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Task-specific modulation of anticipatory postural adjustments in individuals with hemiparesis

Harm Slijper[a], Mark L. Latash[a], Noel Rao[b], Alexander S. Aruin[b,c,*]

[a]Department of Kinesiology, The Pennsylvania State University, University Park, PA 16802, USA
[b]Department of Physical Therapy, University of Illinois at Chicago, 1919 West Taylor Street, Chicago, IL 60612, USA
[c]Marianjoy Rehabilitation Hospital, Wheaton, IL 60187, USA

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Abstract

Objectives: To study adaptation of anticipatory postural adjustments (APAs) in paretic and non-paretic muscles of individuals with hemiparesis to changes in the direction of the self-initiated perturbation and additional manual support.

Methods: Electrical activity of leg and trunk muscles on both sides of the body and ground reaction forces were recorded in 10 patients with hemiparesis and a group of matched control subjects. Subjects released a standard load, held in the hand of the extended relatively unimpaired arm. The load was released either in front of the body or to the side, with or without the impaired arm touching an external stable surface.

Results: APAs were reduced in individuals with hemiparesis, especially on the paretic side. In paretic muscles, the modulation of APAs with the direction of the perturbation was decreased or showed atypical patterns. Also the effects of touch were decreased in patients. Center of pressure displacements shortly after load release were similar in control subjects and patients.

Conclusions: The results suggest that the ability of individuals with hemiparesis to prepare for a self-initiated predictable perturbation is reduced and that they may use alternative strategies of postural stabilization.

Keywords: Vertical posture; Anticipatory postural adjustments; Hemiparetic; Electromyogram; Human

1. Introduction

Maintenance of vertical posture in the field of gravity is probably the most common component in a variety of motor tasks humans perform in daily life. Many motor actions performed by a standing individual perturb the postural equilibrium. These perturbations are due to mechanical joint coupling and changes in the body configuration that lead to a shift in the projection of the center of mass (COM). Commonly, such movements are accompanied by anticipatory changes in the activity of postural muscles that are generated by the central nervous system (CNS) in a feed-forward manner, that is, they can be seen prior to the onset of the focal movement (Aruin and Latash, 1995b; Belenkiy et al., 1967; Brown and Frank, 1987; Crenna et al., 1987). The apparent role of these adjustments is to counteract the predictable effects of an upcoming perturbation on the postural equilibrium.

Studies of anticipatory postural adjustments (APAs) in healthy individuals have suggested that the process of generation of APAs is affected by 3 major factors: expected magnitude and direction of the perturbation, voluntary action associated with the perturbation, and current postural task (e.g. stability conditions) (Aruin et al., 1998). In particular, it has been shown that the intensity of APAs is graded as a function of the magnitude and direction of a forthcoming postural perturbation (Aruin and Latash, 1995b; Bouisset et al., 2000; Dick et al., 1986; Horak et al., 1984; Lee et al., 1987). The results of experiments with load manipulations in which the magnitude of motor action and the magnitude of perturbation were manipulated separately have suggested that both the magnitude of the action and the magnitude of the perturbation can affect APAs (Aruin and Latash, 1995b; Aruin and Latash, 1996; Dufosse et al., 1985; Paulignan et al., 1989).

Changes in APAs with changes in postural stability have been controversial. APAs have been shown to decrease in conditions of both very stable (Nardone and Schieppati, 1988) and unstable standing (Aruin et al., 1998; Gantchev and Dimitrova, 1996; Nouillot et al., 1992; Pedotti et al.,

* Corresponding author. Tel.: +1-312-355-0902; fax: +1-312-996-4583.
E-mail address: aaruin@uic.edu (A.S. Aruin).

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1989). In very stable conditions, the requirements to stabilize posture under the action of a transient, motion-related perturbation is alleviated (Nardone and Schieppati, 1988). On the other hand, in unstable conditions, APAs themselves may be viewed as sources of perturbations that can move the center of pressure (COP) beyond the decreased area of support (Aruin et al., 1998). Recently we have shown changed APAs patterns in subjects who were lightly touching a stable external surface (Slijper and Latash, 2000). Under these conditions, the APAs were attenuated, similarly to those seen under mechanically stable conditions, suggesting that the subjects perceived the light touch as a stabilizing factor.

Following a cerebro-vascular accident (CVA), a large number of patients suffer from significant hemiparesis on the contralateral side of the body. The hemiparetic syndrome commonly includes spasticity, weakness for voluntary movement, and impaired motor coordination (Bohannon et al., 1987b; Bobath, 1970). Individuals with hemiparesis can demonstrate deficit of antagonist inhibition (Gowland et al., 1992), impaired temporal and spatial muscle recruitment (Filiatrault et al., 1991; Levin and Dimov, 1997), impaired coordination of elbow and shoulder movements (Levin, 1996), alterations in gait patterns (Wagenaar and Beek, 1992), and asymmetry of stance with impaired balance control (Aruin et al., 2000; Chaudhuri and Aruin, 2000; Mizrahi et al., 1989; Sackley, 1991; Turnbull et al., 1996). It has been suggested that the failure to coordinate postural muscles with focal movement may contribute importantly to the instability of individuals with hemiparesis (Bennis et al., 1996; Dettmann et al., 1987; Garland et al., 1997; Hedmann et al., 1997; Horak et al., 1984; Massion et al., 1999; Stevenson and Garland, 1996). Studies have shown that both anticipatory and compensatory mechanisms are impaired in those patients (Bohannon and Larkin, 1985; Fishman et al., 1997; Garland et al., 1997; Hedmann et al., 1997; Rogers et al., 1993). In particular, APAs have been shown to be decreased and/or delayed with respect to those seen in healthy individuals (Garland et al., 1997; Hedmann et al., 1997; Horak et al., 1984). These patients also show impaired acquisition of APAs associated with a newly learned task (Massion et al., 1999).

In the current study, we were interested in whether modulation of APA patterns with changes in mechanical characteristics of a perturbation and availability of a hand contact with an external object is impaired in individuals with hemiparesis. Specifically, are individuals with hemiparesis able to modify their APA patterns with changes in the direction of the perturbation and with addition of a light manual support? To answer this question, we investigated the patterns of APAs in patients with hemiparesis due to a stroke accident during self-initiated load release from the extended arm and manipulated two factors: (1) initial position of the load with respect to the midline of the body; and (2) presence of an additional light manual support to the other arm.

2. Methods

2.1. Subjects

Ten individuals with hemiparesis due to a cortical or subcortical lesion on either the left or right side participated in the study. All the subjects volunteered for the study after being referred by their primary physician. All individuals with hemiparesis were able to walk and stand independently with or without a cane. All patients had their stroke at least 6 months prior to the test. The characteristics of the individuals with hemiparesis and the control subjects are presented in Table 1. The primary physician assessed the sensation, motor strength and spasticity of the paretic limb. Motor strength of the paretic upper extremities was evaluated with the conventional grading scale (CGS) (Clarkson and Gilewich, 1989). The CGS ranges from 0 to 5: a score of zero means no observable muscle contraction while a score of 5 means a maximal manual resistance to joint displacement. Across all patients these scores ranged from 3 to 4 for the hip and knee joints and was 2 for the ankle joint; motor strength of the upper extremities ranged from 2 to 2.5.

Spasticity of the paretic upper extremity was quantified with a modified Ashworth scale (Bohannon and Smith, 1987); on an average, the score was 2.29 ± 0.37 (SD). Nine individuals with hemiparesis wore an ankle foot orthosis. During the experiment, these subjects stood without the orthosis and did not experience problems doing so.

Nine control subjects were matched in age and gender.[1] None of the control subjects had any motor or neurological disorder interfering with the experimental protocol. All the subjects gave their written consent prior to the experiment.

2.2. Apparatus

A force platform (AMTI, OR-6) was used to record two moments, around a frontal axis (M_y) and around a sagittal axis (M_x), and the vertical component of the reaction force (F_z). During the experiments, the subjects were required to release a load held in the extended arm. Onset of the load release (perturbation) was measured by a miniature unidirectional accelerometer (Sensotec) taped to the load. The axis of sensitivity of the accelerometer was directed along the gravity line. The load used in the experiment was 2.23 kg; it had a short protruding handle that could be grasped by the subjects with the medial part of the palm, little and ring fingers. Disposable self-adhesive electrodes (3M) were used to record the activity of the following muscles on both sides of the body: tibialis anterior (TA), soleus (SOL), rectus femoris (RF), long head of the biceps femoris (BF), rectus abdominis (RA), and erector spinae (ES). In the individuals with hemiparesis, muscles on the paretic side were called 'non-focal' muscles (NF), muscles

[1] The tenth control subjects did not complete the experimental series, his data were not further processed.

Table 1
Characteristics of the 10 hemiparetic subjects and the control subjects

Subject	Age (yrs)	Gender	Handedness	Weight (kg)	Height (cm)	Interval[a] (days)	Lesion	Pathology	Side hemi[b]	Hand sensation[c]	Spasticity[d]
1	50	Male	R	72	177	182	Right basal ganglia hemorrhage	Hemorrhagic stroke	L	Severe	2 +
2	38	Female	R	86	168	874	Left occipital and left cerebellar brain stem infarct	Thrombotic stroke	R	Moderate–severe	2 + /3
3	49	Male	R	78	189	559	Left basal ganglia infarct	Thrombotic stroke	R	Mild	2
4	53	Male	R	73	180	762	Right basal ganglia infarct	Thrombotic stroke	L	Mild	2
5	74	Female	R	76	167	1309	Ishemic white matter disease in brain	Thrombotic brain stem stroke	R	Moderate	2 +
6	26	Male	R	80	182	3072	Left parietal and basal ganglia infarct	Thrombotic stroke	R	Mild	3
7	36	Male	R	72	187	2742	Right parietal lobe and basal ganglia hemorrhage	Traumatic brain injury	L	Moderate	2
8	74	Male	R	66	170	578	Basal ganglia lacunar infarct	Thrombotic stroke	L	Mild	2
9	29	Male	L	79	180	2832	Right occipito parietal hemorrhage	Arteriovenous malformation	L	Mild	2
10	51	Male	R	92	188	2520	Right basal ganglia infarct	Hemorrhagic stroke	L	Severe	2
Patients	48			77.4	178.8	1543					
Standard deviation	16.6			7.5	8.2	1118					
Control	51			74.2	172						
Standard deviation	14.0			15	11.6						

[a] Interval between onset of hemiparesis and the study.
[b] Side on which the hemiparesis was found. L = Left, R = Right.
[c] Loss of sensation.
[d] Spasticity of the affected limb as reported by the Ashworth scale (Bohannon and Smith, 1987): 2 – more marked increase in muscle tone through most of the range of motion, but affected part(s) easily moved; 3 – considerable increase in muscle tone, passive movement difficult.

on the opposing side were called 'focal' (F) since the relatively unimpaired arm performed the focal action, i.e. released the load. Electrode sites were cleaned with alcohol and the electrodes were placed on the muscle bellies, with their centers approximately 3 cm apart. The electromyographic (EMG) signals were amplified by means of differential amplifiers (×3000), and digitized with a 16-bit resolution at 1000 Hz.

Patients touched a touch pad with their paretic hand; the control subjects used their matched hand to apply a touch. Forces applied to the touch pad were recorded using a force sensor. A unidirectional force sensor (208A03, PCB Piezotronics, Inc.) was securely attached to the fortified walker (Fig. 1). A support pad ($6 \times 6\ \mathrm{cm}^2$) was mounted on top of the sensor to allow the paretic hand to be fully supported. The signals from the force sensor were amplified (M482M66, PCB Piezotronics, Inc.) and used to record the force applied by the subject's hand during the experiments. The sensitivity of the transducer was 2 mV/N; its linearity was better than 0.4%. The walker provided safety and was used for support during rest periods between successive series in the experiment. A chair behind the subject was available in case the subject needed an additional short rest (Fig. 1).

A PC with customized software based on the LabView-4.1 package was used to control the experiment and collect the data. The data were analyzed off-line with customized software based on the LabView-4.1 package.

2.3. Procedure

The experimental procedures were organized to test the effects of two factors, manual support and direction of

Fig. 1. Left panel shows a subject holding the load in front and touching the touch pad with the paretic hand. The experimenter is holding the load in between trials to prevent fatigue. During trials, the load was solely held by the subject and was released by quickly opening the hand. The right panel shows a load release at the side of a subject. Subjects were standing on a force plate while EMG signals from leg and trunk muscles were recorded on both sides of the body. The walker in front of the subject and the chair behind provided security and a rest between experimental series.

perturbation. There were two levels of the support factor, 'unsupported' and 'light support' and two levels of the direction factor: subjects either held the load in front (Fr), with the load at the midline of the body and the arm horizontal, or at the side (Si), with the arm abducted to a horizontal position. The order of conditions was fixed. The experiment always started with load release in the front without manual support, followed by the condition in which the subject supported him/herself by touching the support pad with the paretic hand. The same order was kept for the load release at the side.

In the initial position, the subjects stood on the force platform holding the load with the focal arm (in patients the relatively unaffected arm) in front of him/her (at the midline of the body) or to the side (Fig. 1). Subjects stood using their natural stance, i.e. no attention was paid to potential asymmetrical weight bearing, while the foot position was marked and monitored during the entire experiment. All the subjects used the same 2.23 kg load. The control subjects were required to use their left/right hand for load release based on matching to the focal hand of the individuals with hemiparesis.

In conditions with additional manual support, the upper part of the non-focal arm was oriented along the body while the forearm was held horizontal (elbow angle of 90°). Since the majority of the subjects with hemiparesis had a clawing hand, we were not able to have the subjects use their index finger for external support, thus they were required to touch the support pad with the palm of the hand. Similarly, the control subjects were required to use their palm while touching the support pad. The subjects were instructed to simply touch the support pad and not to apply force.

Gaze direction was specified by having the subjects look at the mark on the wall directly in front of the subject, at the eye level. The subjects were required to stand comfortably on the force platform, grab the load with their focal hand, wait for the computer-generated beep and release the load by a quick opening of the hand. The subjects were told to release the load in a self-paced manner, i.e. not to react to the tone signal immediately. Two to 3 practice trials were performed in each direction before the experiment. During practice trials, they were reminded to wait 1–2 s after the tone before the movement initiation. During off-line analysis, we made sure that no movements occurred during the first 500 ms after the tone. After the movement termination, the subjects were asked to wait for about 1 s, to grab the load, and then return to the initial position and wait for the next signal.

Data were recorded for 5 s following the computer-generated tone. Six trials were recorded for each condition. Within a series (condition), the time intervals between the trials were 10 s. The intervals between consecutive series were about 1 min. Fatigue was never an issue as the experimenter helped to hold the load in between the trials. For safety, an experimenter always stood by the subject and a walker was available in front of the subject in case he or she lost balance.

2.4. Data processing

During off-line processing, all signals were filtered with a 50 Hz low-pass, fourth order, zero-lag Butterworth filter, and all the EMG signals were rectified. Individual trials were viewed on a monitor screen (1 ms resolution) and aligned according to the first visible change in the acceleration trace that was associated with the start of a perturbation. This moment will be referred to as 'time zero' ($t_0 = 0$). All the trials from each condition were averaged for each subject separately and used for further analysis. In case no clear onset of perturbation could be determined, the trial was rejected. Across all subjects, this happened 8 times. For each condition, 4 or more trials were averaged.

Since the subjects performed the load release with either the left or the right arm, we classified muscles as either 'focal' (F) or 'non-focal' (NF) (in hemiparetic subjects, this corresponded to the relatively unaffected and affected arm, respectively). To capture both changes in the timing and magnitude of anticipatory muscle activity, we calculated EMG integrals (EMG) in the following manner:

$$\int \mathrm{EMG} = \int_{-100}^{0} \mathrm{EMG} - 2 \times \int_{-500}^{-450} \mathrm{EMG} \tag{1}$$

in which $\int$EMG is the integrated EMG activity from 100 ms prior to t_0 (-100 ms) to t_0 (0 ms) corrected for the baseline activity, $\int_{-500}^{-450}$EMG (Eq. (1)). For comparison across the subjects, $\int$EMG values for each muscle were divided by the integrated baseline activity ($\int_{-500}^{-450}$EMG) of the same muscle seen in the condition when the subject was holding the load in front of the body without manual support. Negative values correspond to a decrease in the background activity during APAs.

To compare differences in the baseline activity on the two sides of the body (for hemiparetic subjects, paretic vs. non-paretic sides), we calculated the asymmetry ratio R under the different conditions. The ratios were calculated for the time interval from -500 to -450 ms with respect to t_0, using the following equation:

$$R_{\mathrm{muscle}} = \frac{\int_{-500}^{-450} \mathrm{EMG}_{\mathrm{muscle}(F)}}{\int_{-500}^{-450} \mathrm{EMG}_{\mathrm{muscle}(NF)}} \tag{2}$$

Horizontal displacements of the COP in the anterior–posterior ($\Delta\mathrm{COP}_x$) and medial–lateral direction ($\Delta\mathrm{COP}_y$) were calculated using the following simplified approximation:

$$\Delta\mathrm{COP}_{x,y} = -\Delta M_{y,x}/F_z, \tag{3}$$

where ΔM is change in the moment with respect to its baseline value (defined as the average value within the time interval from -500 to -450 ms) and F_z is the time varying vertical component of the ground reaction force. This equation does not take into account possible changes in the shear force during the time of the analysis, since more accurate equation is:

$$\Delta \mathrm{COP}_{x,y} = (\Delta F_{x,y} R_z - \Delta M_{y,x})/F_z, \quad (4)$$

where R_z is the distance between the location of the force plate measurement origin and the force plate working surface.

We used the simplified Eq. (3) based on the result of a pilot study in which we calculated the difference between ΔCOP assessments obtained with Eqs. (3) and (4) in two control subjects. The results showed that the differences between ΔCOP calculations were, for different tasks, in range from 0.5 to 4%.

The forces applied to the touch pad could influence the displacement of COP, however, these forces remained relatively unchanged within the time window of COP displacement analysis. These changes ranged from 4.71 to 4.79 N, on average, 1 N corresponding to a maximal error of 0.6 mm in our assessments of COP shifts (see Section 3.1). We therefore assume that no significant error was introduced in assessments of COP displacements across the different conditions.

Since the subjects performed the load release with either the left or the right arm, in individuals with hemiparesis this depended on the side of the lesion, displacements of the COP in the medial–lateral direction were expected to be in opposite directions. Therefore, in subjects who released the load with the left arm, displacements in the medial–lateral direction were multiplied by -1 for comparisons across subjects.

Due to the electromechanical delay, changes in EMG activity precede force production by a few tens of ms (cf. Corcos et al., 1992). Therefore, changes in COP were expected to lag behind APAs (Aruin and Latash, 1995a,b). To quantify the effects of APAs, COP displacements were measured 50 ms after the onset of the perturbation ($\Delta \mathrm{COP}_{x50,y50}$).

Analysis of the forces applied to the touch pad during touch conditions included calculation of the absolute values of the forces at +50 ms after t_0. We also calculated the changes in force at +50 ms compared to the baseline level averaged from 500 to 250 ms prior to t_0.

2.5. Statistics

Statistical analysis included repeated measures analysis of variance (ANOVA) with 'support' and 'direction' as within subject factors and 'group' as a between subject factor. Also ANOVAs with 'support' and 'direction' as factors were used to test differences within each group separately. Post-hoc comparisons between individual levels were made using a Tukey's honest significant difference test.

3. Results

3.1. Forces applied to the support

All the subjects were able to use the touch pad support applying a relatively small force with the supporting hand. Control subjects applied a force of 4.01 ± 0.439 N for 'front-release condition' (Fr series) and 4.39 ± 0.96 N for 'side-release condition' (Si series) 50 ms after the time of load release (t_0). The patients applied forces of 5.8 ± 3.07 and 4.8 ± 2.26 N, respectively. Repeated measures ANOVA did not show differences in produced force 50 ms after t_0 for group[2] ($F_{1,15} = 1.767$; $P > 0.2$) or direction ($F_{1,15} = 0.100$; $P > 0.7$). The forces applied at t_0 +50 ms did not differ significantly from the baseline force (one sample t test; $P > 0.2$). These forces averaged across subjects and conditions never varied by more than 19% (under 1 N) from their baseline value. We do not present data on changes in COP at times longer than 50 ms after the onset of the load release since such data would likely reflect the action of not only APAs but also feedback-based corrective postural reactions. Besides, larger forces could be applied to the touch pad after +50 ms thus making our COP computation unreliable.

3.2. Anticipatory EMG patterns

Prior to load release, changes in the background activity of leg and trunk muscles were seen in both groups of subjects. Fig. 2A shows typical EMG patterns averaged across 6 trials by a representative control subject who was standing on the force plate and releasing the load in front of the body without manual support (left panels). Typically, there was an anticipatory increase in the activity of TA, RF and RA. Changes in RA activity could be very small. BF and ES showed a decrease in the activity, while SOL showed either a small inhibition or no change in the activity. APA patterns were subject-specific: in some subjects, there were no visible bursts in some of the muscles. In this particular subject, changes in the background activity of TA and RA were less pronounced. The left panels in Fig. 2B show similar data for a representative patient. As can be seen in Fig. 2B, the changes in muscle activity prior to the load release (APAs) in the patient were less pronounced.

In control subjects, a change in the direction of the perturbation induced significant changes in the APA patterns. When the load was released at the side, the control subject whose data are illustrated in Fig. 2A showed decreased inhibition of the non-focal SOL ($\mathrm{SOL_{NF}}$) and BF ($\mathrm{BF_{NF}}$) and of the focal BF ($\mathrm{BF_F}$) and ES ($\mathrm{ES_F}$) and decreased excitation in $\mathrm{RF_F}$ (compare the left and the right panels of Fig. 2A). Such modulation of APAs with the direction of the perturbation was less

[2] Due to a technical problem, we did not record force data in two subjects, one control and one patient.

pronounced or even absent in patients (compare the left and the right panels of Fig. 2B).

3.3. Effects of group, direction and manual support on APA activity

TA_F and TA_{NF}, RA_F and RA_{NF} showed no significant modulation with either group, direction of the perturbation, or additional hand support. Their activation patterns will not be discussed further.

Decreased changes in the background muscle activity prior to the unloading were seen in patients across all conditions. Fig. 3 shows averaged across subjects and all conditions EMG indices for both 'focal' and 'non-focal' muscles (RF, BF and ES) in patients and controls. No significant differences were observed in SOL between patients and controls. Note that the decrease in the muscle activity in the patients is mostly restricted to the impaired (non-focal) side. These differences were reflected in significant group effects in the following muscles: BF_{NF}[3] ($F_{1,17} = 15.40$; $P < 0.001$) and ES_{NF} ($F_{1,17} = 6.54$; $P < 0.05$). RF_{NF} showed a close to significant group effect ($F_{1,17} = 3.18$; $P < 0.1$). No significant differences were found in muscles on the relatively unaffected side.

In patients, the modulation of the APA magnitude with a change in the direction of the perturbation was smaller than in controls. Fig. 4 shows EMG integrals averaged across subjects of each group for selected muscles. In control subjects (light bars), there are significant differences ($P < 0.05$) in the magnitudes of APAs between the Fr (open bars) and Si series (lightly striped bars) for the following muscles: SOL_{NF}, BF_{NF}, RF_F, ES_F. In patients, such differences are absent or less pronounced (compare the black and dark striped bars). Note also that for ES_{NF} an opposite pattern is seen. That is, there is a change in the muscle activity during APAs in patients between the Fr and Si series, while in controls the APA magnitudes are similar.

Small changes in APAs with additional hand support were seen only in SOL_{NF}, BF_{NF} and ES_{NF}. In these muscles, an increase in the inhibition with manual support was typically seen in control subjects. In patients an opposite pattern, that is, a decrease in the inhibition of these muscles was seen (these findings are not displayed in Fig. 2A,B).

The above observations are supported by group x direction interactions significant for SOL_{NF} ($F_{1,17} = 9.05$; $P < 0.01$) and BF_{NF} ($F_{1,17} = 17.01$; $P < 0.001$). ES_F showed a close to significant interaction ($F_{1,17} = 3.37$; $P < 0.09$). Subsequent ANOVAs for patients and control subjects separately confirmed that APA EMG activity between Fr and Si conditions in SOL_{NF}, RF_F, BF_{NF} and ES_F showed significant differences between touch and no touch conditions in controls but not in patients.

[3] The differences between controls and subjects were not confounded by an increased variability in the $\int$EMG responses in the patients. No significant differences in variability between controls and subjects in any of the muscles were found.

Integrated EMGs for SOL and ES on both the 'focal' and 'non-focal' sides showed in control subjects and patients different changes with manual support. As can be seen in Fig. 5, SOL_{NF} and ES_{NF} show an increase in the inhibition with manual support in control subjects (compare white and light striped bars). In patients, a decrease in the inhibition was observed with touch (compare the black and dark striped bars). In 'focal' muscles, this pattern was less pronounced. Changes in APA patterns with manual support were reflected in a significant group × support interaction for SOL_{NF} ($F_{1,17} = 5.89$; $P < 0.05$) and a close to significant interaction for ES_{NF} ($F_{1,17} = 3.66$; $P < 0.08$).

3.4. EMG baseline ratios

Ratios of integrated EMG activity in 'focal' and 'non-focal' muscles were calculated to compare changes in the symmetry of baseline activity across conditions (R-ratio, see Section 2). No main effects of group were found for any of the muscles. However in patients (in some muscles; RF, RA and ES), the 'focal' muscle was more active than the 'non-focal' muscle in Si series and not in Fr series. In control subjects, 'focal' muscle was more active than the 'non-focal' muscle only for the Fr series. A significant group × direction interaction ($F_{1,17} = 5.36$; $P < 0.05$) confirmed this pattern.

3.5. Differences among subjects with hemiparesis

Based on the subject characteristics, we divided the patients into two subgroups. Three subjects (#1,2,5; see Table 1) showed higher scores on the Ashworth scale (2.56 ± 0.11 SD). These subjects showed a decreased inhibition in SOL_F (subgroup × support: $F_{1,8} = 6.61$; $P < 0.05$), and a reduced modulation of APAs with manual support in RF_{NF} (subgroup × support: $F_{1,8} = 9.84$; $P < 0.05$) compared to the other individuals with hemiparesis.

In ES_F, the 3 patients with higher Ashworth scores showed an increased inhibition during APAs in Si series, while the less impaired patients showed a decrease in the ES_F inhibition (subgroup × direction: $F_{1,8} = 5.73$; $P < 0.05$). This decrease in ES_F inhibition found for the less spastic hemiparetic patients was similar to the pattern seen in control subjects (see Fig. 4, bottom panel).

3.6. COP displacements

Fig. 6 shows COP time series, averaged across 6 trials, for a representative control subject (left panels), and a representative patient (right panels), for both Si (bottom panels) and Fr series (top panels). Shortly after the load release, COP displacements in both anterior–posterior (COP_x) and medial–lateral directions (COP_y) showed clear modulation with the direction of the perturbation in both controls and individuals with hemiparesis. Repeated measures ANOVAs showed main effects of direction for both ΔCOP_{y50} ($F_{1,17} = 20.17$; $P < 0.001$) and ΔCOP_{x50} ($F_{1,17} = 34.38$; $P < 0.001$). As can be seen in Fig. 6, COPy(m–l) shifted

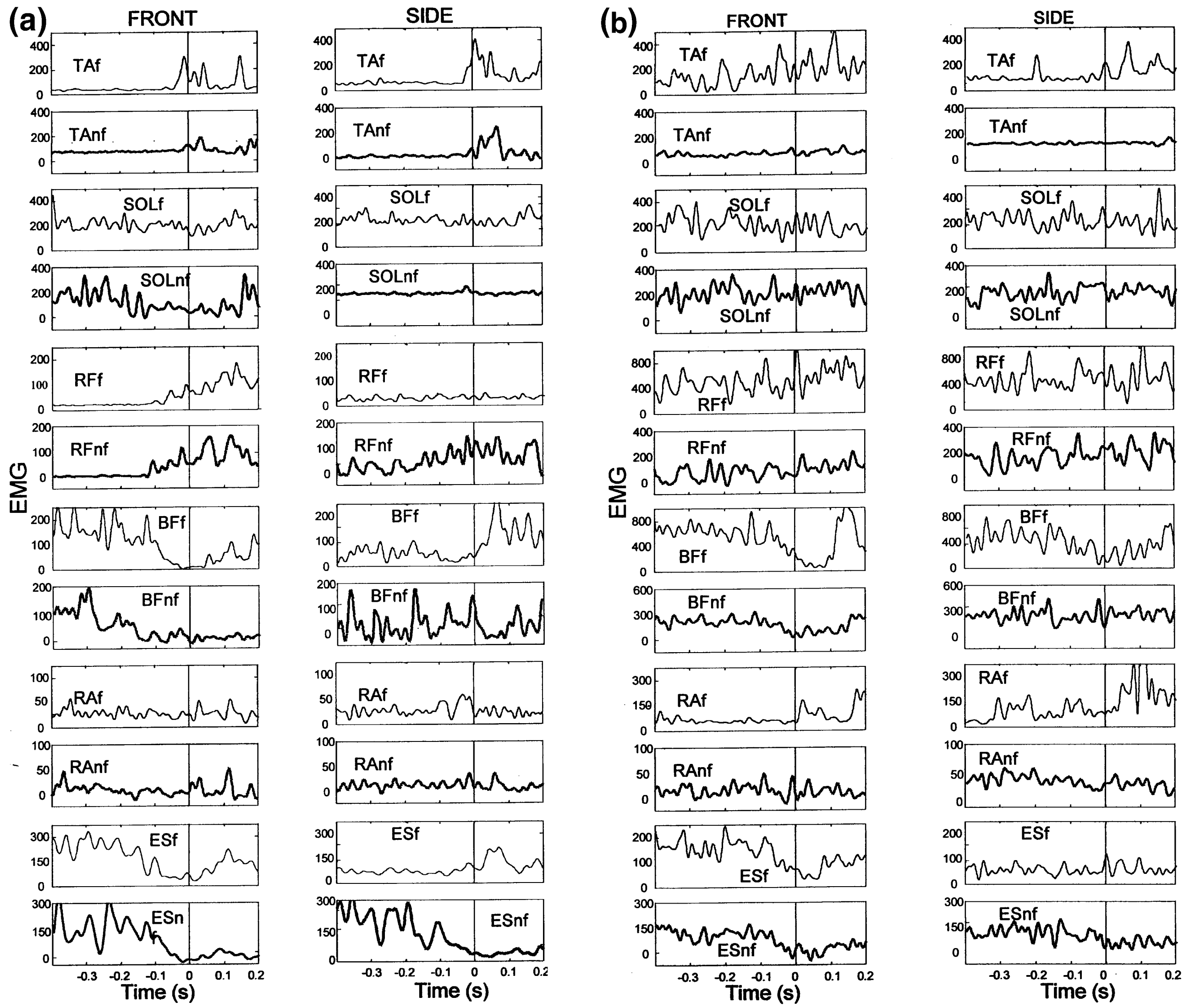

Fig. 2. (A) Typical EMG patterns averaged across 6 trials by a control subject releasing a load in the front (left panels) and at the side (right panels). The subject was standing unsupported. Shown is the activity of focal (F) and non-focal (NF) muscles. TA, tibialis anterior; SOL, soleus medialis; RF, rectus femoris; BF, biceps femoris; RA, rectus abdominis; ES, erector spinae. The time of load release is shown with the vertical line ($t = 0$). Note that EMG activity prior to the load release is reduced with load release at the side compared to load release in the front. Compared to load releases in the front SOL_{NF}, BF_F, BF_{NF} and ES_F show a decrease in the inhibition with a load release at the side. RF_F shows a drop in the excitation with the change in task. EMG scales are in bits. Time scale is in s. (B) The same EMG patterns for a representative individual with hemiparesis. Note that changes in the muscle activity prior to the movement onset are less pronounced as compared to the control subject (Fig. 2A). Also, changes in the EMG activity with the direction of the perturbation are diminished (compare left and right panels).

towards the side of load release during the Si series while this was seen to a lesser extent in Fr trials. During Fr series, COPx(a–p) moved forward while no such displacements were seen with load release at the side. Shown in Fig. 7 are the values of COP displacement during Fr and Si series for both individuals with hemiparesis and control subjects. No differences between controls and patients and between conditions of manual support were found.

4. Discussion

In the present study, we confirmed some of the previous observations related to changed APAs in patients with hemiparesis and, for the first time, investigated the ability of such patients to modulate APAs with changes in the direction of a self-triggered perturbation and with an additional sensory cue. Earlier studies of APAs in different patient populations used fast arm movements to induce postural perturbations (Badke and Di, 1985; Garland et al., 1997; Horak et al., 1984). This method has both advantages and drawbacks. In particular, postural perturbations induced by fast arm movements apparently depend on the acceleration profile of the movement, which in turn depends on the ability of the subject to perform fast movements. This problem has been partly avoided by asking control subjects to perform

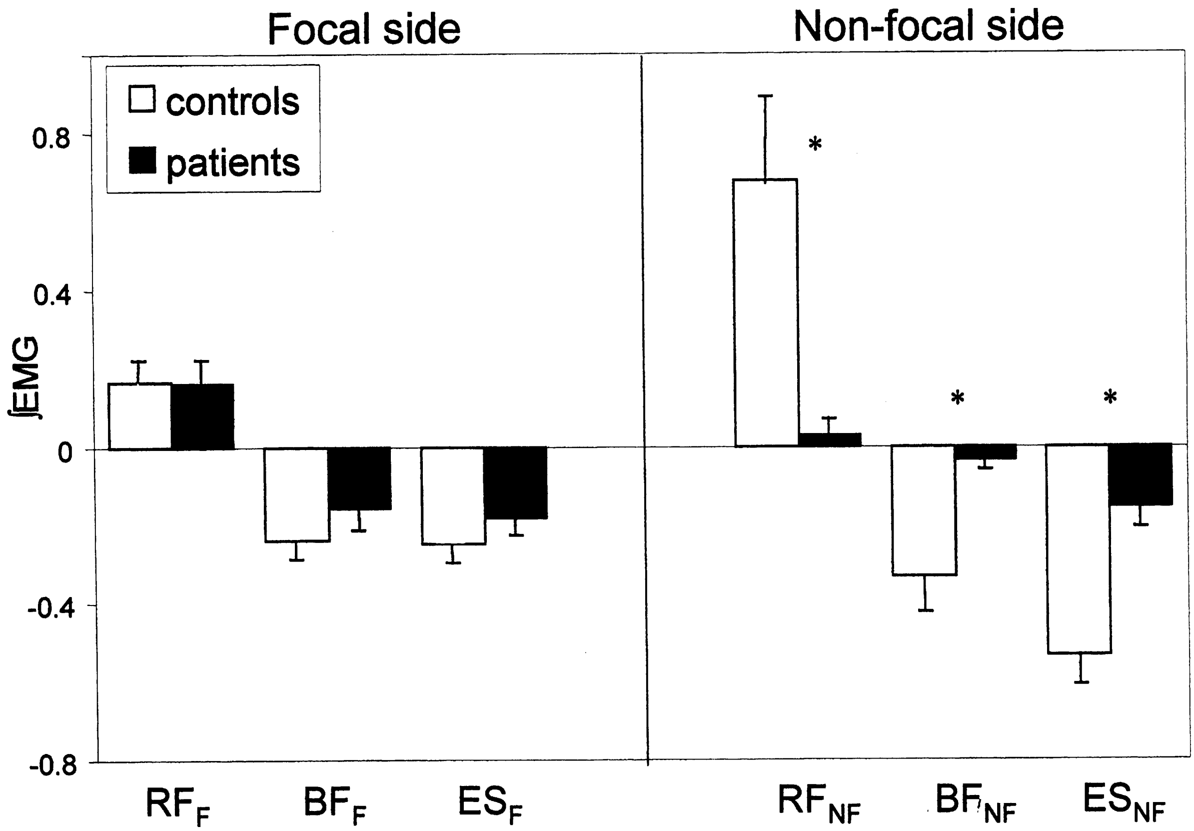

Fig. 3. Shown are values of normalized integrated EMG averaged across control subjects (dark bars) and across patients (light bars) for support and direction conditions with standard error bars. Differences between control subjects and individuals with hemiparesis were seen mostly on the non-focal side (NF), the paretic side in patients. APA activity is in general decreased in individuals with hemiparesis as compared to control subjects. Abbreviations are similar to the ones in Fig. 2. ∫EMG is dimensionless. Significant differences are denoted with asterisks.

movements at comparable speeds. However, the relationship between movement speeds and associated APAs is non-linear such that at low speeds no APAs are seen. Thus, this method has inherent limitations in providing information about possible changes in APAs in subjects whose ability to perform fast movements is significantly impaired.

In this study, as well as in some earlier studies (Aruin and Latash, 1995b, 1996; Aruin et al., 2001; De Wolf et al., 1998) we used a method of self-triggered unloading. This method induces a standard perturbation whose magnitude does not depend on the ability of the subject to move fast. It is also associated with pronounced APAs whose patterns have been described and studied in detail (Aruin and Latash, 1995b, 1996). Using this method in stroke patients, whose ability to move fast may be impaired, we have been able to observe not only a general decrease in APAs in such patients but also more subtle features such as a reduced ability to modulate APAs.

4.1. Reduced APAs in individuals with hemiparesis

Patients after stroke have been reported to show patterns of early postural adjustments prior to 'fast' arm movements qualitatively similar to those seen in healthy subjects performing movements at similar speeds (Horak et al., 1984). However, there were also reports of changes in the timing of the APAs in leg and trunk muscles so that they occurred later, particularly on the paretic side (Hedmann et al., 1997; Horak et al., 1984). An inability to generate APAs was mentioned in a study of patients with frontal lobe lesions (Gurfinkel and El'ner, 1988) and in patients with supplementary motor area (SMA) lesions (Massion et al., 1999; Viallet et al., 1992). Wiesendanger et al. (1987) described patterns of APAs in individuals with hemiparesis who learned a novel load-lifting task. While those subjects showed relatively unimpaired APAs in a natural load-lifting task, they showed a deficit in the acquisition of new APA patterns.

We observed smaller APAs in the paretic postural muscles of the patients prior to releasing a standard load in front of the body while no similar changes were seen in the postural muscles on the other, less impaired side of the body. Control subjects typically showed symmetrical patterns of leg/trunk muscle activation of the two sides of the body (Aruin et al., 2001).

Because of the generally small APAs in the patients, we could not reliably detect the moments of APA initiation and

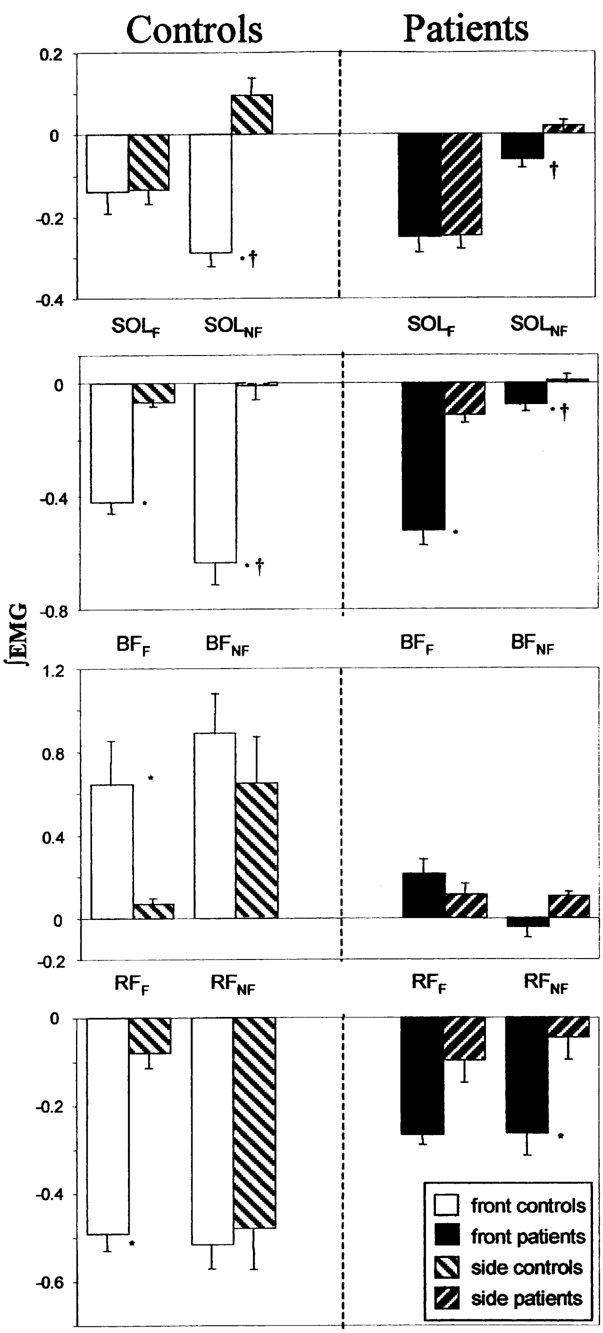

Fig. 4. Integrated EMG for control subjects (left bars) and subjects with hemiparesis (right bars) with standard error bars. Series in which the load was released in the front are shown in solid bars (black and white), while series in which the load was released at the side are shown with striped bars. In SOL$_{NF}$, BF$_{NF}$, RF$_F$, and ES$_F$ the difference in APA activity between the front and side releases is reduced in individuals with hemiparesis compared to the controls. ES$_{NF}$ shows an opposite pattern; in control subjects there is no difference between the front and side releases, while in patients there is. *Significant difference within group (control/patient). †Interaction direction × group ($\alpha = 0.05$).

perform a formal analysis of possible changes in the APA timing. However, these changes were apparent in both leg and trunk muscles (see Fig. 2). These observations are rather different from those reported by Dickstein et al. (1999) in their study of voluntary trunk movements, where similar levels of axial muscle involvement on the two sides of the body and the preference for co-contraction patterns of muscle activation were observed.

It has been reported that in paretic muscles, the force–EMG relation is changed such that less force in generated per unit of muscle electrical activity (Tang and Rymer, 1981). Therefore, a smaller integral EMG index in a paretic muscle is likely to be associated with an even larger decrease in force. In earlier studies of APAs associated with lateral and rotational perturbations (Aruin et al., 2001; Shiratori and Latash, 2000), we saw that such perturbations were associated with asymmetrical changes in the activity of the leg and trunk postural muscles on the two sides of the body.

Differences in the impairment of proximal and distal muscles have been reported in individuals with hemiparesis (Adams et al., 1990; Benecke et al., 1983; Colebatch et al., 1990; Turton and Lemon, 1999; Warabi et al., 1990). Reduction in strength is commonly more apparent in distal muscles (Adams et al., 1990), which has been explained by differences in the cortico-spinal projections to motoneuronal pools innervating proximal and distal muscle groups (Bene-

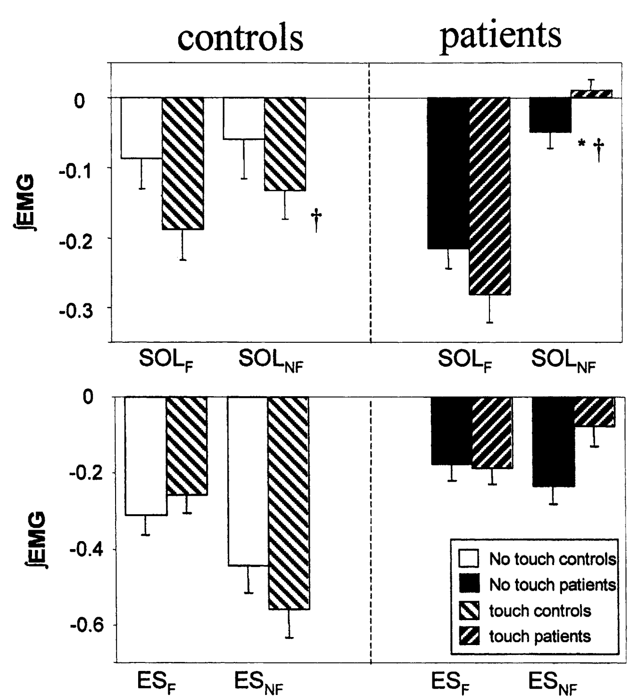

Fig. 5. Integrated EMGs for SOL and ES on the 'focal' (F) and 'non-focal' (NF) sides of the body, averaged across subjects with standard error bars. During APAs, control subjects showed an increased inhibition in SOL$_{NF}$ and ES$_{NF}$, in patients the inhibition in these muscles decreased. In focal muscles, this pattern is less clear. *Significant difference within group (control/patient) ($\alpha = 0.05$). †Interaction direction × group ($\alpha = 0.05$). For abbreviations, see Fig. 2.

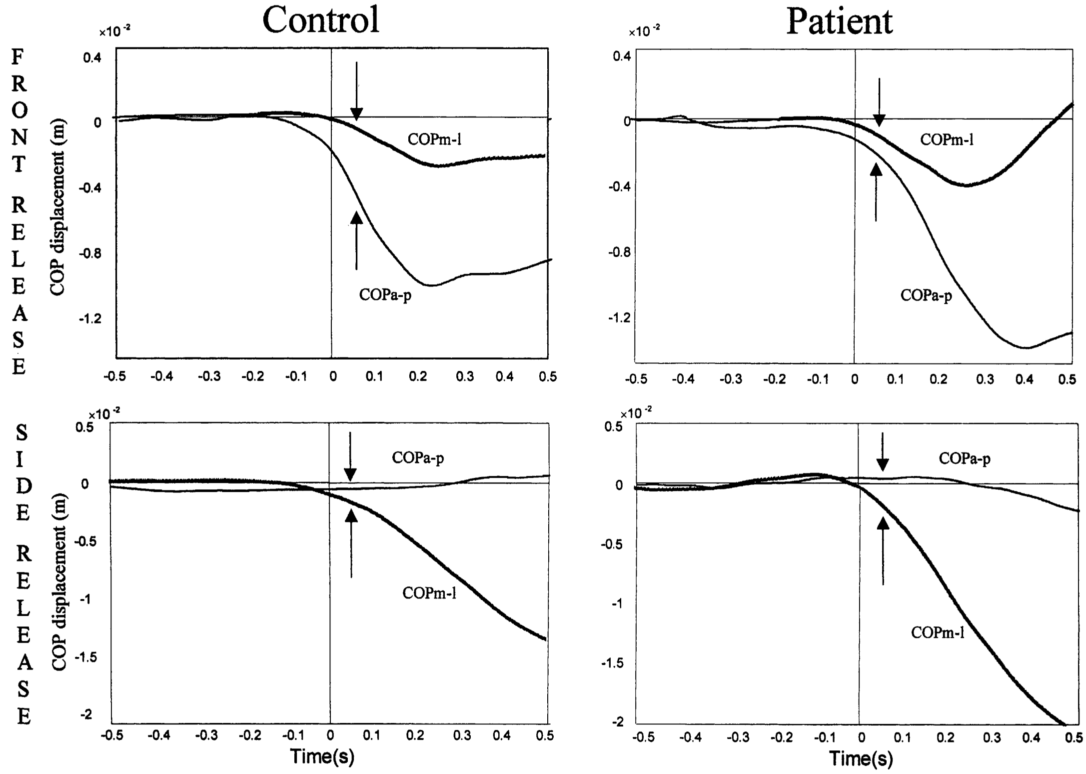

Fig. 6. COP traces in a representative patient (right panels) and a control subject (left panels) for load release in the front (top panels) and at the side (bottom panels). Note that displacements in the medio-lateral (COPm–l thick traces) direction are smaller for load release in the front, while anterior–posterior displacements (COPa–p thin traces) are smaller with load release at the side. Negative values correspond to displacements forward and to the side of the load release.

cke et al., 1983; Colebatch et al., 1990; Turton and Lemon, 1999; Warabi et al., 1990). Contrary to these results, our analysis of APAs shows no clear differences in the magnitude and modulation of APA patterns in proximal (RA and ES) or distal (TA and SOL) muscles.

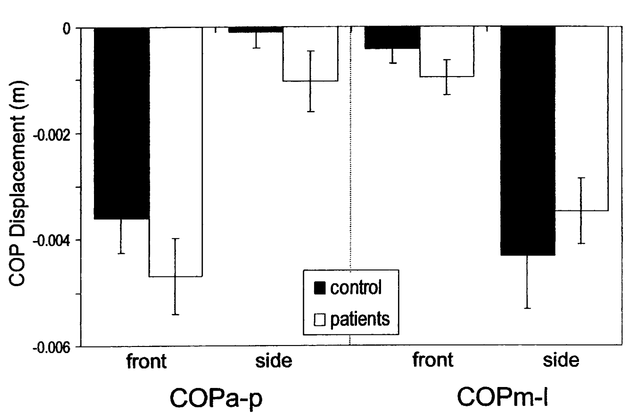

Fig. 7. Averaged across subjects, values of COP displacements during load releases at the side and in the front for controls and patients. COP displacements 50 ms after the onset of the perturbation (COPa–p, m–l) were decreased for COPa–p (anterior–posterior) during Fr series and for COPm–l (medial–lateral) during Si series. No significant differences between patients and controls were observed. Negative values correspond to displacements forward and to the side of the load release. Displacements are in m.

The differences in APAs in patients and controls were not accompanied by significant differences in COP displacements between these groups. Changes in the background activity of postural muscles (APAs) have been shown to be more sensitive to changes in the task or to a neurological disorder than displacements of the COP (Bouisset and Zattara, 1987; De Wolf et al., 1998). The significant changes in the postural muscles with no comparable changes in COP displacements could also mean that individuals with hemiparesis were able to deal effectively with the perturbations by using alternative strategies. We emphasize this point later (Section 4.3).

4.2. Altered modulation of APAs in individuals with hemiparesis

Providing external support and/or sensory cues is an important component of motor rehabilitation of patients after stroke (Aruin et al., 2001; Glanz et al., 1997; Schwartz et al., 1999). Therefore, we view as particularly important our observations of the reduced ability of such patients to modulate their APAs with changes in task requirements and with an additional sensory cue (light touch).

Healthy individuals have been shown to be able to modulate APAs with changes in the direction of fast voluntary arm movements (Aruin and Latash, 1995a) as well as with changes in the direction of a force pulse applied against an external object (Aruin et al., 2001). The patients, however, showed a markedly decreased ability to adjust their APA patterns to changes in the direction of the perturbation. These impairments were seen mostly in the 'paretic' postural muscles. ES in the paretic side showed an opposite pattern: while no modulation of APAs with the direction of the perturbation was seen in the controls, differences between front and side release conditions were observed in the patients. This suggests an adaptation involving less impaired proximal muscles, ES, to a larger degree, while in controls mostly the activity in distal muscles was modified.

There were also signs of a decrease in the ability to modulate APAs in 'non-paretic' muscles, in particular in RF and ES. These observations speak against a hypothesis by Horak et al. (1984) that changed APAs on the 'non-paretic' side partly compensate for the inadequacy of APAs in 'paretic' muscles and are more in accordance with the results of Massion et al. (1999) who showed that APAs in the unaffected arm of hemiparetic patients were similar to those seen in healthy individuals.

Bennis et al. (1996) reported task dependent modulation of APAs in patients after stroke associated with catching a load, which was lower than in healthy subjects. However, this study looked only at changes in the background activity of arm muscles and did not study postural stabilization during standing. The apparent differences between our results and those reported by Bennis et al. (1996) may be due to different changes in control mechanisms of vertical posture and of upper limb posture in individuals with hemiparesis.

A light finger touch has been shown to lead to a decrease in postural sway in standing healthy subjects (Jeka and Lackner, 1994) and also in patients with vestibular disorders (Lackner et al., 1999). It has been shown that light touch is also associated with a marked decrease in APAs in young healthy adults (Slijper and Latash, 2000). This observation suggests that APAs are generated taking into account not only expected parameters of an upcoming perturbation (cf. Bouisset and Zattara, 1987) but also sensory signals reflecting the general stability of the body (cf. Riley et al., 1997). In the previous study (Slijper and Latash, 2000), we compared the effects of touch and of firm grasp on APAs in leg and trunk muscles and found no differences, i.e., both led to similar reductions in APAs as compared to unsupported standing.

In the present series of experiments, we found that APAs in control subjects were increased, while in our previous study we found a decrease in APA activity. How can this difference be reconciled? In the previous study, we found a decrease in the excitation of both dorsal and ventral muscle groups with an additional touch and we showed that these changes were similar in magnitude, decreasing the co-activation around the joints. The postural response was in this sense more 'task-specific' and efficient. In the current experiment, the sudden redistribution of mass was counteracted by an anticipatory decrease in activity in the dorsal muscle groups and a subsequent increase in anticipatory activity in ventral muscle groups. A reduced co-activation as seen in the previous study could be accomplished by an increased inhibition in dorsal muscle groups, alleviating the necessity of additional bursts of activity in ventral muscle groups. Responses in both experiments could in this sense be viewed as similar.

The ability to modulate APAs with finger touch was altered in patients. This observation may potentially result from two factors. First, the patients are likely to have impaired sensation in the paretic arm so that the touch is less efficient in providing a reliable sensory cue (Holden et al., 1994; Jeka and Lackner, 1994). This possibility is compatible with the reported involvement of the somatosensory cortical areas in impaired APAs (Birjukova et al., 1989; DeWald et al., 1995).

Finger forces during our present experiments were higher than those in studies by Jeka and his colleagues (Jeka and Lackner, 1994; Jeka et al., 1998) and also somewhat higher than those in the previous study of healthy subjects (Slijper and Latash, 2000). The impaired control of the upper extremity in our patients prevented them from limiting the contact forces to under 1 N (as in Jeka's studies). While the typical absolute magnitude of the contact forces was potentially able to contribute to postural stabilization during quiet standing, its changes during APAs were very small (under 1 N) such that they could not contribute significantly to changes in the COP position within our typical window of analysis.

4.3. Possible role of adaptive postural strategies

The fact that the different APAs patterns in postural muscles in controls and individuals with hemiparesis were not accompanied by differences in COP displacements suggests that subjects could have used different strategies of postural stabilization.

For instance, in our experiments, we allowed the subjects to stand comfortably. It is known, however, that individuals with hemiparesis typically reduce the loading of their paretic side by shifting their body weight to the non-paretic leg (Bohannon and Larkin, 1985; Chaudhuri and Aruin, 2000; Dettmann et al., 1987; Pai et al., 1994). Actually, an important component of motor rehabilitation of stroke patients is to make them distribute their body weight more symmetrically on the two legs (e.g. Nichols, 1997). It has been shown in a recent study (Aruin et al., 2000) that using mechanical means to improve the symmetry of weight distribution in stroke patients may be an effective tool to overcome this difference in stance from healthy people.

An earlier study of APAs in below-the-knee amputees has demonstrated characteristically asymmetrical APAs in the upper leg and trunk muscles of the two sides of the body (Aruin et al., 1997). These differences were interpreted as reflections of an adaptive strategy in such patients who obviously were unable to use the lower leg muscles in a symmetrical way: the patients shifted the weight to the intact leg just prior to making a fast movement, and used APAs in the contra-lateral to the amputation side of the body, while the prosthetic leg was used more like a cane.

The mentioned weight shift towards the 'non-paretic' side in stroke patients suggests that they may also employ a similar adaptive strategy, i.e. generating asymmetrical APAs in the muscles on the two sides of the body. As it has been suggested for individuals after a below-the-knee amputation (Aruin et al., 1997), it seems that the central nervous system of an individual with hemiparesis avoids excessive use of the muscles in the affected limb even when the task requires it, i.e. when subjects released the load at the contralateral side. Moreover, the reduced/altered modulation of APAs in patients makes them maladaptive to the ever-changing environmental requirements for postural stabilization. This could, in turn, slow their recovery from stroke and lead to an increased risk of falling.

Acknowledgements

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