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Disruption of Coordination Between Arm, Trunk, and Center of Pressure Displacement in Patients With Hemiparesis

Ksenia I. Ustinova, Valery M. Goussev, Ramesh Balasubramaniam, and Mindy F. Levin

To determine how arm movements influence postural sway in the upright position after stroke, interactions between arm, trunk, and center of pressure (CoP) displacements in the sagittal direction were investigated in participants with hemiparesis and healthy subjects. Participants swung both arms sagittally in either of 2 directions (in-phase, anti-phase) and at 2 speeds (preferred, fast) while standing on separate force plates. Variables measured included amplitude and frequency of arm swinging, shoulder and trunk range of motion, CoP displacements under each foot and of the whole body, and the relationships between the arm, trunk, and CoP displacements. CoP displacements under the non-paretic leg were greater than those under the paretic leg, which may in part be related to the larger amplitude of swinging of the non-paretic arm. CoP displacements under each foot were not related to arm swinging during in-phase swinging at the preferred speed in healthy subjects. When speed of arm swinging was increased, however, the CoP moved in a direction opposite to the arm movement. In contrast, in individuals with hemiparesis, CoPs and arms moved in the same direction for both speeds. During anti-phase swinging in healthy subjects, the trunk counterbalanced the arm movements, while in participants with hemiparesis, the trunk moved with the affected arm. Results show that stroke resulted in abnormal patterns of arm-trunk-CoP interactions that may be related to a greater involvement of the trunk in arm transport, an altered pattern of coordination between arm and CoP displacements, and an impaired ability of the damaged nervous system to adapt postural synergies to changes in movement velocity.

Key Words: bilateral arm movement, hemiplegia, stroke, center of pressure, motor control, rehabilitation

K.I. Ustinova is with the Research Institute of Neurology in the Russian Academy of Medical Sciences, 123098, Moscow, Russia. V.M. Goussev, R. Balasubramaniam, and M.F. Levin are with Center for Interdisciplinary Research in Rehabilitation (CRIR), 6300 Darlington, Montreal, Quebec, H3S 2J4, Canada. In addition, Ustinova and Levin are with the School of Rehabilitation at the University of Montreal, Montreal, Quebec, Canada, and Balasubramaniam is with Sensory Motor Neuroscience in the School of Psychology at the University of Birmingham, UK.

Introduction

Different patterns of interaction between arm and postural (center of pressure, CoP; center of mass, CoM) displacements have been described in healthy subjects. Aruin and Latash (1995) and Patla et al. (2002) reported that counter-displacement of the supporting segments was insufficient to avoid displacements of the CoM in the same direction as the arms when both arms were displaced during bilateral arm raising. Other authors recorded a postural over-compensation, in which displacement of the trunk in the opposite direction was greater than needed to compensate the forward displacement of the mass of one (Bouisset & Zattara, 1981) or both arms (Hodges & Richardson, 1999). Such differences may be related to the dependence of postural reactions on the parameters of movement, such as velocity and segment weight (Abe & Yamada, 2001; Hodges et al., 1997; Horak et al., 1984; Lee et al., 1987; Vernazza-Martin et al., 1999).

It is unclear how postural reactions accompanying ongoing coordinated arm movements in standing are altered when central control of movement and limb biomechanics are changed after stroke-related brain damage. Some authors have reported that anticipatory postural adjustments are altered in patients with hemiparesis. Horak et al. (1984) and Garland et al. (1997) recorded a prolonged latency and decreased amplitude of muscle activation in the trunk and legs in response to destabilizing rapid unilateral arm flexion in patients with chronic hemiparesis who had good functional standing balance. Similarly, Slijper et al. (2002) noted that anticipatory postural adjustments were decreased and showed atypical patterns on both the paretic and non-paretic sides compared to healthy subjects in response to self-initiated predictable unloading of the arm. The activity of trunk and leg muscles preceded the arm displacement suggesting that the anticipatory nature of the response was not disturbed in these patients. In addition, Palmer et al. (1996) reported alterations in the sequence of trunk muscle (ipsi- and contralateral latissimus dorsi) recruitment during rapid unilateral arm abduction. These studies have described only the temporal postural responses during discrete arm movements in patients with hemiparesis, while no study has described the spatial patterns of activation between the arms and supporting segments (trunk and legs) during continuous, rhythmical bilateral arm movements produced while standing.

The interaction between arm and trunk movements may also be altered in patients with hemiparesis due to the excessive displacement of the trunk for arm transport as has been previously reported during unimanual reaching and grasping (Cirstea & Levin, 2000; Levin et al., 2002; Michaelsen et al., 2001; Roby-Brami et al., 2003), disruptions in temporal coordination between arm and trunk movements during seated reaches to targets placed within and beyond the reach of the arm (Archambault et al., 1999; Esparza et al., 2003), and bilateral deficits in trunk control following unilateral brain lesions (Carr et al., 1994; Esparza et al., 2003; Ferbert et al., 1992). The increased role of the trunk for arm transport and problems of trunk control in individuals with hemiparesis may represent additional challenges to inter-segment coordination and result in a destabilization of posture during tasks requiring arm movements from a standing position.

We hypothesized that due to altered limb biomechanics and trunk control, inter-segment coordination during continuous rhythmical bilateral voluntary arm movements may be disrupted after stroke. We characterized the spatial interaction between arm, trunk, and CoP displacements under different speed and movement conditions in healthy subjects and in individuals with hemiparesis. Some results have appeared in abstract form (Ustinova et al., 2003).

Methods

Subjects

Twelve adults participated in this study: 6 healthy subjects (control group) and 6 adults with hemiparesis. Adults with hemiparesis consisted of a convenience sample of individuals who were included if they had unilateral stroke-related brain damage in the dominant hemisphere in the territory of the middle cerebral artery and were under 75 years of age. Exclusion criteria were the presence of the following factors: cerebellar or brain stem lesions; significant verbal, visual, or cognitive deficits; perceptual problems; pain or orthopaedic problems in the arms or legs; marked deficit in balance (less than 35/56 on the Berg Balance Scale described below); inability to extend the arm (less than 35/66 on the Arm Motor Section of Fugl-Meyer Stroke Assessment Scale described below); marked deficit in proprioception (less than 6/8 on the Sensory Evaluation of the Fugl-Meyer scale); or an onset of stroke less than 6 months previously. All participants were informed of the experimental procedures and signed a consent form conforming to the requirements of the hospital's Ethics Committee. The control group included 3 men and 3 women without any pain; no neurological or orthopaedic deficits involving the arms, legs, or trunk; and of a mean age (±*SD*) of 37.8 ± 11.7 years. The experimental group included 4 men and 2 women with a mean age (±*SD*) of 46.6 ± 19.3 years.

All patients had lesions in the left hemisphere only. They were tested clinically by experienced clinicians using a battery of tests to assess their arm motor deficits and their sitting and standing balance. Impairment of the arm was evaluated with the Arm and Hand section of the valid (Berglund & Fugl-Meyer, 1986) and reliable (Duncan et al., 1983) Fugl-Meyer Stroke Assessment Scale (Fugl-Meyer et al., 1975). This assessment included an evaluation of tendon reflex excitability, the performance of voluntary movements, and finger-to-nose coordination of the affected arm on a 66-point scale, where 66 indicates normal function. Spasticity was measured using the valid (Goulet et al., 1996) and reliable (Nadeau et al., 1997) Composite Spasticity Index (CSI; Levin & Hui-Chan, 1992). For the testing, the patient was seated comfortably, and three tests were performed. Biceps tendon jerks were scored on a scale of 0 (no response) to 4 (maximally hyperactive response). Resistance to full-range passive elbow extension performed at a moderate speed was scored on a 5-point modified Ashworth Scale (Ashworth, 1964). Since this measurement most closely represents tone (Berardelli et al., 1983), it was doubly weighted. Thus, a score of 0 indicated *no resistance* and a score of 8 corresponded to *maximally increased resistance.* Wrist clonus was measured on a scale from 1 (*no clonus*) to 4 (*sustained clonus*). Scores on the CSI varying from 1 to 4, 5 to 9, 10 to 12, and 13 to 16 corresponded to *no, mild, moderate,* and *severe spasticity,* respectively. The ratings of severity were determined from clinical experience and previous use of the scale in adults and children (Jobin & Levin, 2000; Levin & Hui-Chan, 1992).

Finally, the 56-point Berg Balance Scale (Berg et al., 1989) was used to evaluate postural stability when sitting, standing, and stepping. Performance on the Berg scale has been associated with the risk of falling in elderly subjects (Shumway-Cook et al., 1997). Berg scores between 41 and 56 indicate good ability to maintain balance, while scores between 21 and 40 correspond to a fair ability. All clinical and demographic data are presented in Table 1.

Table 1 Clinical Scores and Demographic Data of Participants With Hemiparesis

Subject	Age/sex	Lesion (location and type)	Time since lesion (months)	Fugl-Meyer score	Composite Spasticity Index	Berg balance score
1	60/M	MCA, thalamic lesion, hemorhagic	28	65	5	55
2	72/M	MCA, ischemic	17	63	5	50
3	40/M	MCA, parietal lobe, internal capsule, hemorhagic	28	54	9	56
4	57/M	MCA, temporal lobe, ischemic	15	55	11	35
5	24/F	MCA, temporal lobe, ischemic	24	50	10	53
6	27/F	MCA, parietal lobe, internal capsule, ischemic	18	35	12	55

Note. M, male; F, female.

Experimental Procedure

While standing on separate force plates under each foot, participants swung their arms symmetrically about the horizontal axis passing through the shoulders under two conditions of movement coordination (Figure 1). Subjects were asked to swing the arms from the shoulder joints while relaxing their elbows, wrists, and hands. This meant that subjects should let their arms swing as naturally as possible and not attempt to stiffen or voluntarily move their elbows and wrists. In the in-phase condition (Figure 1A), both arms moved synchronously in the forward/backward direction. In the anti-phase condition (Figure 1B), the arms moved in opposite directions. Movements in each condition were performed at two different speeds: self-paced (preferred speed) and fast (1.2× preferred speed). The participant's feet were placed at the lower medial edge of each force plate so that they were approximately 30 cm apart. The base of support was not larger than the width of the hips. Participants wore flat shoes for each session. Two sets of 30-s trials (approximately 37.5 arm swinging cycles per trial) for each movement condition were recorded on separate days. In the first set, participants performed self-paced in-phase and anti-phase movements (5 trials for each coordination condition), and their preferred speed was calculated from these trials. In the second set (5 trials for each condition) subjects swung their arms at a speed equal to 1.2× the preferred speed calculated in the first set of trials (fast speed). The frequency of swinging was maintained by asking subjects to match their movements to a metronome signal. In response to an initial "ready" signal, participants began swinging their arms in either the in-phase or anti-phase condition. Once the subject was able to maintain a steady pace of arm swinging, the metronome was turned off and data recording was begun. The participants did not receive metronome pacing throughout the whole trial so as not to influence the rhythm of arm swinging. This ensured that the responses of the participants were produced by internal "natural" timing and coordination processes and were not externally driven. Although the amplitude of arm swinging was not stressed, participants were requested to maintain the same amplitude of arm swing during all trials.

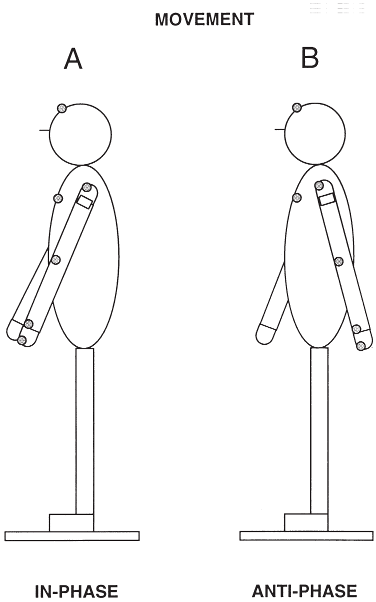

Figure 1 — Schematic diagram of experimental set-up showing in-phase (A) and anti-phase (B) arm swinging.

Data Analysis

Three-dimensional kinematic data were collected with 10 infra-red emitting diodes (IREDS) placed on the forehead (1), base of the sternum (1), middle of the 3rd metacarpal of the hands (endpoints; 2), styloid processes of the ulnae (wrists; 2), lateral epicondyles of the humerus (elbows; 2), and acromion processes of the shoulders (2). The movement of the markers was recorded by an Optotrak Motion Analysis system (model 3010, Northern Digital, Waterloo, Ontario) at a sampling frequency of 120 Hz. Positional x, y, and z data were low-pass filtered at 20 Hz using a Butterworth filter. From filtered data, peak-to-peak arm displacements in the sagittal (anterio-posterior) direction were calculated from endpoint markers, while peak-to-peak displacements of the trunk were calculated from the marker placed on the sternum. The frequency of arm swinging was calculated from the tangential velocities of arm movements derived from positional data as the number of movement cycles per second. A movement cycle was defined as occurring between subsequent peaks in the tangential velocity traces of the endpoint marker.

Kinetic data, including the ground reaction forces, moments, and displacements of the centers of pressure (CoP) in the sagittal (anterior-posterior) direction were recorded from separate AMTI OR6-7 force plates placed under each foot. The force plate signals were sampled at 120 Hz. The amplitudes of the CoP displacements in the sagittal direction and the distribution of weight on each leg were used as indices of body stability during arm swinging. Weight-bearing was calculated as the average difference (in %) of the vertical forces applied to the left and right force plates during the entire time of performance of arm swinging. A difference of ≤ 5% was considered to be indicative of normal weight distribution. In addition, the trajectories of displacement of the CoP of the whole body in the sagittal direction were calculated by using the following equation (Winter et al., 1996):

$$CoP_{wholeA/P} = LCoP_{A/P} \cdot LF_Z / (LF_Z + RF_Z) + RCoP_{A/P} \cdot RF_Z / (LF_Z + RF_Z)$$

where $LCoP_{A/P}$ and $RCoP_{A/P}$ are the displacements of the left and right CoPs in the sagittal (anterio-posterior) direction, and LF_Z and RF_Z are the total vertical forces, summarized from four force transducers placed at the four corners of each force plate.

In order to determine the interaction between the arm and CoP displacements, a cross-correlation analysis between appropriate variables was performed according to the equation:

$$R(\tau) = \frac{\int_0^T x(t+\tau) \cdot y(t) \cdot dt}{\|x\| \cdot \|y\|}; \quad \|x\| = \left(\int_0^T x^2(t) \cdot dt \right)$$

where x and y are the displacement of the arm (the endpoint marker) and the center of pressure, respectively; t is time; τ is the time lag; variables x and y are data obtained from the left or right side of the body.

Coefficients of variation (CVs) were used to describe the dispersion of the CoP under each foot in the sagittal direction for swinging at both speeds for both groups. The CV was computed as the standard deviation divided by the mean CoP position.

Coefficients of cross-correlation, calculated at a zero time lag, detected the directions of the displacements of the endpoint of each arm with the CoPs of the ipsilateral foot and of both feet, with the displacement of the upper trunk (sternal marker) and with the rotation of the upper trunk (see below). A negative mean coefficient (–0.25) was interpreted as movement of both parameters in opposite directions, while a positive coefficient (0.25) indicated displacement in the same direction. Mean coefficients falling between –0.25 and 0.25 were considered as indicating no relationship between the parameters.

Angular displacement of the shoulder (shoulder flexion) was determined by computing the angle between the vector joining the acromion and lateral epicondyle marker of the arm, with the vertical line passing though the acromion marker. To estimate rotation of the trunk about its midline, we measured the angles between the two vectors projected on the horizontal plane: one vector joining the right and left acromion (shoulder) markers and the line representing the frontal direction or x-axis. Ranges of motion were expressed as the absolute difference between minimal and maximal values.

Kinematic and kinetic data were analyzed in the same coordinate system, with its origin at the geometrical center between both force plates, and horizontal and vertical axes parallel to the respective walls of the experimental room.

Statistical Analysis

Since the variances of cross-correlation values were similar for the groups, parametric two-way repeated measures ANOVAs were used to determine the influence of the subject group (healthy vs. stroke) and speed conditions (preferred vs. fast) on the cross-correlation coefficients. Analyses were performed within condition of swinging for right and left sides separately. Also, for anti-phase movement, the influence of factors group and side (left and right) was analyzed using a two-way ANOVA. Differences in the coefficients of variation (CV) of the dispersion of the means of the CoP oscillations in both subject groups were tested during in-phase swinging using a two-tailed variance ratio test (Zar, 1974). Because requirements for the use of parametric statistics were not met for the other variables, non-parametric statistics were used for the rest of the comparisons. Wilcoxon matched pairs tests were used to determine the differences in frequency and amplitude of arm swinging, amplitude of displacement of CoPs, and weight distribution on right and left legs between groups and conditions. Finally, relationships between clinical severity (arm hemiparesis and standing balance) and parameters of arm/CoP and arm/trunk interactions were determined with Spearman correlation coefficients. A minimal significance level of $p < .05$ was used for all tests.

Results

Arm Movements

Subjects in both groups swung their arms in-phase and anti-phase at two movement speeds. Amplitudes of arm displacement and frequencies of arm swinging varied with movement condition (Table 2). Participants with hemiparesis swung their arms at a similar frequency as healthy subjects during the in-phase condition performed at the preferred speed, but the frequency of arm swinging was lower in these participants for all other conditions (in-phase movement performed at the fast speed and anti-phase movements at both speeds; 0.60 to 0.80 Hz in subjects with hemiparesis compared to 0.78 to 0.99 Hz in healthy subjects; Wilcoxon matched pairs tests, $p < .05$; Table 2). All subjects were able to significantly increase the frequency of arm swinging in fast compared to preferred speed conditions, despite the presence of spasticity and arm motor impairment in most individuals with stroke.

In healthy subjects, the amplitude of arm swinging (displacement of the endpoint) varied from 618 to 779 mm. Amplitudes did not change across speed or movement conditions, and there were no differences between left and right arms. In contrast, compared to the healthy group, the amplitude of arm swinging had a tendency to decrease with increasing speed in participants with hemiparesis, but this decrease was significant only for the right, hemiparetic arm (456 to 574 mm; Table 2).

Table 2 Means ± *SE* of Parameters of Arm Swinging (Endpoint Frequency and Amplitude of Displacement in the Sagittal Direction, Absolute Range of Shoulder Motion and Trunk Rotation) in Healthy Subjects and in Participants With Hemiparesis

	In-phase		Anti-phase	
Variable	Preferred speed	Fast speed	Preferred speed	Fast speed
Healthy				
Frequency (cycle/s)	0.80 ± 0.05	0.99 ± 0.04*	0.78 ± 0.03	0.94 ± 0.05*
Amplitude (mm)				
Left arm	642 ± 90	761 ± 81	776 ± 118	777 ± 86
Right arm	618 ± 91	763 ± 75	760 ± 102	779 ± 82
Range of shoulder motion (°)				
Left arm	66 ± 7.2	75 ± 8.4	72 ± 9.2	76 ± 10.1
Right arm	65 ± 5.5	67 ± 6.4	70 ± 6.1	73 ± 10.4
Trunk rotation (°)	2.3 ± 0.6	3.8 ± 0.7	7.6 ± 2.1	9.6 ± 1.3
Stroke				
Frequency (cycle/s)	0.64 ± 0.08	0.80 ± 0.08*†	0.60 ± 0.07†	0.74 ± 0.08*†
Amplitude (mm)				
Left arm	667 ± 88	609 ± 51	841 ± 53	721 ± 29
Right arm	548 ± 11	456 ± 76†‡	642 ± 77‡	574 ± 68†‡
Range of shoulder motion (°)				
Left arm	60 ± 10.8	63 ± 8.1	65 ± 8.0	59 ± 7.2
Right arm	54 ± 14.8	51 ± 9.4†	57 ± 5.6†	43 ± 5.6†‡
Trunk rotation (°)	5.3 ± 0.9†	6.9 ± 1.4†	30.9 ± 8.6†^	22.9 ± 7.2†^

*Signifies differences between preferred and fast speeds. †Signifies differences between both groups of subjects. ‡Signifies differences between left and right arms. ^Signifies differences between in-phase and anti-phase conditions.

Similarly, the amplitude of shoulder movement measured as the absolute range of movement between flexion and extension did not differ between healthy subjects and patients with hemiparesis for in-phase swinging at the preferred speed while, for all other conditions, the range was significantly less for the right, hemiparetic arm of the patient group (Table 2).

In summary, the characteristics of arm swinging were not altered in patients with hemiparesis for in-phase swinging at the preferred speed while, for all other conditions (in-phase movement performed at the fast speed and anti-phase movements at both speeds), some differences in frequency and amplitude of arm displacements as well as shoulder range of motion occurred.

CoP Displacements

In the in-phase condition (Figure 2), arm swinging resulted in different patterns of CoP displacements in the two groups of subjects that changed with movement speed. Arm movements at the preferred speed in healthy subjects were synchronized and accompanied by small oscillations of all CoPs (left foot, right foot, and of the whole body) in the sagittal direction (Figure 2A, vertical line). During arm oscillations, CoP trajectories had a characteristic reminiscent of "trembling" described for quiet standing by Zatsiorsky and Duarte (2000) with no visible correspondence with the arm movements. However, when the speed of arm swinging was increased, arm movements were accompanied by displacements of CoPs under each leg and of the whole body in the direction opposite to the arm movement (Figure 2C, vertical line).

In patients with hemiparesis, arm movements in the in-phase condition were also synchronized but were accompanied by shifts of the CoP of each leg and of the whole body in the same direction. In contrast to healthy subjects, this pattern of arm-CoP interaction was evident, even at the preferred speed (Figure 2B) and was more marked when the speed of arm swinging increased (Figure 2D).

For this condition, the dispersion of CoPs under each foot were similar between groups at the preferred speed [$CV_{(right)} = 0.34$ and $CV_{(left)} = 0.33$ in healthy subjects, and $CV_{(right)} = 0.47$ and $CV_{(left)} = 0.32$ in patients with hemiparesis]. Dispersion increased with movement speed in healthy subjects [$CV_{(right)} = 0.52$, $F = 18.5$, $p < .05$; and $CV_{(left)} = 0.62$, $F = 16.5$, $p < .01$], but not in participants with hemiparesis [$CV_{(right)} = 0.53$, $F = 1$, $p > .05$; and $CV_{(left)} = 0.42$, $F = 2.3$, $p > .05$]. In contrast, dispersion was not different between groups or speeds for the anti-phase condition.

The amplitude of displacement of the CoP of the whole body in the sagittal plane was similar in both groups of subjects for all movement and speed conditions (Figure 3, hatched bars). When CoP displacements were analyzed separately for right and left legs; however, they were significantly increased on the left side (non-paretic) in participants with hemiparesis compared to both legs of the healthy subjects ($p < .05$ for preferred and $p < .01$ for fast speed). In the stroke group, the amplitudes of displacement of the CoP and the arm on the right (non-paretic) side were significantly correlated with each other across all speeds and conditions ($r = 0.43$, $p < .05$), while this was not the case for the left (paretic) side ($r = 0.22$, $p >$

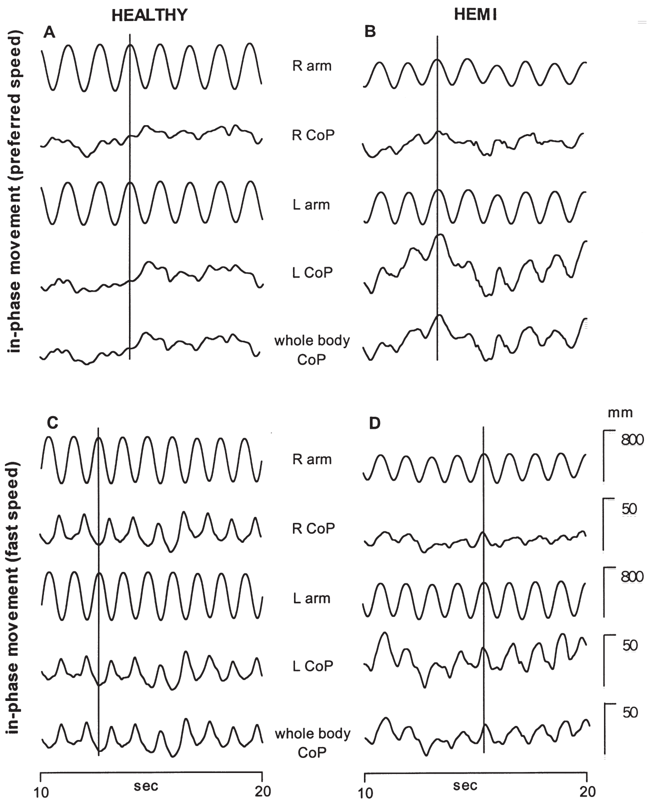

Figure 2 — Trajectories of arm and center of pressure (CoP) displacements for the right and left sides of the body and for the whole body (CoP only). Data shown are the middle 10s of 30 single trial recordings. Representative trials are from 1 healthy subject (left panels) and 1 individual with hemiparesis (right panels) performing in-phase movements at preferred (A, B) and fast (C, D) speeds. Vertical lines are superimposed on the data in each panel to visualize the synchrony or asynchrony between different trajectories. Scaling in A and B is the same as that in C and D.

.05). In addition, the CoP amplitude of the right (paretic) side tended to be less than that of healthy subjects and was significantly different ($p < .01$) from that of the left side in the same individuals, while no such differences occurred in the healthy group (Figure 3, white vs. black bars).

The distribution of weight on the left and right legs is shown in Figure 4A for all individuals in the stroke group. When compared across speeds and conditions, there were no differences between the loading on the right and left legs for either group of subjects (about 50% of the body weight per leg). Figure 4A also shows that there was an asymmetry in weight distribution between right and left legs in some individuals in the patient group (e.g., 43% on right leg and 57% on the left leg).

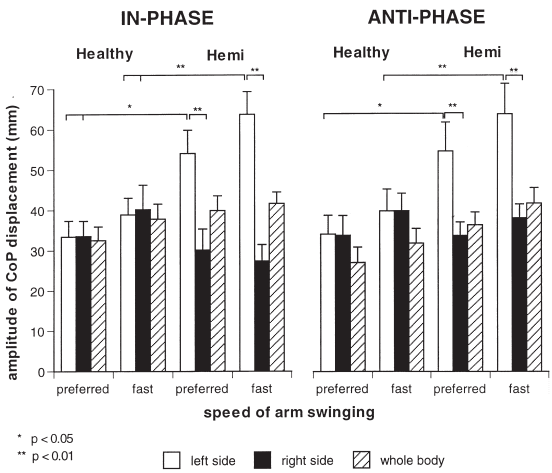

Figure 3 — Amplitudes (mean ± *SE*) of displacements of center of pressure (CoP) for the left side (open bars), right side (solid bars), and whole body (hatched bars) for both groups of subjects for all conditions.

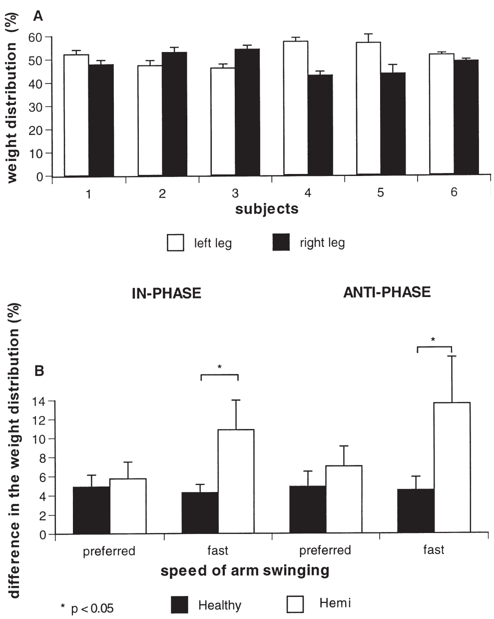

Figure 4 — Weight distribution (mean ± *SE*) for right and left sides of the body expressed as a percent of body weight. A. Distribution of weight between the paretic (right) and non-paretic (left) sides of the body in patients with hemiparesis. B. Difference in weight distribution between right and left sides of the body in healthy subjects (filled bars) and in patients with hemiparesis (open bars) for all conditions.

During arm swinging, the asymmetry of the weight distribution between the two legs, calculated across all speeds and conditions, did not differ between groups of subjects and was within the limits described for healthy individuals due to leg length discrepancy, differences in body position during testing, et cetera (Kostuik & Bentivoglio, 1981). At the same time, however, asymmetry of weight-bearing was significantly greater in patients, reaching more than 10% in some cases when participants with hemiparesis increased the speed of arm swinging (Figure 4B; $p < .05$).

Trunk Displacement.

Trunk sagittal displacement measured as the distance moved by the sternal marker was greater in the in-phase (58 to 75 mm) compared to the anti-phase (26 to 28 mm) condition and for the fast compared to the preferred speed in healthy subjects ($p < .05$). However, in the participants with hemiparesis, trunk displacement was generally less than in healthy subjects in the in-phase condition (53 to 59 mm), and displacement was not modulated with speed or condition (Figure 5; $p > .05$). Despite the smaller sagittal displacement of the trunk, individuals with stroke used significantly more trunk rotation than healthy subjects (Table 2), and this was more evident for the anti-phase compared to the in-phase condition.

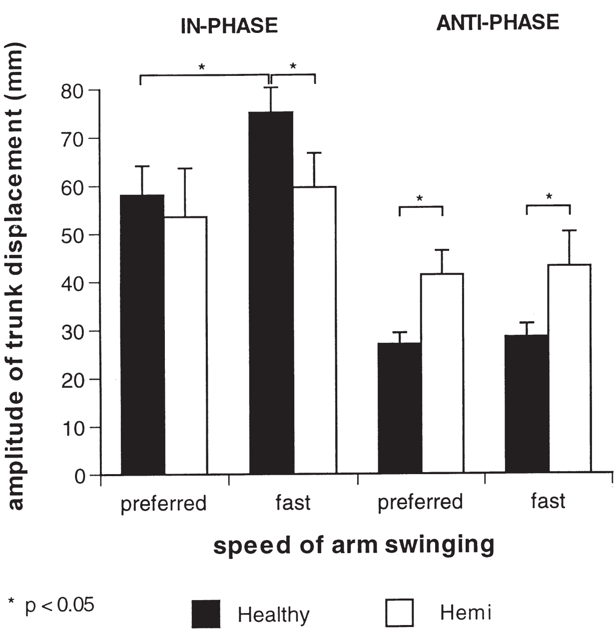

Figure 5 — Amplitude of upper trunk displacement (mean ± *SE*) in the sagittal direction in healthy subjects (filled bars) and in patients with hemiparesis (open bars) for all conditions.

Correlations Between Arm and Upper Trunk Displacements

In healthy subjects during in-phase swinging, the displacements of the arm endpoint and the upper trunk (sternal marker) were strongly negatively correlated (r = –0.83 for preferred speed and r = –0.87 for fast speed), suggesting that the trunk shifted in the opposite direction to the arm movement. While still significant, the coefficients of cross-correlation were lower in the patient group (r = –0.65 and –0.69 for preferred speed and r = –0.62 and –0.70 for fast speed) compared to the healthy group ($p < .05$ for preferred and fast speeds). For the anti-phase condition, cross-correlations were weak (< ±0.25) and showed no preferred pattern.

Cross-correlations between arm endpoint displacement and trunk rotation were also negative on both sides in healthy subjects (Figure 6, black bars; $r <$ –0.48) and for only the left side of patients with hemiparesis (Figure 6, hatched bars; $r <$ –0.31). In contrast, on the right, hemiparetic side of patients with stroke, the cross-correlation between arm endpoint movement and trunk rotation was positive (Figure 6, dotted bars). Thus, while in healthy subjects, the trunk tended to counterbalance the movements of the arms, patients demonstrated a different pattern ($p < .01$ for both speeds) in which the right (paretic) side of the trunk moved in the same direction as the affected arm. For anti-phase movement, trunk rotation was positively correlated with movements of the arm for each side in both groups of subjects. However, in the healthy group, the coupling was markedly stronger on the right side ($p < .05$), while this coupling was higher than that in the healthy subjects for both sides in the patient group.

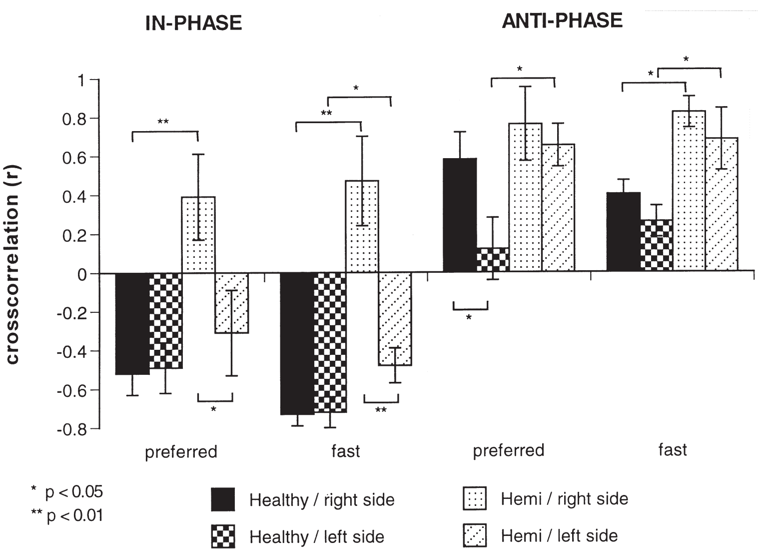

Figure 6 — Coefficients of cross-correlation (mean ± *SE*) between the rotation of the upper trunk and arm displacement at zero time lag in healthy subjects (dark bars) and in participants with stroke (light bars) for all conditions.

Correlations Between Arm and CoP Movements

Different patterns of interaction between arm and CoP displacements for the two speeds and conditions characterized the movements in each group. Cross-correlations for in-phase movement at the preferred speed were close to zero in the healthy group when analyzed separately for right and left sides (Figure 7A) or for the whole body CoP with right or left arm movement (Figure 7B). However, when the speed of arm swinging was increased, the cross-correlation was negative in healthy subjects, indicating that the arm and CoP shifted in opposite directions. ANOVAs revealed significant differences in the means of cross-correlations between preferred and fast speeds in healthy subjects, with no differences between right and left sides ($F_{1,10} = 0.65$, $p > .05$; Figure 7A).

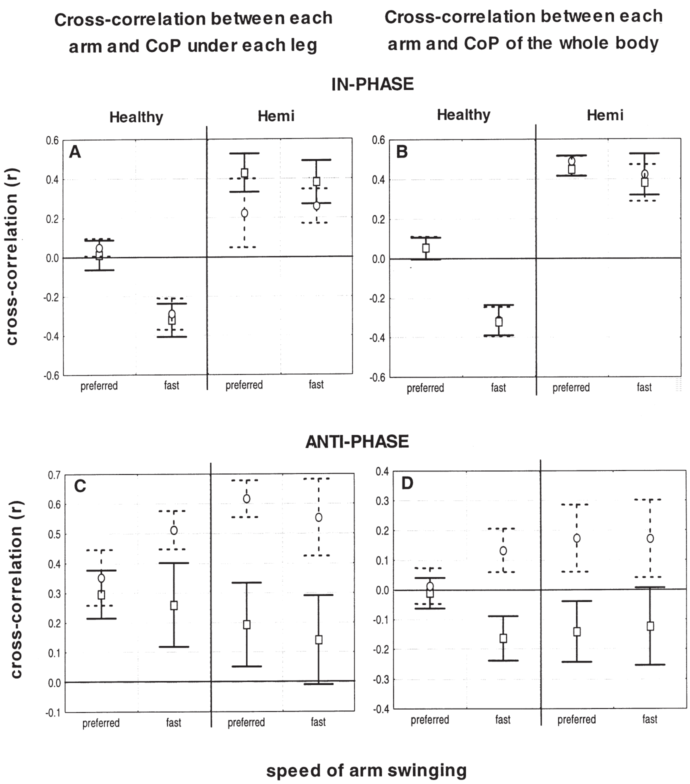

Figure 7 — Coefficients of cross-correlation (mean ± *SE*) between center of pressure (CoP) oscillations and arm displacements at zero time lag in healthy subjects and in participants with stroke for all conditions. Correlations are shown separately for left arms and left CoP (squares and solid lines) and for right arms and right CoP (circles and dashed lines) in A and C. Correlations are shown separately for whole body CoP (right and left legs) and left arms (squares and solid lines) or right arms (circles and dashed lines).

In contrast, in participants with hemiparesis, the coefficients of cross-correlation were positive for movements made at the preferred speed, indicating that the CoPs followed the direction of arm displacement. The patterns of arm and CoP interaction did not change when the frequency of swinging was increased ($F_{1,10}$ = 0.005, $p > .05$; Figure 7A). The patterns of interaction were significantly different from those in healthy subjects for the right ($F_{1,10}$ = 10.09, $p < .01$) and left sides ($F_{1,10}$ = 25.46, $p < .001$; Figure 7).

The anti-phase movement was characterized by a different pattern of interaction between CoP and arm displacements compared to in-phase swinging in both groups of subjects (Figure 7C–D). The cross-correlations were positive (Figure 7C), indicating that each CoP moved in the same direction as the arm. Patterns were analyzed separately for the two speeds of swinging. For preferred and fast speeds, there was a difference in the mean cross-correlation between sides ($F_{1,10}$ = 12.12, $p < .01$) but not groups ($F_{1,10}$ = 0.44, $p > .05$), and there was no effect of speed. Overall, the left side had less positive cross-correlations than the right in both groups ($F_{1,22}$ = 21.10, $p < .001$).

During anti-phase arm swinging, the mean cross-correlations between CoP displacements of the whole body with the direction of left and right arm movements were low (close to zero) for preferred and fast speeds (Figure 7D) in contrast to in-phase movement. Similar differences in cross-correlations for the left and right sides also occurred in both groups of subjects, and these were not influenced by movement speed.

Thus, healthy subjects and patients with hemiparesis used similar patterns of arm and CoP interactions in the anti-phase swinging condition. Differences in the interactions were observed mainly between the right and left sides of the body.

Correlations Between Clinical Scores and Kinematic Measures

Participants with more severe hemiparesis swung their arms with smaller amplitudes. Also, the greater the deficit in standing balance (lower score on the Berg Balance Scale), the greater the amplitude of the CoP displacement under the non-paretic leg (Table 3). No other correlations were found between symptom severity and movement deficits.

Discussion

Our results show that bilateral movements of the arms and the coordination between arm, trunk, and CoP displacements were altered in individuals with mild to moderate hemiparesis, compared to healthy individuals, and that the nature of the alterations was related to the speed of arm movement. Individuals with hemiparesis used less sagittal trunk displacement, more trunk rotation, and different patterns of CoP displacements than healthy participants. These patterns did not show similar adaptations to the increase in speed of arm movement as those seen in healthy subjects.

Significantly, our results show that, in healthy subjects during in-phase arm swinging at fast speeds, the trunk counterbalanced perturbations induced by the arm movements, while in individuals with hemiparesis, the opposite occurred. Thus, in

Table 3 Correlations (Spearmen *r*) Between Clinical Scores and Parameters of Arm and CoP Interaction (Arm, Trunk, and CoP Displacements in the Sagittal Direction, Coefficients of Cross-Correlation) in Participants With Hemiparesis

	Clinical tests	
Variable	Fugl-Meyer score	Berg balance score
Amplitude of paretic arm displacement	0.46*	0.26
Amplitude of trunk displacement	0.23	–0.18
Range of paretic shoulder movement	0.47*	0.26
Trunk rotation	–0.25	–0.20
Cross-correlation between right arm and trunk displacement	–0.29	–0.08
Amplitude of CoP displacement under non-paretic leg	0.04	–0.63**
Amplitude of CoP displacement under paretic leg	0.39	0.19
Cross-correlation between right arm and CoP displacement	0.05	0.26

Note. $^*p < .05$; $^{**}p < .01$.

contrast to healthy subjects, the CoP tended to move in the same direction as the affected arm in individuals with hemiparesis. These differences were related to the severity of arm paresis and stability in standing as measured by standard clinical scales. Despite these differences between healthy subjects and participants with hemiparesis, the displacements of the CoP of the whole body were maintained within a small area between the two legs. The maintenance of the CoP position may have been due to compensatory oscillations of the CoP under the non-paretic leg.

Postural Stability

Previous studies have characterized the differences in stability between healthy subjects and individuals with hemiparesis during quiet standing (Dickstein & Abulaffio, 2000; Shumway-Cook et al., 1988) and whole body perturbation (Hocherman et al., 1984). A common finding is that, under these conditions, greater oscillations occur under the paretic leg. The increase in oscillations on the non-paretic side under the dynamic movement conditions studied here may in part be related to the larger movement amplitude of the non-paretic arm recorded in patients. The larger displacement of the arm thus may have resulted in a larger oscillation of the CoP. Another explanation for the increase in oscillations under the non-paretic leg is that spasticity in the paretic leg may have decreased the magnitude of CoP oscillations on that side (Ustinova et al., 2000). Bilateral arm movements may have led to an increase in muscle tone of the paretic leg, facilitating the use of the leg as a rigid support. At the same time, the regulation of balance may have been produced mainly by muscle action of the non-paretic side. This may be considered an adaptive mechanism for increasing stability in standing similar to that reported by Aruin et al. (1997) in below-knee amputees. Thus, by using a different distribution of postural sway activity on both sides of the body, individuals with stroke and healthy subjects achieved the same level of control over the whole-body CoP.

Another parameter usually characterizing instability in patients is asymmetry of weight-bearing between both legs. Such an asymmetry has been previously observed under static (quiet standing) conditions (Bohannon & Tinti-Wald, 1991; Cheng et al., 1998), during discrete movement tasks in standing (Kusoffsky et al., 2001) and whole body movement (rising and sitting; Engardt & Olsson, 1992). In our experiment, we did not observe a shift in weight to the non-paretic side during rhythmic arm swinging. The lack of weight shift may be related to the dynamic nature of the task and to the fact that participants had only mild hemiparesis and good standing balance. The dynamic nature of the task required shifting the body weight for only brief periods of time from one leg to the other, resulting in a more symmetrical weight-bearing between legs compared to quiet standing tasks. An alternative explanation could be that internal perturbations induced in the sagittal plane were not large enough to create instability in the frontal plane and thus did not require additional loading of the unaffected leg in order to preserve body stability. Thus the stability of the body was not disturbed in our patients during performance of the dynamic bimanual task in the sagittal direction.

Arm-Trunk-CoP Interactions

In healthy subjects, the pattern of interaction between arm and CoP displacements changed with increasing speed. The oscillations of the CoP were not related to arm movements made at the preferred speed, but increasing arm movement speed resulted in a shift of the CoP in the opposite direction to the arm displacement. This is similar to previous findings of speed-related changes in the patterns of arm (shoulder) and leg joint (hip and ankle) coupling during bilateral in-phase arm swinging (Abe & Yamada, 2001). It is possible that the counter-phase relationship between arm and CoP displacements during rapid movement resulted from reactive forces acting on the body following the motion of the arm. This assumption is consistent with the laws of mechanics. Specifically, consider first an idealized case when friction between the feet and the platform is absent. At that point, external forces acting in the horizontal direction on the body-arm system would be zero. The muscle forces and torques responsible for arm motion are internal for this system. As a consequence, the sum of kinetic moments of the system in this direction (the sum of products of inertia and velocity of the arm and the remaining body) as well as the shift of the center of mass of the whole system would be zero despite the arm motion. In other words, the reactive forces acting horizontally on the body and elicited by the arm motion would displace the body in the opposite direction. This situation resembles that when a person is in a floating boat and begins to move towards its bow, whereas reactive forces, acting from the feet on the boat, move the boat in the opposite direction. In our experiment, friction prevented the motion of the feet and the body during arm oscillations, but the reactive force acting on the body following arm motion remained and resulted in the shift in the CoP in the direction opposite to the motion of the arm.

Another explanation is that forces transmitted by the arm movement resulted in reactive torques at the ankle to stabilize the body, which in turn resulted in displacements of the CoP as has been observed in healthy subjects (Patla et al., 2002; Vernazza-Martin et al., 1999). It is possible that changes in ankle muscle properties (types of motor units, spasticity, etc.; Dietz et al., 1981; Hufschmidt & Mauritz, 1985) in individuals with hemiparesis may alter this response, but this was not directly measured in this study.

In contrast to healthy subjects, the CoP in patients moved in the same direction as the arm displacement. As described above, the counter-shift of the trunk is an obligatory mechanical result of the bilateral arm movements. In addition, the displacement of the CoP is the result of all active and reactive forces acting on the body. Thus, the direction of the CoP displacement depends on shifts of both the arm segments and the trunk. If the counter-displacement of the trunk is of insufficient amplitude to compensate for the shift of the mass of both arms, the CoP would move in the same direction as the arm movement, as shown previously in healthy subjects (Patla et al., 2002). This was indeed the case in the participants with hemiparesis in our study (Figure 5).

The forward movement of the CoP can be explained by the biomechanical limitation of the range of shoulder movement on the hemiparetic side (20–25% less than healthy subjects) and efforts to compensate the limitation in range by increased rotation of the trunk (more than a two-fold increase; Table 2). Only the left, non-paretic side of the trunk actively counterbalanced the arm movement, while the right, paretic side shifted in the same direction as the arm and was accompanied by a decreased posterior displacement of the trunk. This decreased displacement and the fact that the trunk tended to move in the same direction as the affected arm during in-phase arm swinging suggests that the trunk was used to assist in arm transport during swinging. Similar disruptions in spatial coordination have been reported for unilateral movements of the arm and trunk during reaching and grasping tasks from a sitting position in individuals with hemiparesis (Archambault et al., 1999; Cirstea & Levin, 2000; Levin et al., 2002). These studies have shown that impairments in active elbow or shoulder movement are associated with trunk motion in the direction of the arm movement so that the trunk movement contributes to the displacement of the hand for reaching and pointing. Thus, the trunk may be involved in assisting arm transport even in non–goal directed arm movement in patients with hemiparesis.

The larger trunk displacement combined with the larger trunk rotation would have had a destabilizing effect on balance. The decreased posterior displacement of the trunk may have resulted from an effort to maintain a stable upright posture, but this led to the movement of the CoP in the same direction as the arm displacement. These results support the notion that postural responses during bilateral arm movement may mainly be a consequence of adaptation to changed biomechanics, with resulting changes in reactive forces and possibly ankle torques, and suggest that the trunk plays the dual role of assisting arm transport and maintaining balance.

Adaptations to the Change in Speed of Arm Swinging

In healthy subjects, while increasing the speed of arm swinging had no effect on the interaction between the arm and the upper trunk, it changed the pattern of coordination between the arm and CoP displacements, and caused an increase in the dispersion of CoPs under the right and left feet. These speed-related differences might result from the larger displacement of the upper trunk in the opposite direction to the arm movement when the speed of arm movement was increased (Figure 6). In contrast to healthy subjects, increasing the speed of arm swinging did not affect the pattern of arm-CoP interaction or the dispersion of CoP displacements under each leg in the participants with stroke. In other words, the individuals with stroke were less able to adapt their postural reactions to different speed demands. The problem of adaptability (or stereotyped) movement patterns has been reported in individuals with hemiparesis for a variety of tasks. For example, patients with hemiparesis (DiFabio et al., 1986) show limited adaptability of postural strategies to different types of whole body perturbation (DiFabio et al., 1986) and to different types of arm unloading (Slijper et al., 2002). These results suggest that patients with hemiparesis use stereotyped movement synergies and are less able to use the redundancy in the motor system to adapt postural strategies to changing velocities.

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