Gait & Posture 4 (1996) 315–322

Performance in the stability limits test during rehabilitation following stroke

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Received 31 March 1995; accepted 16 June 1995

Abstract

The extent to which the standing posture could be perturbed voluntarily by having the subject displace the centre of pressure (CP) to the outer limits of the base of support was investigated in 20 stroke patients who were undertaking inpatient rehabilitation and 20 control subjects matched by gender and age. The mean age of the stroke patients was 50.7 years (S.D. = 18.5) and testing occurred after a median of 10 weeks post-onset. A force platform was used to quantify displacement of the CP in the forward and backward directions and laterally to each leg during sustained weight-shifting. The distribution of weight between the legs was also quantified during standing and antero-posterior (AP) weight-shifting by measuring the mean position of the CP in the lateral axis. Compared to controls, the stroke patients showed deficits in weight-shifting in both forward ($P < 0.01$) and backward ($P < 0.01$) directions. Forward displacement was greater than backward displacement in both groups ($P < 0.01$). During standing and AP weight-shifting stroke patients deviated from the mid-line of the base of support more than the control subjects, however the deviation was not always towards the unaffected leg. Compared to control subjects the stroke patients had significant deficits in the ability to weight-shift in the lateral direction to both legs. Although the stroke patients showed a trend for less displacement to the affected leg than the unaffected leg, this difference was not greater than the comparable difference in control subjects. The true ability to weight-shift to the unaffected leg may have been masked because of the testing protocol. For this reason modifications are required to the testing protocol. These findings from stroke patients in the early stage post-onset provide objective data on which to base treatment strategies during rehabilitation.

Keywords: Posture; Cerebrovascular accident

1. Introduction

Several aspects of balance control in standing have been shown to be compromised following stroke. Some patients have difficulty in standing at all [1] or can only stand for short periods of time [2]. For those who can stand, the posture is typically less steady than normal and is asymmetrical with less weight on the affected leg [3]. Dynamic aspects of balance control such as the ability to perform movements of the body above the base of support are important in terms of the functional requirements of daily living. Deficits in the ability to withstand self-generated perturbations of the body during standing, therefore, need to be identified, so that intervention strategies can be used during rehabilitation to help regain this fundamental skill.

Dynamic aspects of standing balance have been assessed by asking subjects to lean the body as far as possible in specific directions, without altering foot position. The limits of stability have been quantified by measuring the mean position of the CP during the sustained weight-shift task [4–7]. In normal subjects it has been shown that displacement of the CP decreases as age increases [4,6]. Therefore, this testing protocol seems to

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0966-6362/96/$15.00
SSDI 0966-6362(95)01059-1

be potentially useful for detecting deficits in balance control following stroke.

To date, the stability limits test has only been applied to one sample of stroke patients who were on average 2 years post-onset [3]. The results indicated that there was a decrement in performance in forward and backward weight-shifting, and, as might be expected due to the unilateral nature of hemiplegia, a decrement in performance of weight-shifting to the affected side. Also noteworthy was the finding of decreased weight-shifting to the unaffected side, although it appeared that the decrement was less on the unaffected side than the affected side. In another study [8] in which stroke patients were asked to completely transfer body weight from two-legged stance to one-legged stance a similar decrement was found on the affected side and, to a lesser extent, on the unaffected side in stroke patients, who were at least 6 months post-onset. On the basis of this latter finding it has been recommended [8] that balance retraining should be expanded to include not only weight-shifting to the affected side but also to the unaffected side.

A modified version of the stability limits test has been applied to five healthy subjects and six stroke patients with a weight-shifting protocol in which subjects were asked to displace the CP to 50% of maximum voluntary displacement in the forward direction and two lateral directions [9]. The group of stroke patients varied widely in the time since stroke onset, ranging from 2 to 66 months. One of the objectives of this study [9] was to quantify the extraneous movements during these weight-shifting tasks. Stroke patients were not found to be different from the normal subjects in the extent to which they could displace the CP in the forward and two lateral directions, although there was a trend for less displacement to both the affected and unaffected legs. This trend may have become significant if the balance control system was challenged more fully than the 50% level of performance required in this study. It is interesting to note from this study [9] that during weight-shifting in the AP axis the stroke patients relied more on the unaffected leg.

A common feature of the clinical studies of weight-shifting to date is the relatively chronic nature of the stroke samples. Retraining of weight-shifting is frequently advocated during rehabilitation. A recent review [10] has noted the importance of weight-shifting for treatment of balance disorders in several intervention approaches following stroke. Yet, very little data have been published about weight-shifting in stroke patients who are actually undertaking rehabilitation. Treatment goals need to be based on objective data and it cannot be assumed that deficits in stroke patients at an early stage are identical to deficits at a relatively later stage. Performance may be different at a relatively late stage post-stroke because of motor learning and the process of natural recovery. Alternatively, chronic stroke patients may have developed secondary adaptations which adversely influence performance. For example weight-shifting in the forward direction may be restricted by tightness in the calf. Since it is necessary to obtain data from the relevant stroke population, this study aimed to use the stability limits test to quantify the deficits in weight-shifting during the rehabilitation phase following stroke.

In summary, the literature revealed several issues that need to be addressed in stroke patients undertaking rehabilitation. Firstly, the extent of deficit due to stroke needs to be quantified during weight-shifting in the AP axis. On the basis of data reported from previous studies it was hypothesised that in the AP axis stroke patients would displace the CP less than healthy subjects in both directions [3], but that both groups would displace the CP less in the backward direction than the forward direction [5,11]. Secondly, it is important to consider whether stroke patients deviate to the unaffected side during maximum weight-shift in the AP axis, which may indicate a compensatory strategy. Based on previous data from longer term stroke patients [9] it was hypothesised that stroke patients undergoing rehabilitation would show a greater deviation to the unaffected side than healthy subjects. Finally, the extent of abnormality due to stroke needs to be quantified in the lateral axis. On the basis of previous studies with longer term stroke patients [3,8] it was hypothesised that stroke patients undertaking rehabilitation would displace the CP less to both the affected and unaffected legs than healthy subjects, but that the deficit would be greater on the affected leg.

2. Method

2.1. Subjects

The first 20 patients who were referred by the physiotherapy staff at three metropolitan rehabilitation hospitals and who satisfied the following criteria were included in the study:

(1) first cerebrovascular accident (CVA) within the last 8 months,

(2) currently participating in physiotherapy training programme as an inpatient in rehabilitation,

(3) able to understand verbal commands [12],

(4) at least 1 month since CVA,

(5) medically stable for travel by taxi to the Research Laboratory,

(6) able to transfer in and out of the taxi with supervision and assistance from a physiotherapist,

(7) able to stand for 30 s unaided.

Patients were excluded if there was a history of other neurological disease or injury or any other factors such as leg injuries which could affect balance in two legged stance.

Twenty patients (14 male, 6 female) with a mean age of 50.7 years (S.D. = 18.5) were tested after a median time interval of 10 weeks (interquartile range from 6 weeks to 15 weeks) following stroke. Eleven subjects were right hemiplegic and nine subjects were left hemiplegic. The patients' medical records, which included computed tomography data for 11 of the 20 patients, indicated that the lesion was caused by infarct for 55%, by haemorrhage for 30% and unknown for 15%. The lesions were in the sub-cortical or cortical regions for 80% of patients, unknown for 15% of patients and due to subarachnoid haemorrhage for one patient (5%) who had typical signs of unilateral hemiplegia. There were no patients with brainstem lesions included in the sample.

Twenty healthy subjects, matched for age and gender and with no history of CVA or other neurological disorders or factors known to affect balance, volunteered to participate in this study. The mean age of the control subjects was 51.6 (S.D. = 18.4) years.

2.2. Apparatus

A Kistler force platform system was used to measure the ground reaction forces as the subject stood on the platform. Outputs from the system included force in the three orthogonal axes. The co-ordinates of the CP were derived from the force information and all signals were acquired using an analogue-to-digital converter and stored for subsequent analysis on a PDP11/23 computer.

A light movable frame was built to provide a stable hand support for the subjects whilst stepping on and off the platform and for safety reasons during the testing procedures. A visual target, consisting of a 25-centimetre diameter yellow circle on a white background, was placed at eye level on a wall 5 m in front of the force platform.

2.3. Procedure

On arrival at the testing laboratory, the procedures, which were approved by the Institute's Ethics Committee, were described by the researcher and each subject gave informed consent to participate in the study. For each age-matched control subject the 'affected leg' was assigned to correspond to the side of the affected leg of the stroke patient to whom they were matched.

Subjects wore flat-heeled lace-up or sturdy shoes for all trials. For safety reasons subjects were encouraged to use the supporting handrail prior to the trials as the feet were being positioned on the platform. No hand support was allowed during the trials.

As shown in Fig. 1, the subjects were positioned on the platform in a standardised position so that the balance control system was challenged equally in the two groups. In the lateral axis the medial borders of the shoes were parallel and 5 cm from the mid-line of the platform. In the AP axis the heels and front of the shoes were evenly aligned and the middle of the feet were positioned approximately above the mid-line of the platform in the lateral axis. The position of the shoes was outlined with a marker pen so that the placement of the feet could be easily replicated for each trial. This outline was subsequently used when the subject was no longer on the platform to measure the dimensions of the base of support by sampling a point force applied at the front, back and most lateral points of the outline. Mean length of the base of support was 27.6 cm (S.D. = 2.3) for the stroke patients and 27.8 cm (S.D. = 2.6) for the control subjects. Mean width of the base of support was 31.3 cm (S.D. = 1.7) for the stroke patients and 31.6 cm (S.D. = 1.9) for the control subjects.

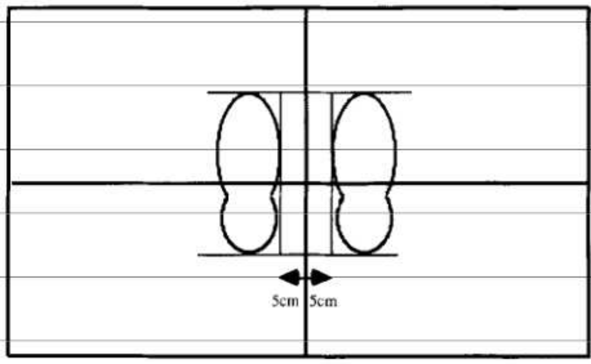

Fig. 1. Position of feet on force platform.

Body weight was measured by sampling the vertical force signal as each subject stood still on the platform for 5 s. The mean body weight was 71.7 kg (S.D. = 12.6) for the stroke group and 71.4 kg (S.D. = 9.8) for the control group.

At the beginning of testing subjects were encouraged to lean as far as possible in each direction within their limits of safety, avoiding movement of the base of support or falling. The position of the CP during standing and weight-shifting was sampled during three consecutive trials of 5 s duration with a rest of approximately 1 min between each trial. Subjects generally remained standing on the platform between the three consecutive trials. The position of the feet was carefully monitored so that the base of support was replicated accurately for each trial. For safety reasons the experimenter stood centrally behind the subjects during all trials and a safety rail was positioned in front throughout the testing, but subjects were advised to use it only in the case of an emergency.

2.3.1. Standing performance. Prior to commencing the weight-shifting tasks the mean position of the CP in the AP and lateral axes was sampled for 5 s during steady standing when the subjects were asked to stand with equal weight on both feet.

2.3.2. AP weight-shifting performance. Weight shifting in the AP axis was tested by asking the subjects to lean forward or backward, using an ankle strategy, and to take as much weight towards the toes or heels as possible and to hold the position for 5 s without altering the position of the feet on the platform. So that any series effects due to order of testing was avoided the initial direction for AP weight-shifting was alternated between subjects in each group.

2.3.3. Lateral weight-shifting performance. Similarly, lateral weight-shifting was tested by asking the subjects to shift the hips and shoulders to the affected or unaffected side with the initial direction for lateral weight-shifting alternated between subjects in each group.

A demonstration of each task was given just prior to the set of three trials. At the beginning and during each trial subjects were required to look at a target placed at eye level 5 m in front of the platform. Data collection was initiated after the subject had assumed the test position and had indicated they were ready. Data collection was terminated 5 s later with an auditory signal.

Outputs were sampled at 100 Hz in order to ensure that any 50-Hz interference could be adequately filtered subsequently. The sampled data were digitally filtered using Fourier coefficient truncation at a frequency of 20 Hz [13].

2.4. Statistical analysis

2.4.1. Derivation of performance score in standing. The position of the CP in the lateral and AP axes during standing was derived by calculating the mean over each sampling period. An overall performance score was obtained by averaging the three trials. The mean position of the CP in the AP axis during standing was used as the neutral reference point for calculating the amplitude of displacement in the AP axis during the AP weight-shifting trials.

2.4.2. Derivation of performance score for weight-shifting in the AP axis. For each trial of AP weight-shifting a score was derived by calculating the mean position of the CP in the AP axis. The following scores were available: forward weight-shift (referenced to neutral position in standing); posterior weight-shift (referenced to neutral position in standing); total weight-shift in the AP axis. For each of these three dependent variables an overall performance score was obtained by averaging the three trials.

2.4.3. Derivation of performance score for weight-shifting in the lateral axis. For lateral weight-shifting to each side a score was derived by calculating the mean position of the CP in the lateral axis during the sampling period. For each trial the amplitude of displacement in each direction (affected, unaffected) was obtained by referencing the weight-shifting score to the mid-line of the base of support since the feet were positioned accurately and symmetrically about the mid-line of the platform. Three scores were obtained: lateral weight-shift to the affected leg; lateral weight-shift to the unaffected leg; total lateral weight-shift. For each of these three dependent variables an overall performance score was obtained by averaging the three trials.

2.4.4. Inferential statistical techniques. Inspection of the data suggested that not all of the data sets were normally distributed. In order to have a consistent analytical approach all of the comparisons between the two groups were performed using the Mann–Whitney *U*-test and within-subject comparisons were performed using the matched-pairs Wilcoxon signed-rank test.

3. Results

3.1. Performance in standing

During standing the mean position of the CP in the AP axis (neutral reference position) in control subjects was located 15.8 (S.D. = 2.2) cm from the front and 11.9 (S.D. = 2.0) cm from the back of the base of support and in stroke patients 15.6 (S.D. = 1.8) cm from the front and 12.0 (S.D. = 1.5) cm from the back of the base of support. No systematic difference was found in the location of this reference point between the two groups ($t = 0.04$, $P > 0.05$).

In the lateral axis the median position of the CP was located 0.3 cm (IQR = −0.7 to 0.4) from the mid-line for control subjects and 0.8 cm (IQR = −1.1 to 2.4) from the mid-line for stroke patients. A positive score indicated that the CP was deviated towards the unaffected leg.

3.2. Relationship between the dimensions of the base of support and performance scores

In the AP axis, stroke patients displaced the CP 33% (S.D. = 10.7) of the length of the base of support compared to control subjects who displaced the CP 48.6% (S.D. = 9.0) of the length of the base of support. In the lateral axis stroke patients displaced the CP 42.2% (S.D. = 10.9) of the width of the base of support compared to control subjects who displaced the CP 62.5% (S.D. = 7.7) of the width of the base of support. In the control subjects the Spearman rho correlation coefficient revealed a relationship of moderate strength between total displacement in the AP axis and the length of the base of support (rho = 0.71) and total displacement in the lateral axis and the width of the base of support (rho = 0.63). The corresponding relationships were non-significant, $P > 0.05$, in the stroke patients. Because our study and a previous study [7] demonstrated that a relatively large amount of variability in the performance scores of control subjects was associated with the dimension of the base of support, subsequent analysis was performed using performance scores expressed as a proportion of the relevant dimension of the base of support.

3.3. Stability limits in the AP axis

Fig. 2 shows the box plots for forward and backward weight-shifting in each group separately, indicating that

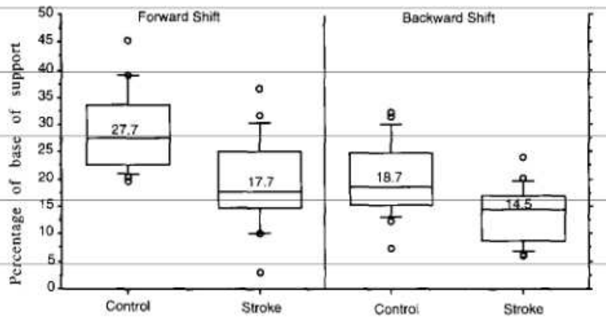

Fig. 2. Box plots showing the performance scores for weight-shifting in the forward and backward directions in control subjects and stroke patients. The boxplot shows the median, 25th and 75th percentiles (box limits), the 10th and 90th percentiles (whiskers) and individual values which lie outside these limits.

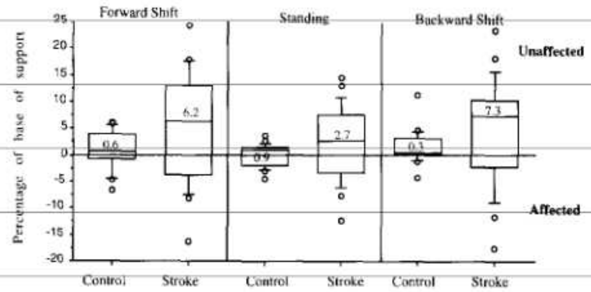

Fig. 3. Box plots of the position of CP in lateral axis during standing and forward and backward weight-shifting (symbols are same as described in the legend of Fig. 2). Positive values indicate deviation towards the unaffected leg; negative values indicate deviation towards the affected leg.

the control subjects obtained higher scores in both directions. The Mann–Whitney U-test confirmed that control subjects displaced the CP more than the stroke patients in the forward direction ($Z_U = -3.27$, $P < 0.01$) and in the backward direction ($Z_U = -2.65$, $P < 0.01$).

Fig. 2 shows that in each group there was a trend for displacement in the forward direction to be greater than in the backward direction. The Wilcoxon signed-rank test confirmed that displacement was greater in the forward direction than the backward direction for control subjects ($Z_W = -3.136$, $P < 0.01$) and for stroke patients ($Z_W = -2.501$, $P < 0.01$).

3.4. Deviation in the lateral axis during AP weight-shifting

Fig. 3 shows box plots of the CP in the lateral axis during forward shifting, standing and backward shifting for each group. A positive score indicated that the CP was deviated towards the unaffected leg and a negative score indicated that the CP was deviated towards the affected leg. Fig. 3 shows that the median values for the stroke patients were positive during standing, forward and backward weight-shifting, demonstrating that there was a trend for more weight to be loaded onto the unaffected leg during these three tasks. In contrast the median values for the control subjects were close to zero and the distributions were less varied than the stroke patients. The 25th and 75th percentile values of the control subjects, as shown in Table 1, were used to categorise the performance of the stroke patients. Table 1 shows that a very large percentage of stroke patients fell outside the interquartile range of the control subjects, although the CP did not always deviate towards the unaffected leg. When taking into account the direction of deviation of CP from mid-line, the Mann–Whitney U-test did not confirm that the difference between the two groups was statistically significant for standing ($Z_U = -1.136$, $P > 0.05$), forward weight-shift ($Z_U = -1.271$, $P > 0.05$) or backward weight-shift ($Z_U = -1.542$, $P > 0.05$). However, the absolute deviation, irrespective of direction, was greater for stroke

Table 1
Percentage of subjects categorized outside interquartile range of control subjects in lateral axis during standing and forward and backward weight-shifting

	25th Percentile score (% base)	75th Percentile score (% base)	Percentage of subjects < 25th percentile of control subjects	Percentage of subjects in interquartile range of control subjects	Percentage of subjects > 75th percentile of control subjects
Control group standing	−2.23	1.41	25	50	25
Stroke group standing	−3.55	7.49	30	15	55
Control group forward shift	−1.08	3.85	25	50	25
Stroke group forward shift	−3.93	13.02	40	5	55
Control group backward shift	−0.12	3.23	25	50	25
Stroke group backward shift	−2.45	10.16	30	10	60

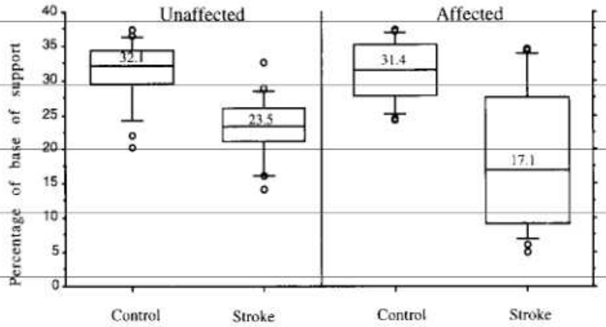

Fig. 4. Box plots showing the performance scores for weight-shifting to the affected and unaffected legs in control subjects and stroke patients (symbols are same as described in the legend of Fig. 2).

patients than control subjects for standing ($Z_U = -3.79$, $P < 0.01$), forward weight-shifting ($Z_U = -4.06$, $P < 0.01$) and backward weight-shifting ($Z_U = -4.22$, $P < 0.01$), confirming the greater proportion of stroke patients observed in the outer quartiles (Table 1).

3.5. *Stability limits in the lateral axis*

Fig. 4 shows the box plots of the performance scores for displacement of the CP in the lateral axis during lateral weight-shifting. Fig. 4 shows that there were wide variations in performance scores for the stroke patients when shifting to the affected leg. There was very little overlap between the distributions of the two groups, highlighting that there was a large deficit in performance for the stroke patients in both directions. The Mann–Whitney *U*-test confirmed that there was a significant difference between the two groups for weight-shifting to the unaffected ($Z_U = -4.27$, $P < 0.01$) and the affected legs ($Z_U = -3.68$, $P < 0.01$). Although Fig. 4 shows that there was a trend for the stroke patients to shift less to the affected leg than the unaffected leg, this difference was not found to be significantly greater than the comparable difference in the control subjects ($Z_U = -0.89$, $P > 0.05$).

4. Discussion

4.1. *Stability limits in the AP axis*

The results of this study have shown that control subjects were able to displace the CP 49% of the length of the base of support, demonstrating similar performance scores to those of healthy subjects in a previous study [4]. In contrast stroke patients undertaking rehabilitation displaced the CP only 33% of the length of the base of support. The stroke patients were significantly worse than control subjects at displacing the CP in both the forward and backward direction, thereby confirming that the deficits at this early stage were similar to those previously reported in a more chronic stroke sample [3]. In both of these studies standing balance was fully challenged by asking the subjects to lean forward as far as possible. This may explain why a decrement in performance was found in these two studies whereas stroke patients in another study [9] showed no trend for a decrement when they were required to displace the CP to 50% of maximum performance in the forward direction.

It is interesting to note that the neutral position from which forward and backward displacements were referenced was not different between the two groups. Therefore, differences in performance scores between the two groups and between the two directions cannot be attributed to any systematic difference between the two groups in location of the neutral position in standing.

The finding that displacement was less in the backward direction than the forward direction for both groups was in accordance with our hypothesis. It is likely that the decreased displacement in the backward direction was due to the relatively short length of foot over which displacement occurred in the backward direction. Although there was an attempt to ensure that subjects felt safe when shifting backwards by having the experimenter stand behind the subject and when shifting forwards by having a stable safety rail in front of the subject, it is also possible that the subjects perceived that it was safer to shift forward than backward. This could occur because in the forward direction the hands can be more readily used to protect from potential falls and the visual system can provide information about the environment.

4.2. *Deviation in the lateral axis during standing and AP weight-shifting*

During steady standing, forward and backward weight-shifting between 85% and 95% of stroke patients were laterally deviated beyond the interquartile range of lateral deviation shown by the control subjects. Although there was a trend for the deviation to be toward the unaffected side, the difference was not statistically significant. This may have been due to the instructions to stand with equal weight on both feet during the standing trials. Alternatively, this may have been due to the inclusion of patients with the 'pusher syndrome' which is characterised by atypical weight-bearing patterns with more weight on the affected leg than the unaffected leg [14]. Examination of the CAT Scan data for two patients who showed relatively large consistent deviations towards the affected side during the three tasks (Fig. 3) did not contribute to diagnosing the cause of these atypical weight-bearing patterns since two other patients with the same diagnosis (infarct in the posterior limb of the internal capsule) did not show the same pattern.

Although the stroke group as a whole was not significantly deviated towards the unaffected side during the three tasks, the majority of patients were deviated beyond the 75th percentile of control subjects towards this direction. In these patients the cause of the lateral deviation towards the unaffected side may have been due to sensorimotor loss, fear of relying on the affected leg or abnormal perception of verticality, which has been found to be associated with poor body alignment in standing following stroke [15]. Further research is needed to investigate the underlying mechanisms of abnormal deviations, both towards the affected and unaffected legs.

One of the limitations of the current testing protocol is that it does not measure displacement of the CP under each foot during AP weight-shifting. With two legs on the force platform a stroke patient could obtain an apparently high performance score for AP weight-shifting by relying primarily on one leg. Since displacement of the CP in the lateral axis during AP weight-shifting was outside the interquartile range of normal performance for at least 85% of the stroke patients, alternative methods are required to quantify AP weight-shifting for each leg separately.

4.3. Stability limits in the lateral axis

In the lateral axis the major finding was that stroke patients were less able to displace the CP than healthy subjects both to the affected and unaffected legs. Although there was a trend, the analysis did not find a greater deficit for weight-shifting to the affected leg than the unaffected leg in the stroke patients. The most likely explanation for not detecting worse performance on the affected leg than the unaffected leg in stroke patients was the observation that some stroke patients were systematically restricted in their ability to shift weight to the unaffected side because of the requirement to keep the base of support fixed during data collection. It was observed that during weight-shifting to the unaffected side the heel of the affected leg tended to rotate inwards in some patients. This movement of the base of support would have invalidated the measurement of the CP and was not permitted in this study. For some patients the only way they could keep the affected leg in contact with the platform in the standardised position during weight-shifting to the unaffected leg was to keep some weight on the affected leg, thus restricting the displacement of the CP to the unaffected leg. This difficulty was not observed in the control subjects. Therefore, it is likely that for some stroke patients the true ability to shift weight to the unaffected leg was masked in this study because the testing protocol required that the affected leg remain stationary. This finding indicates a need to alter the testing protocol for stroke patients so that a true estimate of weight-shifting to the unaffected leg can be obtained.

The findings of this study have established a marked deficit due to stroke in both lateral weight-shifting to the affected leg and weight-shifting in the forward and backward directions. If the goal of intervention is to normalise standing balance, treatment strategies should focus on increasing displacement of the body in these three directions and controlling the CP closer to the mid-line during AP weight-shifting. It may also be advisable to increase weight-shifting to the unaffected side, as suggested previously [8], although this needs to be confirmed in a further study of rehabilitation patients with a testing protocol which gives an unbiased estimate of the deficit on this side. The present study is the first to quantify performance scores for the stability limits test in stroke patients with a first unilateral CVA at an early stage in rehabilitation. The data from control subjects of similar age provide clinicians with objective evidence on which to base treatment goals. The deficits found in the stroke patients may have been due to the primary sensorimotor deficits caused by the stroke, such as muscle weakness, or may have been due to cognitive factors. Careful diagnosis of the causative factors is needed so that specific training strategies can be implemented.

Acknowledgements

The authors gratefully acknowledge the assistance of the staff and patients at Caulfield General Medical Centre; North West Hospital, Mount Royal Campus; and Royal Talbot Campus of Austin Hospital.

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