-dimensional kinematic analysis was used to quantify reaches made to a close and a distant target (near the limit of arm's length). Unrestrained reaches were compared with those in which shoulder girdle and trunk movements were restrained by a harness.

Results—During unrestrained reaching, abnormal trunk recruitment and limitations in elbow and shoulder movements were correlated with the degree of clinical stroke severity ($r = -0.91$ to -0.96) in hemiparetic patients. During trunk restraint, ranges of elbow and shoulder joint movement increased in both groups. In addition, elbow and shoulder interjoint coordination improved. This was caused by increases in the range of joint motion as well as by a better dynamic temporal relation between joints.

Conclusions—Trunk restraint allowed patients with hemiparetic stroke to make use of arm joint ranges that are present but not normally recruited during unrestrained arm-reaching tasks. Thus, the underlying "normal" patterns of movement coordination may not be entirely lost after stroke. Appropriate treatments, such as trunk restraint, may be effective in uncovering latent movement patterns to maximize arm recovery in hemiparetic patients. (*Stroke*. 2001;32:1875-1883.)

Key Words: arm ■ hemiplegia ■ motor control ■ recovery ■ therapy

When healthy individuals reach for objects placed within arm-reaching distance, a smooth coordination between elbow and shoulder movements occurs while the trunk is virtually motionless.^{1,2} A necessary requisite for controlled reaching is the coordination of the action of transporting the arm away from the body while activating appropriate muscles to stabilize the trunk and scapula. On the other hand, when reaching to objects placed beyond arm's length, the trunk assumes an active role in arm transport. The recruitment of additional degrees of freedom (*df*) of the shoulder girdle and trunk occurs in a stereotypic way. Use of the trunk becomes part of the general reaching strategy. The trunk is recruited before recruitment of the arm joints such that the trunk begins moving before the beginning of hand movement and can continue moving even after the hand has stopped at the target.³ The limits of reach, describing the boundary between reaches that do or do not involve the trunk, occur for targets placed at distances equivalent to 80% to 90% of arm's length and may be related to comfort during grasping.⁴

Previous studies in hemiparetic patients have described excessive trunk or shoulder girdle movement in pointing²

and in reach-to-grasp movements¹ for targets placed close to the body. Levin and colleagues⁵ have suggested that this increased recruitment is a compensatory mechanism by which the central nervous system may extend the reach of the arm when the control of the active range of arm joints is limited. Other studies have reported that elbow-shoulder interjoint coordination is disrupted in hemiparetic patients.⁶⁻⁸ In contrast to healthy individuals, reaching in hemiparetic patients is characterized by a lack of smoothness, as evidenced by both temporal and spatial segmentation.⁷

Therapists may approach the rehabilitation of reaching in several ways. For example, one assumption underlying traditional reflex-based neurofacilitation approaches is that the acquisition of trunk and shoulder girdle stability must precede the retraining of arm movement.^{9,10} Unwanted movements and spasticity are inhibited and normal patterns are facilitated under the assumption that regaining voluntary control over key movements will transfer to functional improvement. However, empirical evidence for this assumption is lacking. More recently, the rehabilitation of reaching has been based on a task-oriented ap-

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proach in which movement is behaviorally driven and the interaction of the individual with the environment is stressed.^{11,12} This approach may tolerate or even encourage compensatory involvement of other degrees of freedom to move the hand closer to the object.¹³ It has recently been suggested, however, that the presence of excessive trunk movement in hemiparetic individuals while reaching may limit the potential recovery of normal arm movement patterns.^{14,15} Reducing compensatory mechanisms by limiting trunk displacement may encourage the return of movement patterns typically seen in healthy individuals. To date, the effectiveness of this type of "restraint therapy" on arm motor recovery in chronic hemiparetic patients has not been assessed.

As a first step in the process of determining the clinical efficacy of restraint therapy, we evaluated the effects of limiting compensatory trunk movement on the recovery of arm interjoint coordination during reaching to targets placed within arm's reach in hemiparetic patients. A reach-to-grasp instead of a pointing task was used to evaluate the efficacy of the treatment approach for the retraining of a functionally relevant movement. Preliminary data have been presented in abstract form.¹⁶

Subjects and Methods

Eleven hemiparetic (age, 54.8 ± 13.9 years) and 11 healthy individuals (age, 55.0 ± 13.7 years) participated after signing informed consent forms approved by the Ethics Committee of the Rehabilitation Institute of Montreal, conforming to the declaration of Helsinki. Patients had sustained a single unilateral stroke of nontraumatic origin 5 to 69 months previously. Participants had no hemispatial neglect or apraxia and could understand simple instructions. Those with shoulder pain or other neurologic or orthopedic conditions affecting the arm or trunk were excluded. The healthy group consisted of age- and sex-matched individuals without neuromuscular or neurologic problems affecting the arm or trunk.

Clinical Evaluation

Before data collection, all patients underwent a series of clinical tests administered by an experienced physiotherapist that evaluated balance and the status of their affected arm. Upper extremity impairment was evaluated with the arm section of the Fugl-Meyer Scale¹⁷ for voluntary movements made into and out of abnormal movement synergies as well as pain and sensation of the arm. The scale ranges from 0 to 66, with scores >65 reflecting normal movement. In our patients, Fugl-Meyer scores ranged from 19, indicating severe motor impairment, to 65, reflecting almost no impairment. Spasticity of elbow flexors was determined by the valid and reliable Composite Spasticity Index.¹⁸⁻²⁰ This index sums measures on 3 scales: (1) biceps brachii tendon jerks evoked with a reflex hammer; (2) resistance to stretch of passive elbow flexors at moderate speed (modified Ashworth Scale²¹); and (3) wrist clonus, for a total possible score of 16. Spasticity in our patients ranged from 2 (mild) to 10 (moderately severe). Finally, sitting and standing balance was measured on the Berg Balance Scale,²² having a total of 56 points in which function is scored as poor (0 to 20) to good (40 to 56). All patients scored higher than 44 (mean 50.8 ± 4.6) on this scale, indicating that they had little problem with balance (Table 1).

Reaching Task

Participants were seated on a chair and reached forward to grasp a cone (7-cm diameter base, 17.5 cm high) placed in the sagittal plane in the trunk midline (Figure 1). Because seat height and extent of thigh and foot support may affect reaching distance,²³ seat height was adjusted to 100% of lower leg length, which was measured from the lateral knee joint line to the floor with the participant standing. In

addition, $\approx 75\%$ of the thigh was supported on the chair, and the feet made full floor contact. The cone was placed at midsternal height at 2 different distances (targets) defined in terms of the participant's arm length (T1, one-half arm's length; T2, arm's length). Arm's length was measured from the medial border of the axilla to the distal wrist crease. The targets were placed so that biomechanically, only arm movement was required to grasp and retrieve the cone. Initial hand position was directly in front of the lower third of the sternum, the thumb 5 cm in front of the sternum, and the elbow close to the side of the body. With full vision, participants reached toward, grasped, and returned the cone to the midchest region at a comfortable self-paced speed (trunk-free condition). Reaches to T1 and T2 were then repeated with the trunk secured to the chair back with a harness minimizing shoulder girdle movement and preventing trunk flexion and rotation (trunk-fixed condition). Twenty trials were recorded for each target distance and condition, and testing order of the 4 blocks was randomized.

Movement kinematics (sampling frequency, 100 Hz) were recorded with 10 infrared light-emitting diodes placed on the tips or interphalangeal joints of the index and thumb, the wrist ulnar styloid process, the lateral humeral epicondyle, bilateral acromion processes, 2 points along the vertical axis of the sternum, the hip (anterior superior iliac spine), and the anterior knee above the patella. Data from sternal, hip, and knee markers were monitored to ensure that participants did not slide forward on the chair to extend their reach during the task. Data were collected for 2 to 6.5 seconds, with the use of an Optotrak Motion Analysis System (Northern Digital, model 3010).

Data Analysis

Data analysis focused on 4 types of movement variables: end point and trunk trajectories, tangential velocities, maximal joint and trunk excursions, and interjoint coordination.

From filtered (low-pass cutoff, 20 Hz) position data, 2- and 3-dimensional trajectories were plotted. Tangential velocity profiles of the end point and trunk were computed from the magnitude of the velocity vector, using time derivatives of x , y , and z positional data for markers placed on the fingertip and sternum, respectively. Although the task involved reaching, grasping, and returning the cone to the body, only the transport component of the hand to the target was analyzed. The requirement to grasp and retrieve the cone was used so that participants would make natural goal-directed movements.^{13,24} Trajectory smoothness was determined by the index of curvature (ratio of actual end point path length to that of a straight line joining initial and final positions). This index has been found to better characterize trajectories than area measurements.²⁵ Thus, a straight line has an index of 1, whereas that of a semicircle has an index of 1.57. To quantify the temporal segmentation of the trajectory, the number of movement units in the tangential velocity was summed for each target and movement condition. A movement unit was defined as a maximum in the tangential velocity trace preceded by increasing values for at least 20 ms and followed by decreasing values for at least 20 ms.²⁶

Movement times and peak velocities were determined from tangential velocity traces. Movement times were defined as differences between movement onsets and offsets, determined for each trial as the times at which the tangential velocity rose above or fell and remained below 10% of the peak tangential velocity of the end point and trunk, respectively.

To determine changes in joint ranges and to analyze spatial and temporal interjoint coordination patterns, vectors joining the appropriate infrared light-emitting diodes were used to compute, using vector algebra, shoulder (2 df =flexion/extension and horizontal abduction/adduction) and elbow (1 df =flexion/extension) angles. In addition, trunk flexion was measured in millimeters from the sagittal displacement of the sternal marker. Sagittal trunk displacement was expressed as a percentage of end point path length to account for arm length differences between participants.

Interojoint coordination patterns between shoulder and elbow movements were determined. First, angle/angle diagrams between shoulder horizontal adduction/abduction and elbow flexion/exten-

TABLE 1. Demographic Data and Results of Clinical Testing for Stroke and Healthy Individuals

S	Sex/Age	Time Since Lesion, m	Fugl-Meyer Score (66)	Spasticity Score (16)	Berg Balance Scale (56)	Peak* Tangential Velocity, mm/s	End Point Trunk* Movement, mm/%†	Type and Location of Lesion
Stroke individuals								
S1	M/54	17	65	2	56	1374.9	17.7/2.9	L temporal, ischemic
S2	M/65	5	61	6	53	1808.7	86.8/16.7	L thalamus, hemorrhagic
S3	M/56	69	64	7	50	1288.1	83.5/12.6	L posterior internal capsule, hemorrhagic
S4	F/22	10	55	7	56	888.5	97.4/19.5	L MCA, ischemic
S5	M/44	21	53	7	56	2075.6	21.2/4.6	L frontoparietal lesion, hemorrhagic
S6	M/58	72	51	10	55	1054.2	70.4/15.0	L MCA, ischemic
S7	F/47	18	49	9	48	611.8	50.4/8.7	L carotid artery, parietal and subcortical lesions, ischemic
S8	F/59	35	40	10	45	666.8	210.4/42.1	R MCA, ischemic
S9	M/72	12	34	9	46	750.1	186.2/42.3	L MCA, ischemic
S10	F/71	13	32	10	50	919.4	270.4/41.6	R MCA, ischemic
S11	M/55	32	19	10	44	649.9	278.2/63.2	R posterior internal capsule, ischemic
x						1098.9	124.8/24.5	
SD						489.4	95.1/19.6	
Healthy individuals								
H1	F/44					1382.0	11.1/1.6	
H2	F/33					1285.9	18.9/4.3	
H3	M/74					1755.2	20.2/3.9	
H4	M/60					1383.5	21.7/4.0	
H5	F/80					1333.8	63.5/14.8	
H6	F/45					1743.6	15.3/3.6	
H7	F/63					1149.4	20.7/4.7	
H8	M/54					982.9	19.2/4.2	
H9	M/52					1389.2	24.6/4.9	
H10	F/50					1116.1	25.5/4.5	
H11	F/52					1981.0	43.1/8.9	
x	55.0					1409.3	25.8/5.5	
SD	13.7					248.7	14.9/3.5	

*Data listed are for Target 2.

†Indicates amount of trunk displacement as a percentage of the distance to the target.

sion as well as between shoulder and elbow flexion/extension were averaged and plotted for each individual in each condition. The relation between angular displacements was determined by linear regression in which the slope and cross-correlation were calculated.

Statistical Analysis

We tested the hypotheses that reducing or arresting compensatory movements would increase the arm joint excursions and improve patterns of interjoint coordination. We compared maximal joint excursions of 3 df for movements made to T1 and T2 with and without trunk restraint with 2-factor (group, condition) ANOVAs and appropriate post hoc tests (Tukey honestly significant difference tests). If trunk restraint leads to changes in joint excursions, improvements would be identified when range of motion values approach mean values recorded in healthy individuals performing the same task. Within-group comparisons were made with paired Student’s *t* tests. Consistency of specific variables was estimated with the coefficient of variability, defined as the ratio between the standard deviation and the mean times 100. Parametric statistics were used for comparisons between groups when requirements for homogeneity of variance were met. A significance level of *P*<0.05 was used for all tests.

Results

Kinematics of Unconstrained Reaching in Healthy Individuals

End point trajectories were smooth and hook-shaped. The hook-shaped trajectory was consistent with orienting the forearm and hand for grasping during the approach phase (Figure 2; top left). End point tangential velocity profiles had one predominant peak. In most individuals, the deceleration phase was interrupted by a second small peak, and in all healthy individuals, there was a small peak corresponding to a terminal adjustment just before grasping. The mean number of peaks for T1 was 2.9±0.6 and for T2 was 2.3±0.5.

The mean arm curvature was significantly higher for T1 (1.54±0.13) than for T2 (1.20±0.12; Student’s *t* test, *P*<0.001; Figure 3), suggesting that healthy individuals used a more curved trajectory to grasp the target closer to the body.

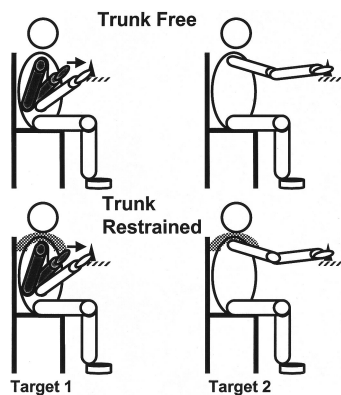


Figure 1. Experimental setup. Seated individuals reached toward target placed at one-half or full arm's length with either the trunk free to move (top) or fixed to chair back by a harness (bottom).

The group coefficient of variability was <10% for both T1 (8.4%) and T2 (9.7%).

Healthy individuals used minimal trunk displacement to reach either target, which was not surprising because both were placed within arm's reach. For the group, mean trunk displacement was negligible for T1 and $5.5 \pm 3.5\%$ of target distance for T2. The high variability for T2 was a result of the data of the oldest individual (80 years of age), whose trunk movement contributed 14.8% of target distance. For the other 10 participants, excluding this individual, the variability was much smaller ($\pm 1.7\%$).

Since T2 was placed in line with T1, individuals used virtually the same interjoint coordination pattern for reaches to both targets except that the total angular displacements were greater for T2. This was reflected in a near superposition of patterns in most individuals. A typical example of the

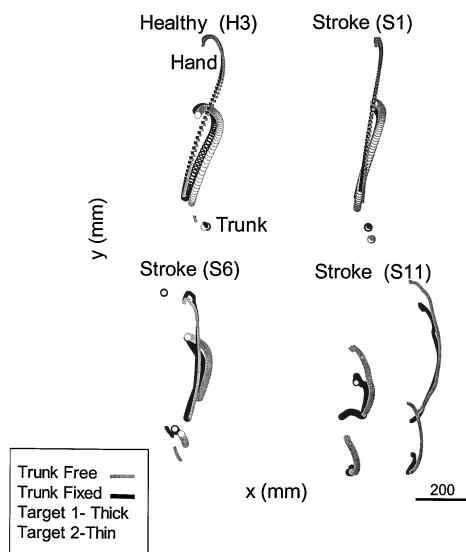


Figure 2. End point (hand) and trunk trajectories viewed from above (x-y plane) for healthy individual (H3) and hemiparetic patients with mild (S1), moderate (S6), and severe (S11) clinical symptoms. Movement trajectories made with trunk unrestrained (gray lines) or restrained (black lines) to close (thick) and far (thin) targets are superimposed. Traces for T1 (target 1) and T2 (target 2) are separated for individual S11 for clarity.

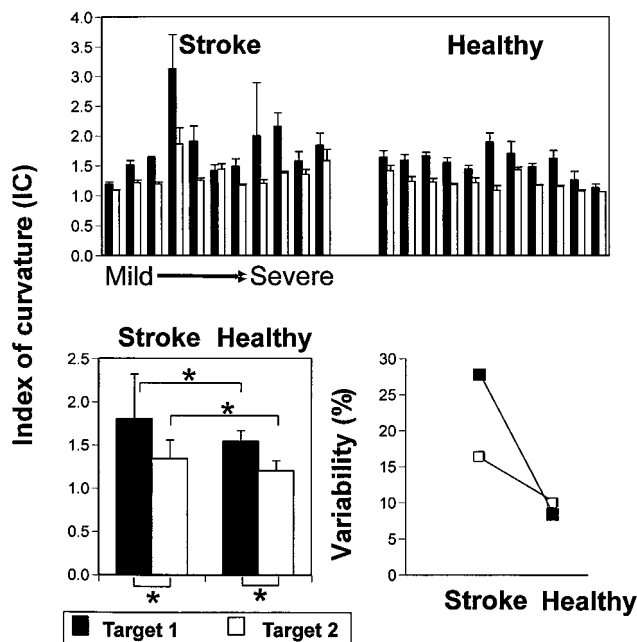


Figure 3. Mean (\pm SD) values of index of curvature for end point trajectories made to target 1 (black bars) and target 2 (open bars) in stroke and healthy individuals in trunk free condition. Order of presentation of individuals in each group is same as Table 1. Top, Mean values by individual. Bottom left, Group means. Bottom right, Differences in coefficients of variability ($SD/mean \times 100$) by target and group. *Significance at $P < 0.05$ level.

elbow-shoulder interjoint coordination pattern for one healthy individual reaching to T2 is shown in Figure 4 (top left).

Effects of Trunk Restraint in Healthy Individuals

Trunk restraint had little effect on tangential velocity, end point trajectories, and interjoint coordination patterns (Figure 5) in healthy individuals. For example, the peak tangential velocity for T2 decreased from 1409.3 mm/s to 1351.5 mm/s when the trunk was restrained (Table 2). Trajectory profiles and patterns from trials in which trunk movement was blocked were virtually indistinguishable from those in which the trunk was free (Figure 2, top left). The number of peaks in the tangential velocity profiles was not affected by trunk restraint. For example, for T2, this number decreased from $2.3 (\pm 0.5)$ to $2.1 (\pm 0.4)$ peaks (Table 2). Nevertheless, restriction of the trunk movement was associated with a significant increase in elbow extension in 6 of 11 and 9 of 11 healthy individuals for T1 and T2, respectively (Figure 6). For T2, the mean elbow extension significantly increased $\approx 8^\circ$ (paired t test, $P < 0.05$) and mean shoulder horizontal adduction increased $\approx 5^\circ$ (paired t test $P < 0.001$), whereas there was no change in shoulder flexion with trunk restraint (Table 2).

Analysis of the slopes of the shoulder/elbow angle/angle diagrams was made for restrained and unrestrained reaches to T2 only. Higher slopes indicate relatively more shoulder horizontal adduction compared with elbow extension, whereas lower slopes indicate the inverse. Slopes were highly variable in healthy individuals, ranging from 0.372 to 2.068 (0.903 ± 0.452) when trunk motion was unrestrained and from

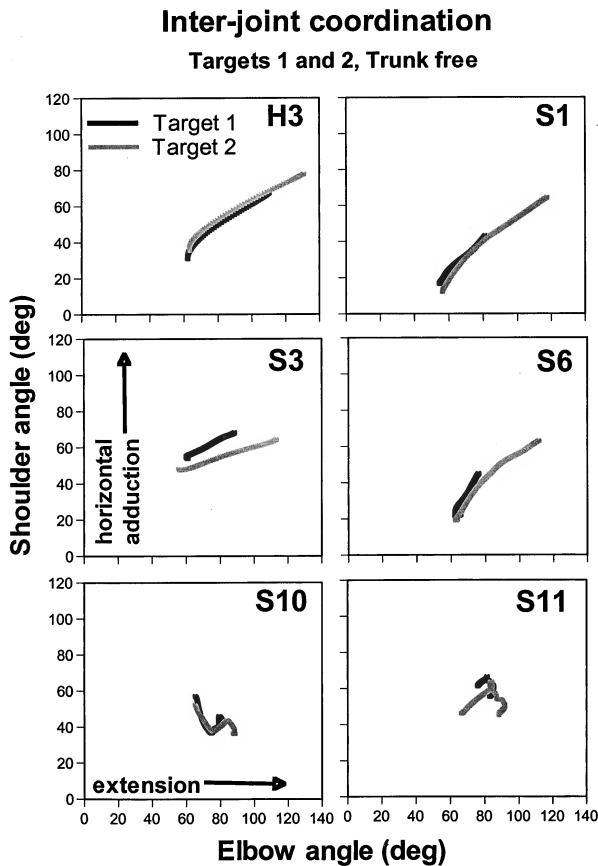


Figure 4. Shoulder-elbow interjoint coordination patterns for unrestrained movements made in 1 healthy individual (top left, H3) and 5 individuals with stroke with mild (S1), moderate (S3, S6), and severe (S10, S11) clinical symptoms. Movements to target 1 (black) and target 2 (gray) are superimposed.

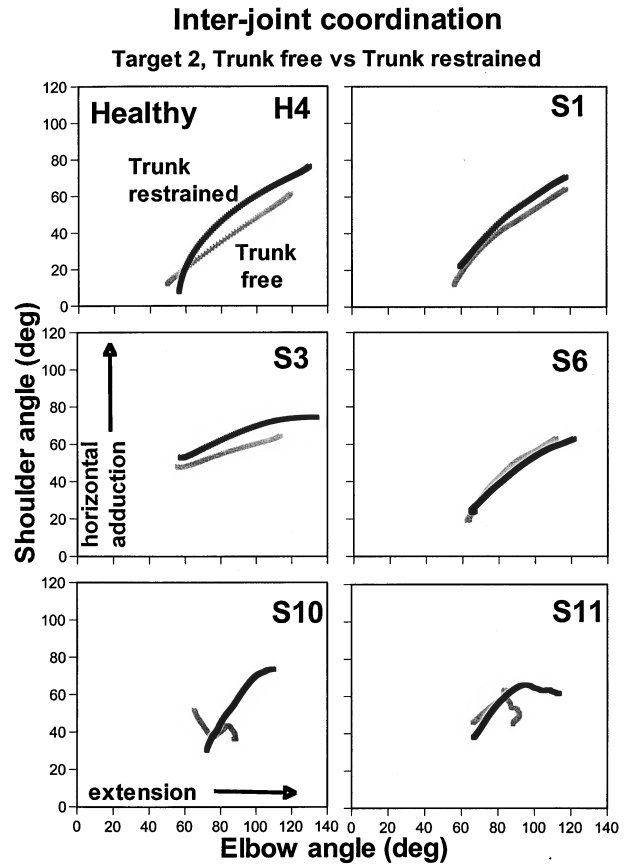


Figure 5. Shoulder-elbow interjoint coordination patterns for 1 healthy individual (top left, H4) and 5 hemiparetic individuals (see Figure 4) with mild to severe stroke symptoms for unrestrained (trunk free, gray) and restrained movements (trunk restrained, black).

0.456 to 1.065 (0.769 ± 0.223) when the trunk was restrained. This difference was nonsignificant. Despite the large range in slopes, the correlations between shoulder and elbow movements for both conditions were >0.94 ($P < 0.0001$; Table 2).

Kinematics of Unrestrained Reaching in Stroke Patients

Hemiparetic patients made slower arm movements than did healthy individuals. Mean peak tangential velocities (Table 2) for free movements to T1 and T2 corresponded to 75% and 78%, respectively, of those in healthy individuals.

Arm and trunk trajectories were less smooth in hemiparetic compared with healthy individuals (Figure 2). All patients were able to reach toward and grasp the cone. However, end point trajectories tended to be more hook-shaped, as shown for S6 and S11 in Figure 2. One exception was S1, who used more wrist extension for grasping, and, consequently, his hand paths were straighter. As in healthy individuals, the mean arm curvature was significantly higher ($P < 0.05$) for T1 (1.80 ± 0.52 , coefficient of variability=27.8%) than T2 (1.34 ± 0.22 , coefficient of variability=16.4%, Figure 3). In addition, when compared with healthy individuals, both indexes of curvature were also significantly higher and more variable. Finally, there were a significantly larger number of

peaks in the tangential velocity profiles for movements to both targets (4.2 ± 2.0 for T1 and 4.3 ± 2.3 for T2).

Hemiparetic patients used considerably more trunk recruitment to move the hand to the target than did healthy individuals. Compared with negligible trunk recruitment in healthy individuals reaching to T1, hemiparetic patients used between 3.0 and 179.6 mm of trunk movement (mean, 51.2 ± 56.7 mm). For T2, the mean trunk displacement for hemiparetic patients was 124.8 ± 95.1 mm compared with 25.8 ± 14.9 mm for healthy individuals ($P < 0.001$), representing a mean of 24.5% of the target distance (Table 1 and Figure 2, bottom right). The amount of trunk displacement used for reaching was significantly correlated with clinical stroke severity ($r = -0.91$), so that the more severe the clinical syndrome (lower Fugl-Meyer score), the greater the trunk displacement. Interestingly, there was also a significant negative correlation between the amount of trunk displacement and the coefficient of correlation between elbow and shoulder movement ($r = -0.96$). This indicated that those individuals who used the most trunk displacement had the most disrupted coupling (dyscoordination) between arm joint movements.

The degree of clinical stroke severity was also related to angular displacement. Individuals with the mildest symptoms used the most elbow and shoulder movement for reaching

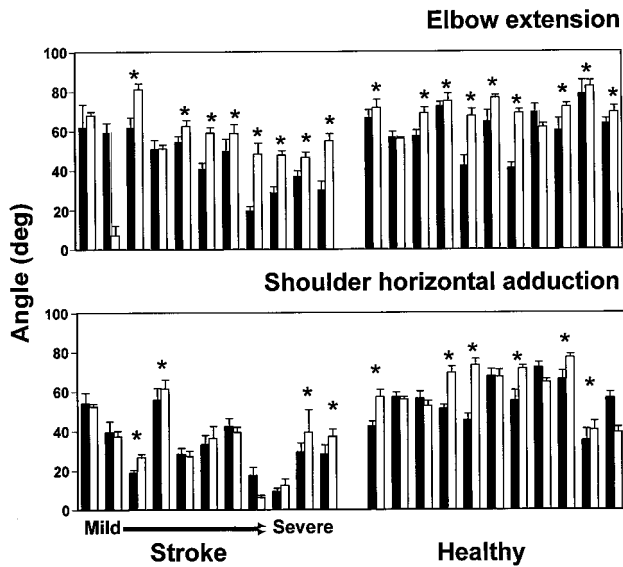


Figure 6. Individual mean (\pm SD) values for total elbow extension (top) and shoulder horizontal adduction (bottom) for stroke and healthy individuals reaching to target 2 when the trunk was free (black bars) and restrained (open bars). Data for individual stroke patients are listed in same order as in Table 1. Asterisks above pairs of bars indicate significant increases in joint ranges.

(Figure 6). However, for T2, the overall amount of elbow extension was $\approx 16^\circ$ less in hemiparetic compared with healthy individuals ($P < 0.05$, Table 2). Similarly, the mean amounts of shoulder flexion and horizontal adduction were significantly less in hemiparetic patients for movements to

both targets ($\approx 7^\circ$ to 8° and 22° to 23° less for T1 and T2, respectively, $P < 0.001$, Table 2).

Effects of Trunk Restraint in Hemiparetic Patients

In contrast to healthy individuals, trunk restraint resulted in a decrease in movement speed to both targets in hemiparetic patients. This was significant for T2, for which peak tangential velocity decreased to 831.2 ± 494.8 mm/s ($P < 0.05$). For patients with mild to moderate stroke, restraining the trunk had no significant effect on curvature or arm trajectory variability for either target (Figure 2) or on the number of peaks (Table 2). However, in more severely affected individuals (S9 to S12), trunk restraint led to a decrease in the total end point displacement. In other words, for these individuals, limiting trunk movement made it more difficult for the hand to reach the target. At the same time, the most striking effect of trunk restraint was the increase in elbow and shoulder joint ranges for all individuals. Elbow extension increased on average 4° (paired t test, $P < 0.001$) for T1 and 14° (paired t test, $P < 0.001$) for T2 (Table 2 and Figure 6). Shoulder flexion increased 14° for T1 and 11° for T2 ($P < 0.001$). For shoulder horizontal adduction, although group effects were not significant, trunk fixation resulted in increases of $> 5^\circ$ in 6 of 11 individuals for T1 and in 4 of 11 individuals for T2 (Figure 6).

In contrast to healthy individuals, trunk restraint significantly altered the pattern of interjoint coordination, an effect that was most evident in clinically severe patients (Figure 5). The slope of the shoulder/elbow relationships significantly changed in 4 of 7 mild-to-moderate and 4 of 4 severe patients.

TABLE 2. Comparison of Data From Stroke and Healthy Individuals Reaching to 2 Targets When the Trunk Was Free to Move or Restrained

	Trunk Free				Trunk Restrained			
	Target 1		Target 2		Target 1		Target 2	
	x	SD	x	SD	x	SD	x	SD
Stroke								
Elbow extension, degrees	27.6	10.4	45.2	14.6	32.2	6.9	59.1	11.2
Shoulder horiz add, degrees	22.9	13.5	32.4	14.6	27.2	11.4	34.1	15.9
Shoulder flexion, degrees	14.3	9.8	19.2	12.4	28.6	14.1	30.6	8.7
Peak velocity, mm/s	736.7	307.3	1098.9	489.4	648.7	332.5	831.2	494.8
No. of peaks	4.2	2.0	4.3	2.3	4.3	1.9	4.2	1.6
Index of curvature	1.80	0.52	1.34	0.22	1.88	0.59	1.35	0.24
Slope of angle/angle relation			0.417	0.415			0.638	0.380
Angle/angle correlation, r^2			0.734	0.340			0.913	0.131
Healthy								
Elbow extension, degrees	28.6	9.4	61.5	11.1	29.9	8.1	69.9	6.5
Shoulder horiz add, degrees	30.3	6.7	55.0	10.0	32.4	8.3	60.7	8.5
Shoulder flexion, degrees	21.7	14.0	41.6	16.2	23.6	15.9	43.8	12.8
Peak velocity, mm/s	986.3	134.0	1409.3	248.7	939.1	199.4	1351.5	245.0
No. of peaks	2.9	0.6	2.3	0.5	2.6	0.4	2.1	0.4
Index of curvature	1.54	0.13	1.20	0.12	1.55	0.17	1.22	0.08
Slope of angle/angle relation			0.903	0.452			0.769	0.223
Angle/angle correlation, r^2			0.942	0.051			0.961	0.025

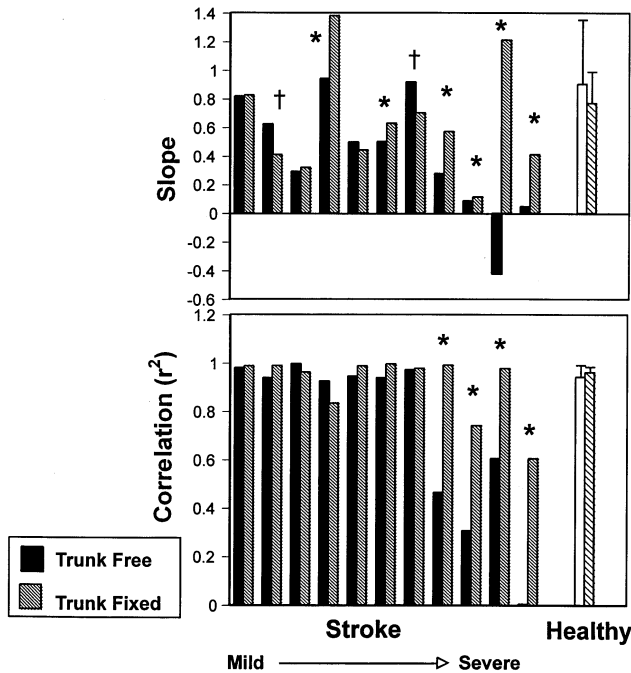


Figure 7. Shoulder-elbow interjoint coordination patterns for target 2. Slopes (top) and correlation coefficients (r^2 , bottom) for individual stroke patients (black and thinly hatched bars) and mean values for healthy individuals (white and thickly hatched bars). Data shown for trunk free (solid bars) or restrained (hatched bars) movements. Data for individual stroke patients are listed in same order as Table 1. Correlation coefficient for S11 (bottom) was <0.05 . Asterisks above pairs of bars indicate significant increases in values; daggers indicate significant decreases.

In addition, when the trunk was restrained, correlations significantly increased in the 4 severe patients who had poor shoulder/elbow correlations when reaches were made without trunk restraint (Figure 7).

Discussion

Unrestrained Reaching in Healthy and Hemiparetic Individuals

Our data showed that when reaching to grasp objects placed within the arm workspace, both healthy and hemiparetic individuals made hook-shaped trajectories. Trajectories were wider for grasping objects placed closer to the body presumably to allow proper hand orientation as the target was approached.^{27,28} Both groups showed similar tendencies in trajectory formation, but hemiparetic patients had more variable trajectories and tended to use more trunk displacement. Patients used more trunk recruitment to compensate for significantly decreased active elbow and shoulder movements while reaching. Compensatory trunk recruitment has been reported previously when reaching for targets placed close to the body.^{1,2} In the present study, there was a strong relation between clinical stroke severity with trunk displacement as well as with deficits in interjoint coupling used during reaching. This implies that hemiparetic patients may use different reaching strategies according to their clinical severity. At the same time, the use of trunk-assisted reaching enables even the most severely affected patient to reproduce

end point trajectories similar to those in healthy individuals. This is consistent with previous findings of relative preservation of end point trajectory paths during planar 2-joint movement, 3-dimensional pointing, and grasping in hemiparetic individuals.^{1,2,7} It is also consistent with suggestions that movement may be planned in terms of end point coordinates within an external rather than a body-centered frame of reference^{29,30} and that this type of motor planning may be partially preserved in nonapraxic hemiparetic patients.⁷

Despite the relative preservation of end point trajectories, interjoint coordination was severely disrupted in most patients (see Figures 2 and 4, S11). This underscores the need for therapists to assess not only the capacity of patients to perform activities of daily living with the affected arm but, more importantly, to evaluate key components of limb control associated with movement quality.³¹ In particular, with respect to reaching and manipulating objects with the hemiparetic arm, assessment should focus on the amount of compensatory trunk and shoulder girdle movements as well as the range of active joint movement used. This type of analytical approach is not possible with the use of functional outcome scales such as the Barthel Index³² or the Frenchay Arm Test³³ that mainly assess the level of independence for task completion. A need exists for the development of scales to allow clinicians to isolate and quantify such key task components. Bernhardt et al³⁴ have described an assessment of an object manipulation task in hemiparetic patients that is based on observational analysis of movement speed, trajectory jerkiness, and path indirectness. They compared therapists' ratings of videotapes of patients performing the task to criterion measures analyzed with an instrumented motion analysis system. Moderate to highly accurate judgments by therapists on these 3 parameters were reported. Compensatory movements, however, were not assessed. Recently, a new scale has been proposed that focuses on movement quality, which includes compensatory movement in well-defined functional tasks, including reaching.³⁵ Quality of movement information derived from these types of scales may complement functionality information from other assessment tools and help therapists design more effective treatment programs for hemiparetic patients.

Effect of Trunk Restriction on the Increase of Arm Range of Motion

The effects of trunk restraint indicate that hemiparetic patients did not use their potential joint range for free arm movements. A likely explanation stems from recent findings of Levin et al.³⁶ They defined articular ranges in which hemiparetic patients could make isolated elbow flexion and extension movements by using a reciprocal muscle activation pattern. The angular range was correlated with the motor deficit such that the most severely affected patients could only make isolated elbow movements in midrange. With further encouragement, movement beyond the defined ranges was possible, but this required more effort and was accompanied by a pattern of excessive agonist/antagonist coactivation. For elbow extension, the excessive coactivation occurred when patients attempted to extend the elbow beyond the angular position defined by the static stretch reflex

threshold for the antagonist elbow flexors. If these findings at a single joint may be extended to the multijoint reaching task, it may be postulated that restriction of trunk movement enabled patients to extend their reach by using the joint range characterized by coactivation. The additional energy cost of using more elbow extension probably was avoided by hemiparetic individuals when reaching without trunk restraint. Indeed, evidence from studies in healthy individuals suggests that minimization of metabolic energy costs may govern the selection of muscle activation patterns, movement trajectories, and interjoint coordination by the central nervous system.³⁷ A better understanding of the mechanisms underlying the increases in elbow and shoulder motion may be gained by an electromyographic analysis of muscle activation patterns during restrained and unrestrained reaching.

Effect of Trunk Restriction on Arm Reaching Patterns

Trunk restraint decreases the number of joints involved in reaching because it blocks shoulder girdle and trunk movements naturally accompanying arm movements. Indeed, scapular movement contributes $\approx 60^\circ$ to both shoulder flexion and abduction.³⁸ However, the task still involved a redundant number of degrees of freedom (3 for the glenohumeral joint, 2 for elbow, 2 for wrist) to position and orient the hand in space for reaching. Thus it did not reduce the movement to a 2-dimensional task.

The increase in joint ranges with trunk restraint may be partly due to an adaptation involving anticipation of changed external load conditions. Indeed, in healthy individuals, adaptation to perturbation of single joint movement may occur within one trial,³⁹ and preliminary results indicated that this type of adaptation may also occur in mild to moderately affected hemiparetic patients.⁴⁰ Another possibility is that the adaptation was triggered by somatosensory input from the trunk or shoulder caused by the trunk restraint.⁴¹ Adamovich et al⁴¹ demonstrated that unexpected trunk perturbations did not affect hand trajectories for reaches made within the workspace. Similarly, we found that healthy individuals preserved arm trajectories marked by smooth interjoint coordination despite the change in the ranges of motion when the trunk was restrained. A similar adaptation may have occurred in hemiparetic patients. The finding that trunk restraint led to an increase in active angular range in hemiparetic patients suggests that they may have retained the ability to adapt their motor commands to new external conditions. An explanation of this adaptability seems necessary. To begin with, it is well documented that hemiparetic patients use abnormal interjoint synergies to accomplish arm movement.^{9,42,43} The arm extension synergy is characterized by scapular elevation and protraction together with shoulder extension, adduction and internal rotation, elbow extension, and wrist flexion. Limiting components of this synergy (scapular protraction and elevation) may encourage the recovery of combined shoulder flexion and elbow extension. In other words, patients are forced to make movements "out of synergy," which probably involves a focused and greater effort on their part. Interestingly, requiring patients to make this additional effort may indeed be effective in increasing active joint range as well as

improving interjoint coordination. The finding that reaching movements using increased angular ranges obtained by this method are made in a more coordinated way is indeed surprising. It suggests that underlying "normal" patterns of movement coordination are not entirely lost after stroke and that appropriate treatments may be applied to uncover them to maximize function. One cost of this recovery may be a short-term decrease in movement speed.

Knowledge of the capacity of stroke patients to recover lost movement elements is essential to the resolution of the debate concerning the degree to which therapy should emphasize the recovery of normal versus the teaching of compensatory strategies for reaching. Traditionally, the choice between rehabilitation strategies has been based on the phase of stroke recovery. Thus, in the acute phase, therapy focuses on the prevention of maladaptive compensatory strategies while promoting the recovery of normal function. In the chronic phase, the emphasis is placed on maximizing function, often through the teaching of compensatory strategies.³¹ Our observation that some recovery of normal reaching patterns could occur in patients with chronic stroke suggests that such a clear division between treatment approaches may not be justified.

A limitation of this study is that the longer-term effects of trunk-restraint therapy were not investigated. The results of a recent literature review indicate that recovery in hemiparetic patients may occur when interventions involve repetitive training and stimulate the active participation of the patient.⁴⁴ However, improvements in patients with moderate to severe clinical syndromes may be associated with increased trunk displacement when unrestrained pointing movements are practiced.⁴⁵ This suggests that in some cases, repetitive training or unrestrained reaching may reinforce undesirable compensatory strategies. It remains to be demonstrated that the use of trunk restraint as a treatment paradigm aimed at decreasing compensatory strategies has the potential of becoming an effective therapy. Further studies are necessary to determine if the improvement may outlast the period of training.

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