Exp Brain Res (1999) 124:137–144

RESEARCH ARTICLE

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Lateral balance organisation in human stance in response to a random or predictable perturbation

Received: 13 October 1997 / Accepted: 17 July 1998

Abstract The effect of the predictability of perturbation to standing balance was evaluated in terms of the muscle activity and response dynamics of five subjects exposed to horizontal forces at the pelvis producing sideways or forward sway. Rapid (EMG onset latencies of 70–80 ms recorded from the left gluteus medius and gastrocnemius) and qualitatively different patterns of response were produced by forward pushes and pushes to either side. However, the EMG response to left push was constant in pattern and timing, whether the push direction was constant and, therefore, predictable over a block of trials or whether the left push trials were interleaved randomly with right push or forward push trials. Moreover, there were no systematic effects of perturbation direction uncertainty on the latency and rate of increase of ground reaction forces. We conclude that prior information does not speed postural responses that differ quantitatively according to the direction of perturbation to balance.

Key words Lateral balance · Perturbation direction · Predictability · Normal subject · Muscle synergy

Introduction

The human postural response to a balance perturbation is fast compared to voluntary reaction time and, thus, might be considered automatic (Nashner and Cordo 1981). However, this should not be taken to imply that the postural response is simpler than a voluntary choice response. The postural response to a balance perturbation usually engages many muscles distributed over the whole body with characteristic spatiotemporal patterning (Nashner 1977). Moreover, the perturbation typically results in sensory input over multiple pathways, and this must be integrated if an appropriate response is to be generated (Gurfinkel and Levick 1991). Such complexity suggests a role for supraspinal (possibly cortical) centres, which is consistent with latencies that are longer than spinal reflexes (e.g. Nashner 1977). Supraspinal contributions presumably provide the basis for higher-level, strategic influence on postural responses based on predictions from prior experience.

In order to elaborate on the role of prior experience, sometimes referred to as “central set” (Brooks 1984; Evarts 1975), Horak et al. (1989) contrasted predictable and unpredictable amplitude of perturbation to balance. With predictable perturbation, Diener et al. (1988) had shown that a change in a parameter of perturbation, such as amplitude of movement of the support surface, leads to a correlated change in EMG response amplitude without a change in spatiotemporal pattern of the response. Horak et al. (1989) found that, when perturbation amplitudes are randomised within a block of trials and are therefore unpredictable, spatiotemporal organisation remains unchanged, but the quantitative adjustment (scaling) of the early EMG response to postural perturbation amplitude disappears. In fact, with perturbations in an unpredictable order, early muscle activity was approximately half-way between the extremes obtained in the predictable situation (but, see Beckley et al. 1991). Why is the early EMG response not scaled with random amplitude? One possible reason is that scaling would require an extra delay in order for sensory information about the perturbation to become available, whereas a default middle level allows an earlier response to be made, which can then be corrected later on the basis of further processing of the incoming sensory information.

The idea of correction of a default postural response was raised by Nashner (1976). However, he was concerned with selection between postural responses that differed qualitatively, i.e. in spatiotemporal terms, rather than quantitatively, i.e. in terms of scaling. In a paradigm in which balance was perturbed in different conditions by support surface translation or rotation, there were unex-

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pected changes of condition between blocks of trials. Over the first few trials in a new block, the postural response changed progressively towards the qualitatively different spatiotemporal organisation suitable for the new condition (but, see Hansen et al. 1988). Nashner (1976) described this change as an adaptation of a reflex. He suggested that integration of several sources of sensory information leads to correction, after some delay, of the initial response, which had been based on the inappropriate pre-programmed response suited to the previous condition. Repeated trials in the new condition allow the development of the correct, new pre-programmed postural response.

Another situation in which two different types of perturbation require qualitatively different postural responses is forward and backward translation of the support surface. A study that examined the effects of predictability of direction of perturbation on postural responses was described by Badke et al. (1987). These authors looked at balance perturbation with directional uncertainty as a possible component of a programme for rehabilitation of hemiparetic stroke patients. They did not document the detailed spatiotemporal pattern of the postural reponse for forward and backward translation. However, they reported that, when the stroke patients were provided with a cue as to the direction of a forthcoming perturbation, their muscle burst onset latencies were significantly shorter than when they were uncertain about whether the perturbation would be forwards or backwards. A similar trend was also apparent in normal control subjects, but the latter result was not statistically significant. More recently, Diener et al. (1991) examined the effects of uncertainty on qualitatively different postural responses elicited by forward or backward tilt of the support surface. Normal controls, patients with cerebellar disease and Parkinson patients were tested. In contrast to the finding of Badke et al. (1987), none of the subjects in the Diener et al. (1991) study showed any difference in latency or form of the EMG with advance information provided in the form of a cue to the forthcoming perturbation.

In the present study, we sought to resolve the question whether, in normal subjects, prior information speeds postural responses that differ qualitatively according to the direction of the perturbation to balance. Unlike the two preceding studies, we used force applied horizontally to the pelvis to produce perturbations, whose effects include the possibility of sideways or forwards sway. We used force at the pelvis because it allowed us to examine the relatively pure stimulus of onset of sustained force (Wing et al. 1993, 1995). In contrast, the previous studies used constant-velocity platform displacement, which constitutes a more complex perturbation to balance – forces associated with acceleration are closely followed by opposite forces associated with deceleration. We used sideways perturbations because they allowed us to apply perturbations of equal difficulty in either direction. For biomechanical reasons, it is difficult to equate forwards/backwards perturbation in terms of amplitude and threat to balance. With equal levels of perturbing forwards or backwards force, subjects may favour preparation for backwards perturbation when uncertain, since backwards sway is harder to correct. With equally probable sideways perturbations, there is no reason to expect such a bias. The effect of the predictability of perturbation direction was analysed by comparing the response to left sway in conditions with push always to the left, unpredictably to the left or right or unpredictably left or forward. Muscles important in resisting left push to the pelvis include the left hip abductor, gluteus medius, and the left ankle plantarflexor, gastrocnemius (Jenner et al. 1995; Kirker et al. 1995). In forwards push, bilateral activation of the gastrocnemius will be of primary importance.

We consider two possible outcomes to the introduction of uncertainty of push direction, which are not necessarily mutually exclusive. One possibility is that the onset of the postural response might be delayed to allow time for the direction of perturbation to be determined and the correct alternative of two possible response patterns to be selected. With a delayed response, greater levels of muscle activation would be expected to make up for the additional sway likely to result from the delay. The second possibility is that, with left-right direction uncertainty, subjects might co-contract the gluteus medius on each side of the body [not unlike a form of ‘mid-level’ activation, as in Horak et al.’s (1989) amplitude-uncertain condition]. With non-linear length-tension functions on either side of the equilibrium position (cf. Feldman 1986; Wing et al. 1995), co-activation would result in a net gain of stiffness in the frontal plane, and thus increase resistance to left or right push in a non-specific manner. Where the uncertainty is between left and forwards push, co-contraction in the hip abductors might be supplemented by co-contraction of both ankle plantarflexors and dorsiflexors. Once perturbation direction has been ascertained, the inappropriate muscles might then be suppressed. To assess co-contraction under uncertainty, we ask whether, after perturbation onset, muscles relevant to the alternative direction are recruited earlier than when it is certain that the alternative will not occur? We also report amount of muscle activity, determined from integrated EMG; under uncertainty, after perturbation, is there increased recruitment of muscles relevant to the alternative direction compared with when it is certain that the alternative will not occur? As an index of the effect of the muscle recruitment patterns in resisting the applied force at the pelvis and reducing sway, we also report the development of ground reaction torque.

Materials and methods

Five adult human subjects, three males and two females aged 29–48 years, without neurological or orthopedic limitations, participated in the experiment. Three of the subjects (S1-AMW, S2-MG, S4-SGK) were the authors. All subjects gave their informed consent for the protocol according to the requirements of the local ethical committee.

Subjects stood erect, with their weight equally distributed on both feet and their arms hanging at their sides. Their feet were placed so that the outer edges were 27 cm apart on a 6-axis force platform (Bertec), which was used to measure ground reaction forces and torques. Perturbations to balance were delivered by two force-servoed linear motors (Linear Drives) mounted at right angles. The motors were connected to the subject via a 6-axis load cell (ATI Technologies) attached to a semirigid belt worn around the pelvis just below the iliac crest. Position of the pelvis in anteroposterior (AP) and lateral (LAT) direction was measured by the linear motors. Surface EMG was recorded with 10-mm electrodes spaced 30 mm apart on the medial gastrocnemius (Gas), gluteus medius (GM), abdominal (Abdo) and paraspinal muscles (PS muscles at the level of the iliac crest) on each side of the body. Kinetic, kinematic and EMG data were digitised at a sampling rate of 1000 Hz and stored for subsequent off-line analysis.

On successive pairs of trials, balance was perturbed by application and removal of a horizontal push force (4% of body weight) applied to the pelvis by the linear motors. Application of force began 0.3 s after an auditory signal, took 8 ms to change level and was sustained for approximately 3 s. During the push, subjects had to resist the applied force to keep their initial posture and minimise sway (defined as displacement of the pelvis). On the following trial, when the force was withdrawn, subjects had to terminate their resistance promptly to limit the tendency to sway in the reverse direction (data from these trials were not analysed). Between trials, subjects were encouraged to keep the pelvis in a consistent position in the transverse plane. Between blocks of trials, subjects were allowed to lift either foot for relaxation; but, if they did this, they had to replace in the same position using markings on the platform.

Uncertainty of perturbation direction was manipulated across three conditions; in one, the direction was predictable; in the other two, it was unpredictable. In the predictable condition, the perturbation was always a push to the left (left push only or LO). In the unpredictable conditions, forces were applied in one of two pairs of directions, either left/forward (LF) or left/right (LR). Condition LF was composed of an equal number of left and forward pushes. Condition LR was composed of an equal number of left and right pushes. Each condition contained a series of 20 pushes in each direction, occurring in random order. The order of the conditions was LO, LF, LR. At the end of the session, the predictable LO condition was repeated as a control (LOC) for possible fatigue effects.

For each condition, kinematic, kinetic and EMG data were collected for a period of 1.3 s, starting 0.3 s before the perturbation. Amplified EMG signals were band-stop (48–52 Hz) and band-pass (3–500 Hz) filtered (4th order Butterworth) and rectified. Kinematic data were low-pass filtered at 10 Hz.

The effect of uncertainty of perturbation direction was examined using an interactive display programme in terms of a number of individual trial measures of the response to left push in each of the three conditions. AP and LAT *positions* of the pelvis were determined as the average of each measure taken over the whole trial. LAT *displacement* was taken as the difference in positions at initial baseline and peak excursion. The *delay* in the rise of torque about the AP axis (Map) following push and the *maximum amplitude* were determined from the ground reaction force/torque traces. The *average rate of change* of Map was computed from the maximum amplitude divided by the time interval between Map onset and maximum amplitude. Muscle onset *latency* was obtained using rectified EMG traces from individual trials. *Amplitude* of muscle activity was determined by integration of the rectified EMG (iEMG) trace, in either short (25–100 ms) or medium (100–175 ms) latency windows. To compare the amplitude of the iEMG response across the three conditions using the results from all subjects, we normalized each muscle's activity in LF and LR by the amplitude in LO. Specifically, we divided the iEMG amplitude obtained on each trial in each window by the mean amplitude of the 20 LO trials for the corresponding window. If the activity was the same for each condition, this would yield a value of 1.

Results

All subjects maintained their equilibrium against the applied force in all conditions without needing to take a step. Figure 1 shows the average response (20 trials) of one subject (S1) to each of the three directions of push. The top trace shows the force applied to the pelvis. The onset of the push force was the time zero for muscle response measure.

With left push, there were clear bursts of activity in GM and Gas of the left leg with, initially, inhibition of the corresponding muscles in the right leg, following shortly thereafter by increased activity in right GM. With the exception of the left Abdo, which showed an early increase, there was, initially, inhibition of the trunk muscles followed later by a period of elevated activity. Push to the right elicited a complementary pattern of activity to that seen in push to the left. In particular, it should be noted that, as with left push, GM exhibited a particularly marked burst of activity. With forward push, there was little or no response in either GM, whereas both Gas showed early increase in activity. There were also symmetric increases in activity of Abdo with inhibition of PS. Similar patterns of leg-muscle activity differentiating between the three directions of push were seen in all subjects. However, the response of Abdo was not so consistent; two of the five subjects exhibited clear symmetric patterning of left and right Abdo on forward push, but only one revealed clear activation of left (right) Abdo on push to the left (right). In the following, we concentrate on the response of GM and Gas.

Figure 2 shows for each of the three conditions a more detailed view of the average response to left push of the hip abductors and ankle plantar flexors for the same subject (S1) as in Fig. 1. The bottom two traces show the LAT sway and Map. The similarity of the EMG response in three conditions is very evident. In each case, there was early suppression of the right GM for about 50 ms, followed by a marked increase in the left GM. The left Gas was recruited very shortly after the left GM, at which time there was a short period of right Gas suppression. As Map began to rise, there was increased activity in the right Gas and right GM, moderating the preceding left-sided response. The right Gas was then suppressed for a longer period, before returning some 300 ms after the push, when all the muscles sustained a steady activity level as the torque started to asymptote at a steady level.

On average for all subjects, a push of 4% of body weight corresponded to 27.7 (±2.4) N. LAT sway amounted to 17.3 (±7.4) mm for the sideway push, with no significant difference according to the condition; AP sway was 19.0 (±7.4) mm for the forwards push. Before the application of the force, there was no significant difference in the steady LAT pelvis position as a function of condition. However, in condition LF, steady AP pelvis position was 24.1 (±7.0) mm further back than in the other two conditions.

Figure 3 provides a direct visual comparison of the response to left push in each condition in terms of left GM

Table 1 Onset (ms) of EMG activity and ground reaction torque around the AP axis (*Map*): average (±SD) for 100 trials of the five subjects during left pushes in the three different conditions: *LO* predictable left push only, *LF* left push during unpredictable left or forward push, *LR* left push during unpredictable left or right push. *L* Left, *R* right, *GM* gluteus medius, *Gas* gastrocnemius

	LO	LF	LR
L GM	79 (±18)	79 (±16)	78 (±14)
R GM	122 (±24)	132 (±28)	133 (±26)
L Gas	77 (±38)	100 (±40)	77 (±43)
R Gas	128 (±51)	149 (±54)	131 (±56)
Map	94 (±12)	99 (±16)	92 (±13)

activity and Map for all five subjects. The similarity of the response across conditions is evident for every subject.

Table 1 summarises onset latency data for each subject. Activity in the left GM started around 79 ms after push onset. In LO and LR, this occurred simultaneously with that of the Gas, but in LF left Gas activity started some 20 ms later (the latter observation being contrary to the expectation that left Gas might be early in this condition). Right GM and Gas activity onsets were approximately simultaneous and 50 ms later than left GM activity onset in each condition (i.e. there was no tendency for right GM to be early in LR). The last row in Table 1 shows the significant delay in rise of Map [$t(98)$; $P<0.005$], and it should be noted that this delay was possibly influenced by a later response in the left Gas.

Normalized response amplitudes of the left and right GM and Gas in LR, LF and LOC relative to the amplitude to the response in these muscles in LO are summarised in Tables 2 and 3 for the time windows 25–100 ms and 100–175 ms after push. In both tables, the entries represent averages (with SD) over the data from all five subjects. Before averaging, the data for each subject were normalised with respect to that subject's average for condition LO. Thus, a value of 1 indicates the same level of activity as condition LO. LOC values were generally equal to LO, except for the right GM and left and right Gas in Table 2 [$t(98)=2.55, 3.14, 2.85$; $P<0.005$].

The values in Tables 2 and 3 are of interest in respect of the possibility of co-contraction. Under the hypothesis of co-contraction, we had expected an increase in activity of either gastrocnemius, but especially of the right Gas in LF and an increase in right GM activity in LR. For these muscles, we used LOC as a basis for comparison and found that the values were either equal or reliably less than LOC. Thus, Table 2 provides no evidence of cocontraction triggered by push in the early window of 25–100 ms after push. Table 3 relates to the later 100 to 175-ms

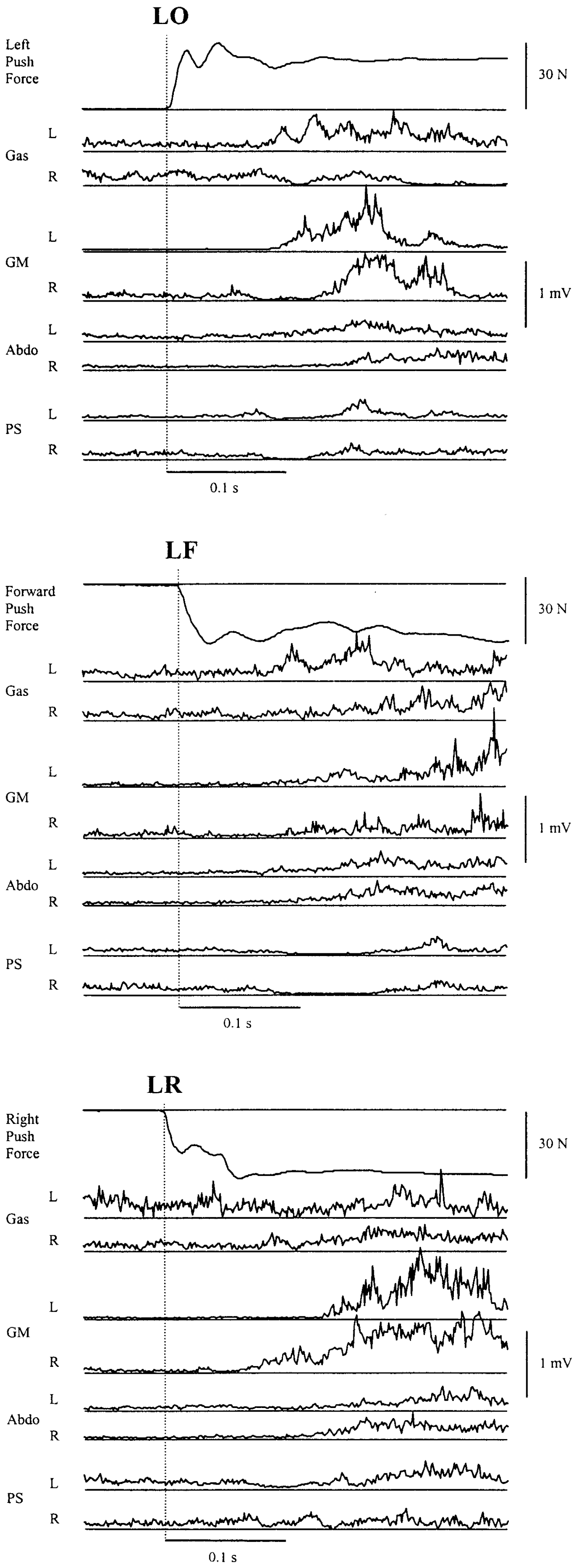


Fig. 1 Muscle response for three different push directions: average (n=20) response to left pushes in *LO* condition, forward pushes in *LF* or right pushes in *LR* of one subject (S1). From top to bottom, the traces show applied force, muscle activity on the left (*L*) and right (*R*) side of the body in the gastrocnemius (*Gas*), gluteus medius (*GM*), abdominal (*Abdo*) and paraspinal (*PS*). Traces aligned on onset of applied force (*dotted line*)

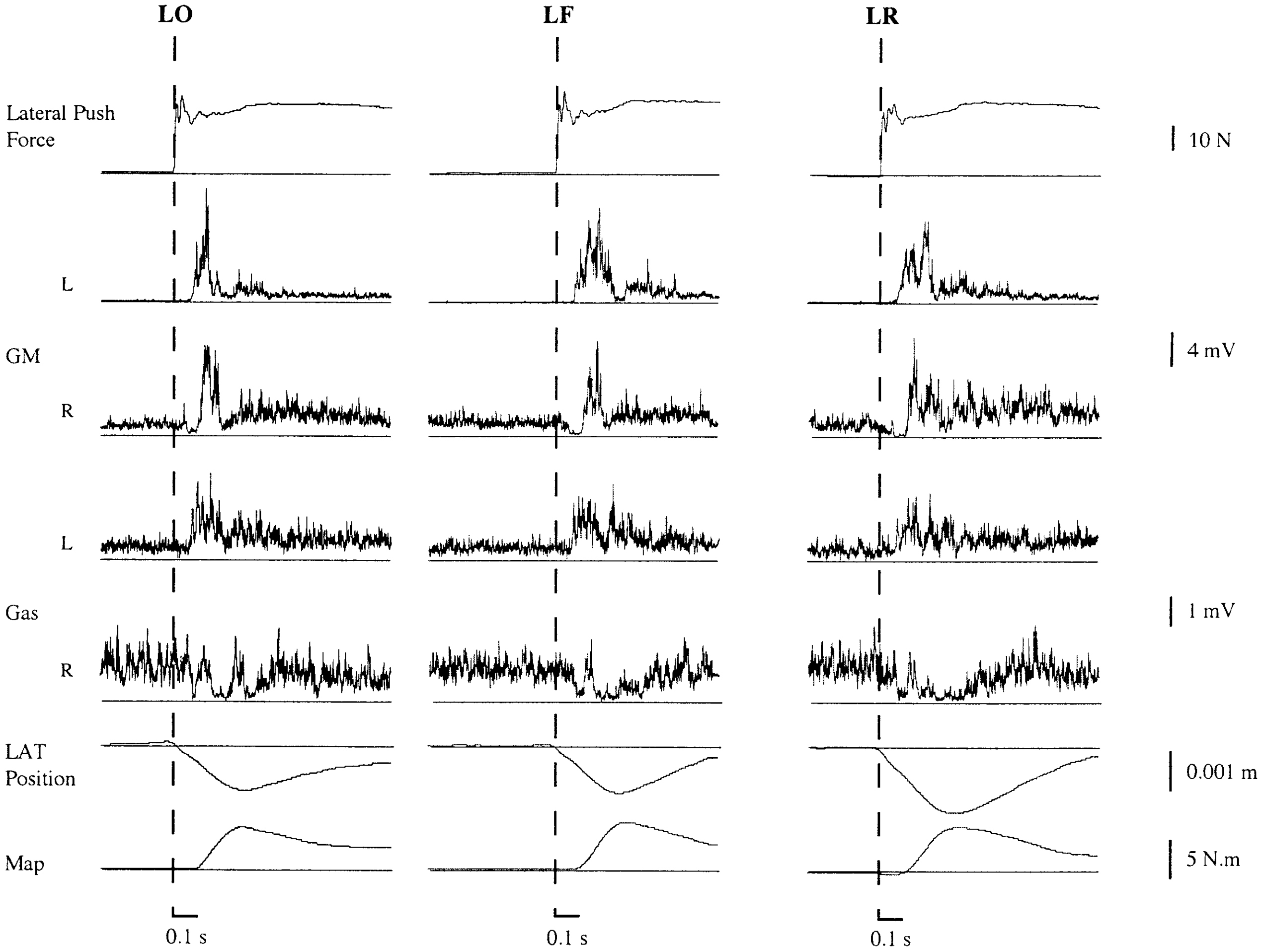


Fig. 2 Responses to left pushes in the three different conditions. Average (n=20) response for one subject (S1) when the condition was left push only (*LO*), left or forward push (*LF*) or left or right push (*LR*). Muscle activity is shown for the left (*L*) and right (*R*) gastrocnemius (*Gas*) and gluteus medius (*GM*). The two lowest traces are pelvis lateral position (*LAT Position*) and ankle torque around the anteroposterior axis (*Map*). Traces aligned on onset (*dashed line*) of applied force (lateral push force, *top trace*)

Table 2 Normalized integrated EMG amplitude activity measured between 25 and 100 ms after push onset. Average (±SD) for 100 trials of the five subjects during left push perturbation in each conditions: *LF* left or forward push condition, *LR* left or right push condition, *LOC* left push only control condition. Other abbreviations as in Table 1

	LF	LR	LOC
L GM	0.86 (±0.36)	0.86 (±0.52)	1.05 (±0.56)
R GM	1.11 (±0.51)	0.90 (±0.42)	1.12 (±0.48)
L Gas	0.84 (±0.46)	0.99 (±0.52)	1.12 (±0.67)
R Gas	0.89 (±0.50)	0.90 (±0.40)	1.15 (±0.54)

window; here, the value for the right GM was reliably greater in LF and LR than LOC [$t(98)$=2.43, 2.31; P<0.005].

Table 4 provides data on the ground reaction torque amplitude and rate. There were no reliable differences be-

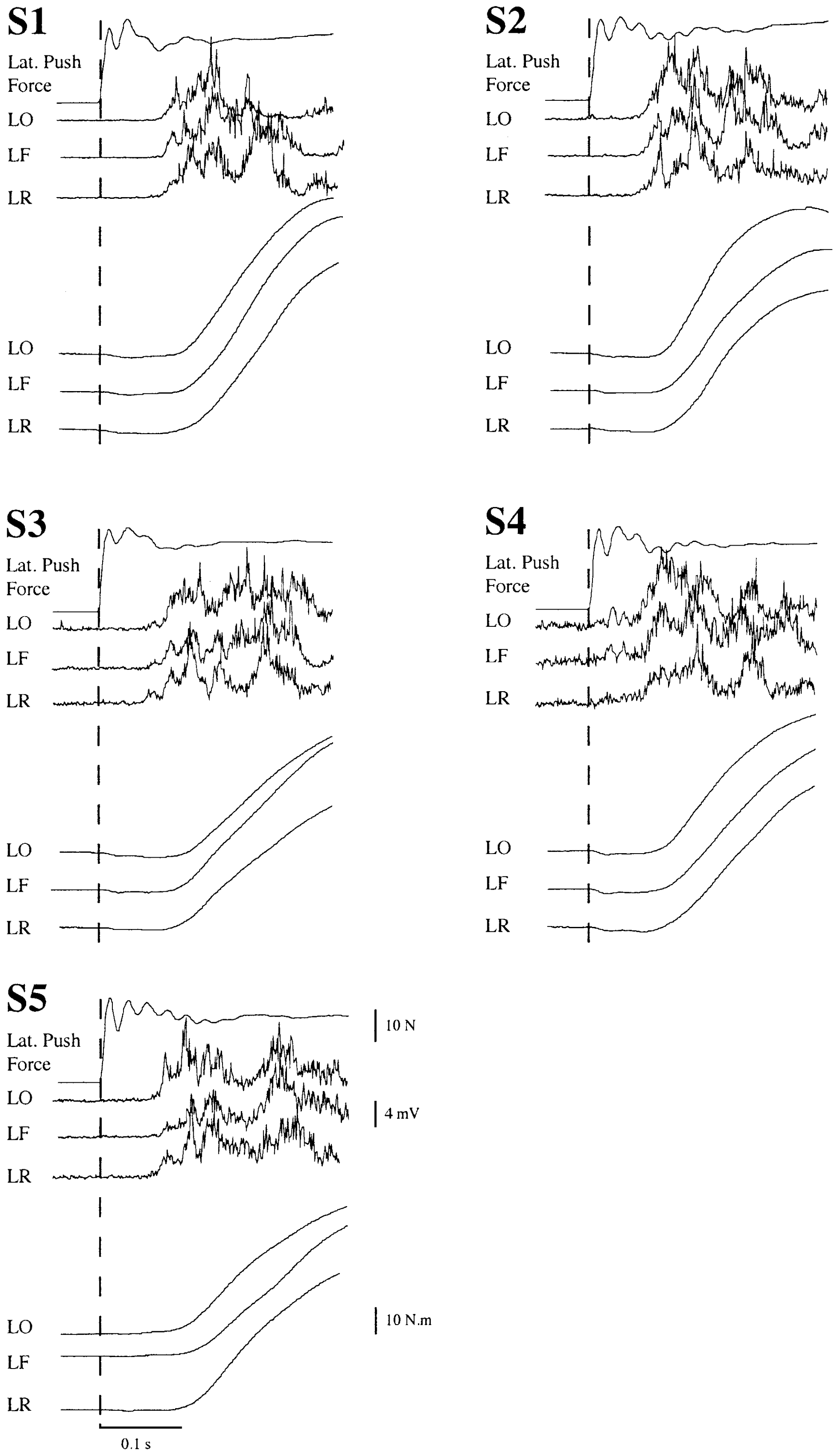
Table 3 Normalized integrated EMG amplitude activity measured between 100 and 175 ms after push onset. Average (±SD) for 100 trials of the five subjects during left push perturbation in each condition: *LF* left or forward push condition, *LR* left or right push condition, *LOC* left push only control condition. Other abbreviations as in Table 1

	LF	LR	LOC
L GM	1.14 (±0.42)	1.12 (±0.71)	0.93 (±0.38)
R GM	1.24 (±0.97)	1.20 (±0.85)	1.09 (±0.66)
L Gas	0.68 (±0.47)	0.88 (±0.48)	1.09 (±0.59)
R Gas	1.06 (±0.77)	0.91 (±0.54)	1.09 (±0.85)

Table 4 Maximum amplitude (*AMax*) and average rate of change (*Slope*) of normalized ground-reaction torque around the anteroposterior axis. Average (±SD) for 100 trials of the five subjects during left push perturbation in each condition: *LF* left or forward push condition, *LR* left or right push condition, *LOC* left push only control condition

	LF	LR	LOC
A Max	1.05 (±0.13)	1.07 (±0.14)	0.98 (±0.13)
Slope	1.00 (±0.26)	0.94 (±0.18)	0.97 (±0.29)

Fig. 3 Comparison of average response (n=20) to left push of all five subjects (*S1–S5*) in terms of the left gluteus medius muscle and torque around the anteroposterior axis when the condition was left push only (*LO*), left or forward push (*LF*) or left or right push (*LR*). Traces aligned on onset (*dashed line*) of applied force (*top trace*)



tween LO and LOC. The values for amplitude were reliably greater than 1 in LF and LR [$t(98)=3.67, 4.86$; $P<0.01$]. There was a reliably lower rate of increase of Map [$t(98)=3.46$; $P<0.005$] in condition LR.

Discussion

In this paper, we show that a horizontal force pushing the pelvis left, right or forwards elicited stereotyped postural responses, which were matched to the particular direction of push in less than 100 ms. The responses led to the development of ground reaction torques that opposed the perturbation, limited sway and restored the position of the pelvis. The primary focus of the study was to determine whether uncertainty about the direction of a forthcoming perturbation would delay the postural response. We reasoned that knowledge about the direction of a perturbation would allow advance preparation of the required postural response and that this would result in an earlier response than if perturbation direction must first be determined before the required postural response can be selected. Comparison of the response to left push in blocks of trials where the push was directed to the left only (LO) with the response to the same stimulus in blocks of trials where the push was directed left or right (LR) or left or forwards (LF) showed that direction uncertainty caused no increase in the time taken to initiate the response. In each case, the left GM responded at 79 ms with onset of the AP ground reaction torque (Map) at 95 ms.

Two previously published studies of the effects of perturbation uncertainty using different procedures have given equivocal results. With forward or backward translation of the support surface inducing backward or forward sway, Badke et al. (1987) observed faster postural responses when a cue was given in advance as to the direction of the forthcoming perturbation. This finding was statistically reliable in the case of hemiparetic stroke patients, but not in the case of normal controls, although in the latter case the trend was in the same direction. Diener et al. (1991) examined the case of normal subjects exposed to support-surface rotations that tended to induce foward or backward sway. They found no change in response delay whether or not the direction of the forthcoming perturbation was cued in advance. Our results, showing constancy of latency with sideways sway induced by a quite different perturbation to balance, therefore support and extend the findings of Diener et al. (1991). However, it should be noted that the latter study reported rather slower estimates of the postural response because postural responses shorter than 100 ms were ignored. Although they argued such responses do not have an appreciable effect, our measures of ground reaction torque clearly indicate that some muscles (we assume GM) must have had an effect before 100 ms.

One implication of the finding that uncertainty does not increase postural response latency is that under conditions, such as LO, where the subject has full knowledge about the direction of the forthcoming perturbation, that information is not used. We speculate that, although the required response to resist left push could be readied before the beginning of the trial, subjects apparently avoid committing themselves to that alternative until confirmatory sensory information is available at the onset of perturbation. In the introduction, we suggested that, faced with a block of trials with uncertainty about direction of perturbation, subjects might change their postural response. In particular, we considered that perturbation might initially produce co-contraction of the hip abductors on each side, since the resultant stiffening would tend to reduce lateral sway. This strategy might be effective for either type of perturbation in LR. However, in LF, co-contraction of ankle plantar- and dorsi-flexors would be called for. With these possibilities in mind, we therefore checked the times of onset and levels of activity in the right GM and right Gas, muscles which would normally not be recruited early in the response to left push. These provided no evidence of such co-contraction. If anything, the right GM and right Gas were later under uncertainty.

In one of the uncertain conditions, left or forward, there was a clear change in anterior-posterior pelvis position. We consider this reflects a strategy for providing a greater safety margin for unpredictable forward pushes. Such a change suggests that there may be subtle changes of central organisation (set) under uncertainty, even though no change is evident in onset latency in the prime mover (left GM). As a corollary, it may be observed that uncertainty did affect timing and amplitude of response of some of the muscles that followed the prime mover. And perhaps as a corollary, there were reliable differences in amplitude measures of ground reaction torque. Thus, while prior information does not speed postural responses that differ according to the direction of perturbation to balance, there are, nevertheless, subtle effects on overall organisation. One interpretation of the failure to observe a reduction in latency when direction of perturbation is known in advance is that, under these conditions, the CNS avoids an earlier commitment to response in order to allow for the possibility that the perturbation is not the one expected. It may be that an earlier response would only be obtained under predictable conditions if the perturbation was of such a magnitude that the later response would result in a loss of balance.

Acknowledgements This study was partly supported by the Stroke Association.

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