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**CONTRIBUTIONS ET DETERMINANTS DES INDICES DE
POSTUROGRAPHIE POUR COMPRENDRE LE COMPORTEMENT
POSTURAL EN STATION DEBOUT APRES UN AVC**

**CONTRIBUTIONS AND DETERMINANTS OF POSTUROGRAPHY INDICES TO
UNDERSTAND THE STANDING POSTURE AFTER STROKE**

THÈSE
PRÉSENTÉE POUR L'OBTENTION DU TITRE DE DOCTEUR EN MÉDECINE

DIPLÔME D'ÉTAT

Adèle CHAUVIN

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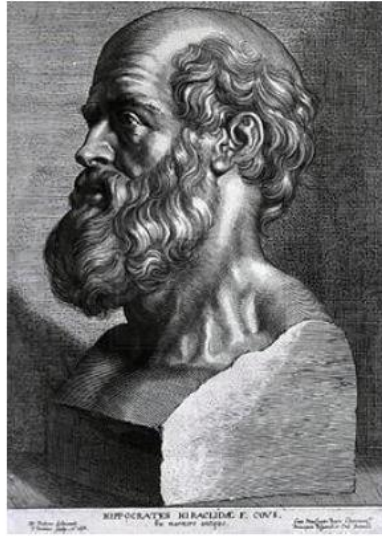
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SERMENT D'HIPPOCRATE

En présence des Maîtres de cette Faculté, de mes chers condisciples et devant l'effigie d'HIPPOCRATE,

Je promets et je jure d'être fidèle aux lois de l'honneur et de la probité dans l'exercice de la Médecine.

Je donnerai mes soins gratuitement à l'indigent et n'exigerai jamais un salaire au dessus de mon travail. Je ne participerai à aucun partage clandestin d'honoraires.

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Table of contents

| | |
|---|----|
| ABSTRACT | 11 |
| RESUME..... | 12 |
| INTRODUCTION..... | 13 |
| METHODS..... | 15 |
| Study design and sample size..... | 15 |
| Participants..... | 16 |
| Posturography | 16 |
| Procedure | 16 |
| Instructions and conditions | 17 |
| Criteria and data analysis..... | 19 |
| Deficits | 19 |
| Balance and gait disorders in daily life, and disability | 23 |
| Statistical analysis | 23 |
| RESULTS..... | 26 |
| Participants..... | 26 |
| Posturographic behavior in standing | 27 |
| Data distributions and influence of the assessment time | 27 |
| Influence of vision on position and instability indices | 29 |
| Relationships between the four posturographic indices | 29 |
| Determinants of the global posturographic behavior in standing..... | 32 |
| Posturographic behavior in the frontal plane | 32 |
| Clinical determinants of WBA | 32 |
| Clinical determinants of lateral instability..... | 35 |
| Postural behavior in the sagittal plane | 37 |
| Clinical determinants of AP-CP _{position} | 37 |
| Clinical determinants of sagittal instability | 37 |
| Posturographic behavior and mobility in daily life..... | 39 |
| Posturographic behavior and balance abilities | 39 |
| Posturographic behavior and gait abilities..... | 39 |
| DISCUSSION | 41 |
| Posturographic behavior in standing | 41 |
| Clinical determinants of postural behavior following subacute stroke..... | 44 |

| | |
|---|----|
| Posturographic behavior and mobility in daily life..... | 46 |
| Study limitations | 47 |
| CONCLUSION | 49 |
| REFERENCES..... | 51 |
| ADDITIONAL MATERIALS | 57 |

ABSTRACT

Objective. (1) To determine the posturographic indices needed to explain the standing behavior after a subacute stroke. (2) To analyze their clinical determinants and (3) their role in balance and gait disorders in daily life.

Methods. Cohort study of 95 patients consecutively admitted to rehabilitation after a first hemispheric stroke. Position and instability posturographic indices were measured in medio-lateral (ML) and antero-posterior (AP) axes. Functional abilities were also assessed. Deficits were quantified at Day 30 or Day 60 post-stroke. Statistics comprised factorial analysis of principal component and, uni-and multivariate analyses.

Results. One instability index and both position indices on each axis, with or without vision, were required to describe the post-stroke postural control. Instability was the first component and contained nearly half of the posturographic information. The primary indices were independently determined by spatial neglect ($p=0.002$) and motor weakness ($p=0.005$). These deficits explained ML instability ($p<0.001$ and $p=0.002$, respectively) as well as AP instability ($<10^{-4}$) and weight bearing asymmetry (WBA) ($p<0.001$), respectively. Balance and gait disorders were partly explained by ML instability ($p<10^{-5}$ and $p<10^{-7}$, respectively) and WBA ($p<10^{-5}$ and $p<10^{-4}$, respectively).

Conclusion. Stroke rehabilitation care must not only target the WBA. Instability and WBA, determined by spatial neglect and motor weakness, are both independently involved in standing posture and, in balance and gait disorders after stroke. Lateropulsion should also be considered.

Key words: stroke, posturography, postural control, balance, instability, weight bearing asymmetry, spatial neglect, motor weakness

RESUME

Objectif. (1) Déterminer les indices posturographiques nécessaires pour expliquer la posture debout après un AVC subaigu. (2) Analyser leurs déterminants cliniques et (3) leur rôle dans les troubles de l'équilibre et de la marche.

Méthodes. Cohorte de 95 patients admis en rééducation après un premier AVC hémisphérique. Des indices posturographiques de position et d'instabilité étaient mesurés dans les axes médio-latéral (ML) et antéro-postérieur (AP). Les capacités fonctionnelles ont été aussi évaluées. Les déficits étaient quantifiés à J30 ou J60. Les statistiques comprenaient une analyse en composantes principales et des analyses uni- et multivariées.

Résultats. Un indice d'instabilité et les deux indices de position, avec ou sans vision, étaient requis pour décrire le contrôle postural post-AVC. L'instabilité était la première composante et contenait près de la moitié des informations. Les indices principaux étaient indépendamment déterminés par la négligence spatiale ($p=0,002$) et la faiblesse musculaire ($p=0,005$). Ces déficits expliquaient l'instabilité ML ($p<0,001$ et $p=0,002$, resp.) ainsi que l'instabilité AP ($<10^{-4}$) et l'asymétrie d'appui ($p<0,001$), respectivement. Les troubles de l'équilibre et de la marche étaient partiellement expliqués par l'instabilité ML ($p<10^{-5}$ et $p<10^{-7}$, resp.) et l'asymétrie d'appui ($p<10^{-5}$ et $p<10^{-4}$, resp.).

Conclusion. La rééducation post-AVC ne doit pas seulement cibler l'asymétrie d'appui. L'instabilité et l'asymétrie d'appui, déterminées par la négligence et la faiblesse musculaire, sont indépendamment impliquées dans la posture debout, et dans les troubles de l'équilibre et de la marche. La latéropulsion devrait être aussi considérée.

Mots clés : AVC, posturographie, contrôle postural, équilibre, instabilité, asymétrie d'appui, négligence spatiale, faiblesse musculaire

INTRODUCTION

Postural disorders are the leading cause of disability after stroke (1,2) and represented the first complain of stroke patients (3). They result in a loss of autonomy (4) and an increased risk of falling (5,6).

The current theoretical model of postural control involves two domains, devoted to body orientation and body stabilization (7,8). Body orientation is defined by the appropriate positioning of the body segments with respect to gravity. Body stabilization is determined by the control of body segments positions with respect to the base of support. This model might help in better understanding balance disorders in the clinic, in order to guide their rehabilitation. It could be especially useful after stroke (9,10) owing to the devastating sequelae induced by balance disorders (11), which should be better explained in terms of impaired body orientation or stabilization (2).

Balance assessment is carried out using specific balance scales dedicated to stroke such as the Postural Assessment Scale for Stroke Patients (12), or generic scales (non-stroke specific) such as the Berg Balance Scale (13) or the mini-BESTest (14). These scales examine in daily life the consequences of both impaired postural orientation and stabilization (1). Body orientation with respect to gravity may be assessed using ordinal scales of lateropulsion (15,16), together with vertically perception assessed by specific instrumental tools (10,17,18). Postural stabilization may be specifically investigated with instrumental tools quantifying the amount of sway, targeting either one body segment using inertial sensors or movement analysis systems, or the coordinates of the center of pressure (CP) projected onto the base of support in sitting or in standing (19). This latter technic is called posturography (20), a very old technic based on the principle that the coordinates of the CP in quiet stance roughly corresponds to the projection of the center of mass to the ground. In this case the coordinates of the center of feet pressure corresponds to the coordinate of the application point of the

resultant upward force exerted by the support surface. Static posturography is now widely used in routine clinical practice, both for the balance assessment and rehabilitation (feedback therapy). It requires one or two immobile force platforms, fixed to the ground. Dynamic posturography is mainly performed for research or rehabilitation.

Static posturography yields several kinds of indices such as position indices and instability indices obtained from the body weight distribution or the mean position of the CP coordinates and the dispersion of the CP coordinates, respectively. In asymmetric conditions such as presented by post-stroke paretic individuals, both parameters are usually presented. However, there is no consensus about the one which might be the primary parameter to encounter balance disorders, and the one which would be secondary. Some papers suggest that the index of asymmetry might represent the primary posturography parameter to assess after stroke and treat after stroke, describing what has been called the weight bearing asymmetry (WBA) (21–25). Some other papers are more focused on the amount of sway (26–28).

Our hypothesis was that both parameters are independent therefore thus both required to describe the standing postural behavior, in terms of instability and asymmetry.

The first objective of the paper was to run a factorial analysis of posturographic parameters in a series of about 100 in subacute stroke patients, to rank the specific contribution of these parameters and determine the minimal useful posturographic data set. Our second objective was to carefully analyze the determinants of each parameter comprised in the minimal posturographic data set, to disentangle the contribution of spatial neglect, which is almost always reported in the literature (9,21,29) and motor weakness the contribution of which might have been underestimated so far. Also the consequence of a lateropulsion on postural indices has little been investigated (21) although lateropulsion is the key determinant of balance in daily life (2). Our third objective was to precise how much posturography explains balance and gait disorders in daily life.

METHODS

Study design and sample size

The study DOBRAS_Initial_Posturography was a monocentric cross-sectional observational study, ancillary to the DOBRAS cohort (Determinants of Balance Recovery After Stroke; ClinicalTrials.gov NCT03203109), in which participants were assessed within the 3 days preceding or following fixed periods of time after a first hemisphere stroke: 30 days (D30), 60 days (D60), 90 days (D90), 120 days (D120), and at discharge of the rehabilitation ward regardless the total length of stay since stroke. Assessments were performed by trained and multidisciplinary examiners, with blinding to the study hypothesis. The sample size was planned to conduct multivariate analyses in a large series of individuals (≥ 200 observations), both for the non-instrumental main studies (2), and ancillary studies performed with devices (posturography, verticality perception).

Protocol approvals, registrations, and patient consents

The DOBRAS cohort was approved by our institutional review board (CHU Grenoble Alpes) who validated the ClinicalTrials.gov registration (NCT03203109). The study was also registered at the National Committee for Informatics and Freedom (Commission Nationale Informatique et Liberté; CNIL-No.2014874-v1) and was performed in accordance with the Helsinki Declaration. According to French law, observational studies do not require approval by an ethics committee, provided that participants have been informed of the specific research and are not opposed to use of their data. All eligible individuals were informed of the DOBRAS study (orally and in writing) and those who did not want to participate signed an opposition form.

Participants

Eligibility criteria for the study DOBRAS_Initial_Posturography were those of the DOBRAS study, plus the ability to perform a posturographic session, i.e. to stand without aid several sequences of 30 sec, within the 6 months following the stroke. Indeed, for this study, we analyzed data of the first posturography session completed on D30, D60 or D90 according to patients' ability.

Inclusion criteria were age ≥ 18 to 80 years and a first-ever unilateral stroke limited to one hemisphere. Exclusion criteria were recurrent stroke; complication at the acute stage (malignant infarct, cerebral herniation, subarachnoid hemorrhage, and hydrocephalus); dementia; previous disability interfering with balance, gait or vestibular disorders; unstable medical condition or psychiatric problems; and not French speaking. These conditions were obtained from the hospital electronic file describing the history of every patient, by interviewing patients and relatives, and by a systematic clinical examination.

Participants of the DOBRAS study, as all patients admitted in our department, followed a personalized rehabilitation program, taking into account deficits and activity limitations. According to their abilities, they had 2 physiotherapy and 1 occupational therapy sessions per day (total 1h30), plus, if needed, sessions with speech therapist, neuropsychologist, psychologist, or orthoptist. Rehabilitation sessions included weight shifting exercises, balance and gait training.

Posturography

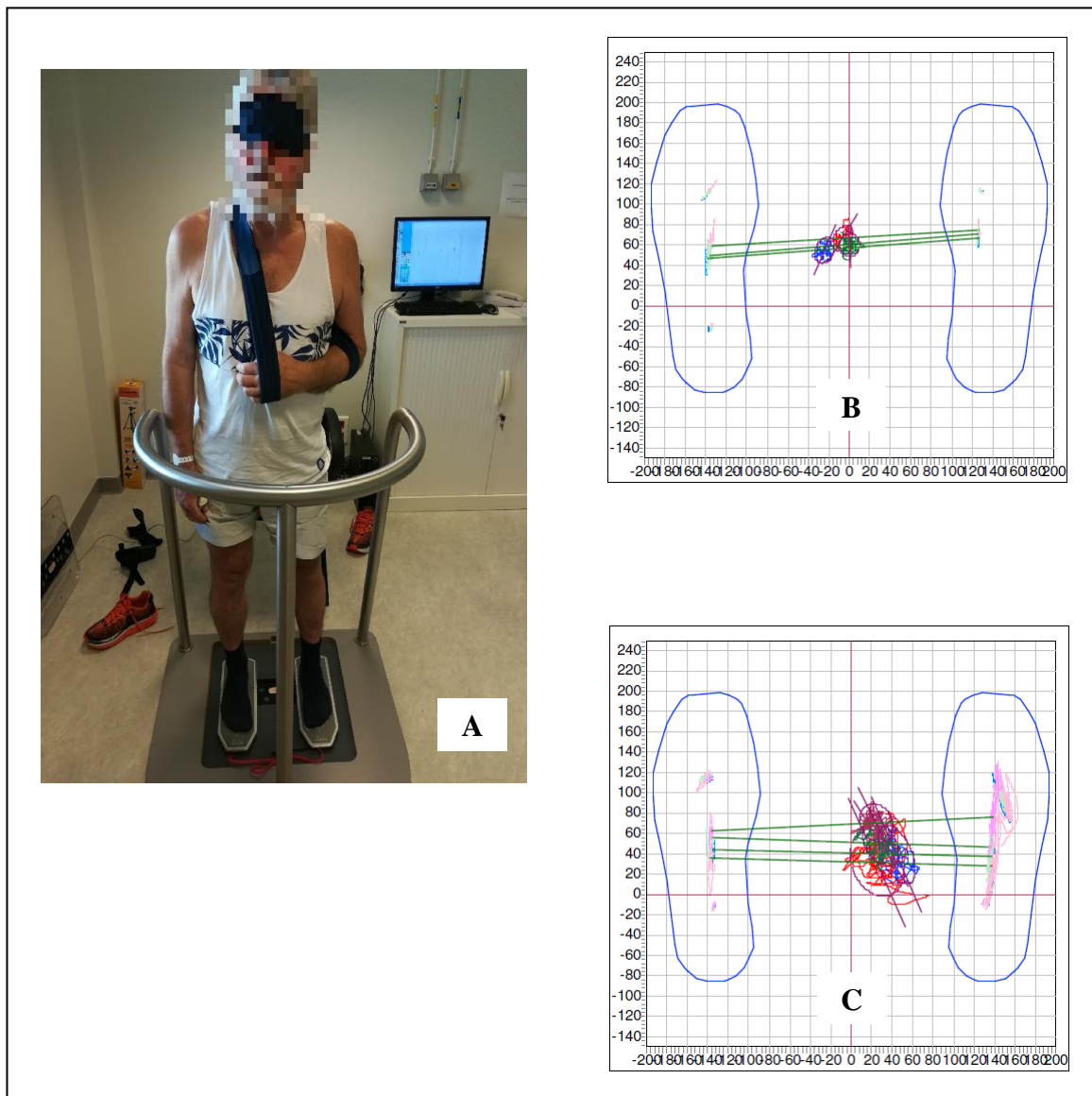
Procedure

Posturography was performed in bipodal stance using the commercial dual force platform Feetest6 (Techno Concept©) fixed to the ground in a quiet room dedicated to this activity. Participants were positioned in socks (without shoes and orthoses), feet parallel on landmarks

drawn on the plate-forms which were 14 cm apart. This base of support the width of which corresponded roughly to the pelvis (Figure 1) is the most common posture spontaneously adopted by humans standing quiet (19). This standardization allowed to accurately and reliably measure the vertical forces (% of body weight [BW]) distributed under each low limb. It also mastered the difficulty of the task and limited confounders on posturographic indices. For security reasons participants stood within a handrail shaped in front of and besides the plate-forms, with a chair behind them. They were helped to stand-up from this chair and sit down for a rest at any time if needed. The examiner checked feet positions on the plate-forms before each trial, then stood at the paretic side to prevent fall during trials. For patients with severe deficits, trials requiring help (handrail grip, human assistance) were considered aborted and, then repeated.

Instructions and conditions

Participants were instructed to remain as still as possible, with arms hanging alongside their trunk, without talking, looking at straight ahead. Three trials of 30 sec were recorded with vision, followed by 3 trials of 30 sec without vision. This systematic order aimed at starting with the easier condition. Patients had a few minutes rest between each trial. If patients encountered too much difficulty in maintaining the standing position, the only completed trials were retained. Participants were instructed to look at a visual target (small color ball of 3 cm diameter) positioned at gaze level on a white wall distant from 2-3 m. This limited visual information was considered sufficient to optimize the use of vision to orientate and stabilize the body, without biasing the task (no clue about the direction of the vertical). The visual fixation aimed at limiting eyes and body movements exploring the surroundings, which would affect the results in the lateral plane. Without vision, trials were obtained by asking participants to close their eyes and keep them closed during the whole trial time. Because of the frequent motor impersistence after stroke (inability to sustain a motor act such as closing the eyes > 30 sec) (30), they also wore a mask during all the recording periods without vision.



The “action forces” are transmitted to the sensors that measure the ground “reaction forces” according to Newton's third law. Ground reaction forces which control the center of body mass in the sustentation polygon can be represented by a 3D vector whose origin is the center of pressure (CP). The stabilometric platform then allows to calculate the coordinates of the CP. The statokinesigram shows the map of the CP displacements in the ML and AP axes.

B, C- Two examples of statokinesigrams during 3 trials of 30 seconds in standing position with or without vision

Figure 1. Posturography

- A. Participant on the dual force platform
- B. Patient showing a postural symmetry and stability
- C. Unstable patient with limb load asymmetry

Criteria and data analysis

To avoid any statistical inflation, we limited the analyses to the main posturographic variables, corresponding on one hand, to the mean position of vertical forces involved (mean CP coordinates), and on the other hand, to the quantity of sway (dispersion of the CP coordinates). As for the position indices, along the antero-posterior (AP) axis we took the mean position of the CP, expressed in mm, a positive value indicating a forward shift (CP). On the medio-lateral (ML) axis, we chose the % of BW loaded under the paretic leg ($WB_{\text{pareticLL}}$). This dimension corresponds to the vertical force which is directly measured by the plate-forms. This is also a more concrete indication about the WBA, a key behavior in standing. Although expressed in different units, this index gives the same information as the lateral shift of the CP, provided that feet positions are symmetrical and precisely known (31). The second type of variable was the quantity of sway on each axes, quantified with the dispersion of the CP coordinates on each axis, which reflects the postural instability being usually assumed that people with postural instability show greater amount of sway than others (32). Postural instability was defined by two standard deviations (2SD) of the CP coordinates along each axis, $ML_{\text{instability}}$ and $AP_{\text{instability}}$. For each posturography index, values of the 3 trials were averaged for the statistical analyses.

Deficits

Deficits analyzed in this study were quantified at the first systematic assessment available, D30 or D60 even if the posturography was performed later.

Deficits were evaluated by a battery of well validated tests and scales, assessing motor weakness, spasticity, sensory loss, visual field defect, cognitive and language disorders.

Motor weakness was assessed by physiotherapists with the Medical Research Council scale which involves testing muscles against gravity and the examiner's resistance (33). Scores range from 0 (no contraction) to 5 (full range of motion against gravity with maximal resistance). Eight key muscle groups (hip flexors and extensors, hip abductors and adductors, knee flexors and extensors, ankle flexors and extensors) of the paretic lower limb were tested with a total score from 0 to 40 (normal strength). Two classes were conceived: "no or light motor weakness" (score > 32) and "moderate or severe motor weakness" (score ≤ 32).

Spasticity was assessed by physiotherapists with the Ashworth Scale (34). Scores range from 0 (no increase in tone) to 4 (limb rigid) depending on the increase in muscle tone during a passive movement. Five key muscle groups (hip flexors and adductors, quadriceps and hamstrings, triceps surae and tibialis posterior) of the lower paretic limb were tested with a total score from 0 to 20. Participants were categorized into 2 groups: "no or light spasticity" (score ≤ 2) and "moderate or severe spasticity" (score > 2).

Hypoesthesia was evaluated by occupational therapists with the Semmes-Weinstein Monofilament test on the paretic lower limb using a set of monofilaments that vary in thickness and diameter. Each filament was identified by the logarithm of the force produced expressed in milligrams. Patients were classified into 2 classes: "no or light hypoesthesia" if the smallest detectable filament ranged from 1.65 (0.008gr) to 3.22 (0.16gr) and "moderate or severe hypoesthesia" if the smallest detectable filament were 3.61 (0.4gr) or above.

The presence of hemianopia has been clinically investigated by physicians.

Aphasia was evaluated by speech therapists with the Boston Diagnostic Aphasia Examination to appreciate the severity of the language disorder. The presence of aphasia was considered if the score was ≤ 4 (35).

Apraxia was assessed by neuropsychologists with the Apraxia Screen of Tulia (AST) (36). Patients with a score < 9 had a diagnosis of upper limb apraxia.

Executive functions were evaluated by neuropsychologists with a composite score ranging from 0 (no deficit) to 3 (severe impairment) based on a screening assessment of cognitive impairments (Cognitive Assessment scale for Stroke Patients and/or Montreal Cognitive Assessment) or on the complete cognitive assessment. Symptoms suggestive of the presence of dysexecutive disorders were slower processing speed, impaired working and short-term memory, impairment in inhibition and cognitive flexibility, impaired planning, or behavioral disorder. Participants were categorized into 2 groups: “no or light dysexecutive disorders” if none or only one score was deficient, or several performances were impaired, and “moderate or severe dysexecutive disorders” if two or more scores were deficient. Severity implied that abilities were poorly or not maintained in daily life.

Spatial neglect was assessed with six main tests by neuropsychologists in both extrapersonal and personal space (37). This impairment is included in the unilateral neglect syndrome, which is also characterized by contralesional hypokinesia, anosognosia and/or anosodiaphoria, and unilateral extinction of visual, sensory, or auditory stimuli.

Three paper and pencil tests evaluated extrapersonal neglect:

- The Bells test: a cancellation task with 7 columns, each containing 5 targets (bells) and distractors (38). The result was considered “normal” if the number of omissions was ≤ 6 .
- The line bisection test: in which patient is asked to bisect 2 represented lines (5cm and 20cm) (39). An average deviation ≤ 6.5 cm from the true center was considered “normal”.
- A copying test (the Gainotti copy): for which the result was considered abnormal if any omissions were observed (40).

Three other tests evaluated personal neglect:

- The Bisiach test: a simple task that assess the ability to reach the contralesional hand with the ipsilesional arm with eyes closed (41). The result was considered “abnormal” if the score was higher than 0.
- The Fluff test: in which the blindfolded patient has to remove 24 targets attached to his clothes in a time limit of 2 mn, with no targets placed on the non-paretic arm (42). Result was considered “normal” if $\geq 13/15$ targets were detached.
- The comb and razor test: in which patient is asked firstly to comb the hair for 30sec and secondly to shave (for men) or to make up (for women) for 30 sec (43,44). The difference in strokes between the two sides of the head or the face was recorded. A score $> 11\%$ indicated a body neglect (44).

Another test, the ecological Catherine Bergego Scale, assessed the two domains in activities of daily living (45). The result is considered “normal” if the score was < 2 .

Lateropulsion which represents a contralesional tilt in a sitting or standing was assessed by physiotherapists using the Scale for Contraversive Pushing (SCP) with total score ranging from 0 to 6 (46). Individuals were categorized as: “upright” (SCP score ≤ 0.5) and “lateropulsion” (SCP ≥ 0.75).

Handedness before stroke was evaluated by occupational therapists through interviews (patient, relatives) to assess the Edinburgh Handedness Inventory (47). Scores range from -1 to +1, and a score ≥ 0.4 categorized the patient as right-handed.

Height and weight were collected to calculate *Body Mass Index* (BMI).

Balance and gait disorders in daily life, and disability

Functional disabilities were also evaluated around the posturography date by a clinical examination with the collection of data on balance disorders and gait independence.

Balance disorders were assessed by physiotherapists with the Postural Assessment Scale for Stroke (PASS), which is used to assess static and dynamic balance of stroke patients evaluating ability to maintain or change a given lying, sitting, or standing posture (12). This scale includes 12 items scored from 0 to 3, for a total score from 0 to 36. Patients were categorized into 2 groups: a PASS score ≥ 28 meant that the patients had a “stable erect stance” and a PASS score < 28 meant that the patients were “not able to stand independently without any help”.

Gait independence was evaluated with the modified Fugl-Meyer Assessment (mGait-FM) (48). This walking scale is specifically dedicated to stroke and evaluate patient performances depending on the degree of assistance with scores ranging from 0 (no walking) to 6 (normal walking). Patients were categorized as having a “functional gait” (mGait-FM ≥ 3) if they were able to walk without human assistance, and as having a “non-functional gait” (mGait-FM ≤ 2) if they were not able to walk or if they were able to walk with human assistance.

Statistical analysis

Distribution of the posturographic parameters, shown in additional materials, was determined using the Kolmogorov-Smirnov test and the Shapiro-Wilk test. Because of the non-Gaussian distribution in data of ML and AP instability, these data were transformed as “ $\log\sqrt{x}$ ” for further analyses except for univariate analyses.

Continuous data with normal distribution were analyzed by the Student t test and otherwise by the Mann–Whitney test or the Wilcoxon test. Continuous data were presented as a mean

(standard deviation) or median (Q1–Q3) and, dichotomized and categorical data as a number (%). When useful, 95% confidence intervals (CIs) were given. For the student's t-test, an effect size "d" larger than 0.80 was considered large, 0.50-0.80 medium and 0.20-0.50 small. For the Mann-Whitney U test, an effect size "r" larger than 0.50 was considered large, 0.30-0.50 medium, and 0.10-0.30 small. Effect size was calculated for significant results.

Posturographic parameters were exhibited in a correlation matrix. Then these parameters were explored by a factorial analysis of principal component extraction with varimax rotation and Kaiser normalization. According to the factor loadings of factorial analysis, three parameters were selected as representative of different components of posturographic data. A backward multivariate analysis of variance (MANOVA) model was applied to test the associations between the three selected parameters and potential clinical determinants.

After analyzing the overall postural behavior, we studied separately the clinical factors of the postural behavior (position and instability) on the sagittal and frontal axes. First at all, a univariate analysis was conducted on each axis. If the clinical factors of position and instability indices on each axis were significant in univariate analyses, they would be further studied in multivariate analyses by generalized linear model (GLM).

Then, on the basis of a systematic review with meta-analysis (49) having calculated the cut-off values for symmetrical weight bearing (WB) (41-59%), we also conducted a qualitative analysis of the six patients of the series (6%) who abnormally overloaded the paretic leg ($\geq 59\%$).

Finally, we evaluated the functional consequences of postural behavior on balance and gait. Correlations between each posturographic parameter and PASS and mGait-FM scores were tested with the Pearson correlation. A multiple linear regression (MLR) was also conducted with a forward-stepwise procedure to determine the best posturographic predictors of balance and gait abilities. We further investigated these relationships and tested the value of

WB_{pareticLL} scores to predict the ability to stand (PASS \geq 28) or walk independently (mGait-FM \geq 5). We plotted receiver operating characteristic (ROC) curves and calculated areas under the ROC curve (AUC). Optimal cut-off values were determined by the Youden Index. From the cut-off values, we calculated sensitivity, specificity, positive predictive values (PPV) and negative predictive values (NPV).

Few data were missing, so imputation was not performed. Two-sided $p < 0.05$ was considered statistically significant, except the p-value in correlation matrix, which was corrected as $p = \frac{0.05}{12} = 0.004$.

Statistical analyses were done with SPSS 23.0.

RESULTS

Participants

Figure 2 shows the flow of the participants. From January 2015 to August 2019, 95 individuals followed in the DOBRAS study had a posturography, mostly on D30 (59/95, 62%) otherwise on D60 (19/95, 20%) or later (17/95, 18%), with a median time of 35.0 (29.0–64.0) days post-stroke. Their median age was 67.0 (56.0–72.0) years. There were 65/95 (68%) males, and 87/95 (92%) were right-handed. Stroke was ischemic in 78/95 (82%) and affected the right hemisphere in 53/95 (56%). Median BMI was 25.8 (22.7–28.0) kg/m². Median motor weakness was 32.0 (24.0–38.3) and half of the patients had moderate to severe deficit. Median spasticity was 0.0 (0.0–2.0) and 21/95 (22%) had a moderate to severe spasticity. Among patients, 74/95 (78%) presented moderate to severe hypoesthesia and 30/95 (32%) had hemianopia. Median SCP score was 0.0 (0.0–1.6) and nearly one third of the patients displayed a lateropulsion. Moreover, 54/95 (57%) presented moderate to severe spatial neglect and 60/95 (63%) had moderate to severe dysexecutive disorders. Apraxia and aphasia were present respectively in 17/95 (18%) and in 27/95 (28%). The median total length of stay since stroke (hospitalization in the acute stroke unit then in rehabilitation) was 86.0 (54.5–132.0) days.

Few data were missing and concerned lower limb spasticity (n=3), hypoesthesia (n=1), and executive functions (n=6). Three patients were not able to stand independently 30 sec without vision, so could not be tested in this condition.

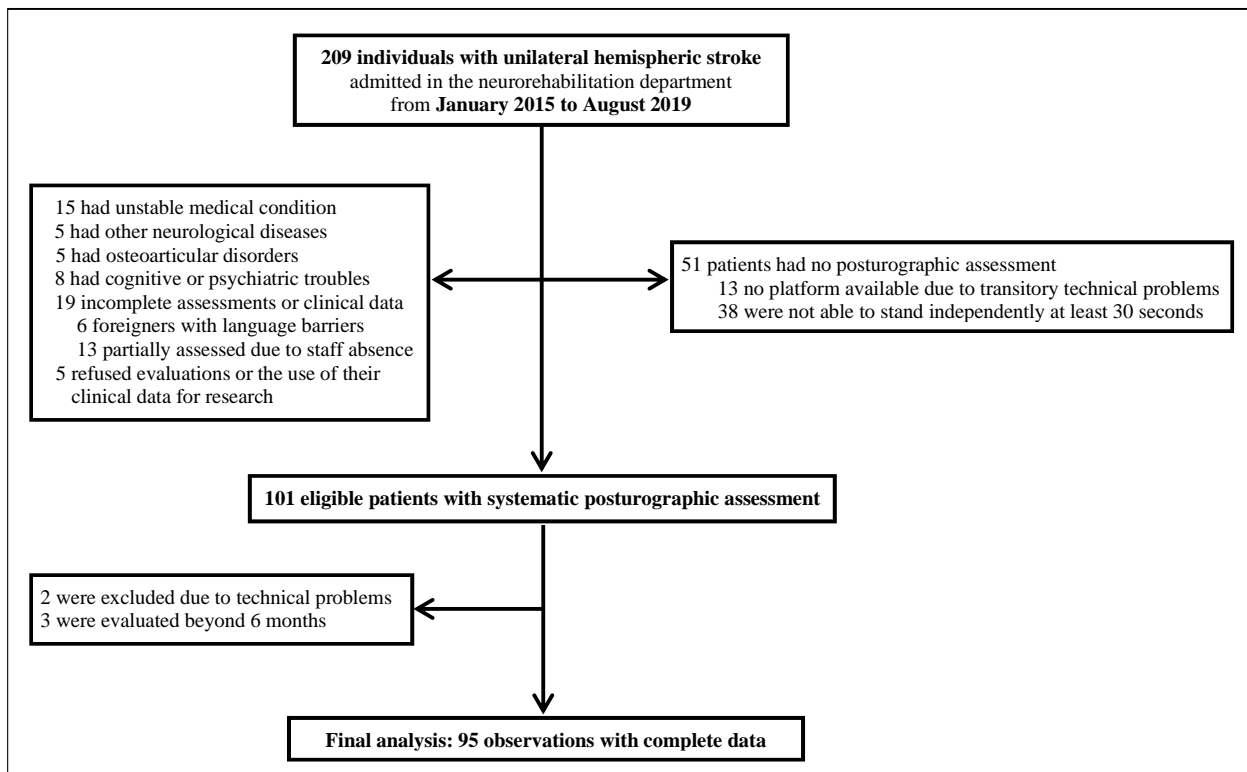


Figure 2. Flow of participants in the study

Posturographic behavior in standing

Data distributions and influence of the assessment time

The distributions of the four stabilometric parameters are shown in Figure 3. The distributions of *Position indices* ($WB_{\text{pareticLL}}$ and $AP\text{-}CP_{\text{position}}$) were Gaussian (Kolmogorov-Smirnov test, Figures 3A-B), so we used parametric tests for these variables. The distributions of *Instability indices* ($ML_{\text{instability}}$ and $AP_{\text{instability}}$) were not Gaussian (Figures 3C-D), so we used non-parametric tests for univariate analyses on these indices, and for multivariate analyses, a transformation ($\log\sqrt{x}$) leading to normalized distributions (Figures 3E-F).

Patients evaluated on D30 showed a lesser instability along ML and AP axes. These results confirmed that patients who could not have a posturography on D30 could not be tested because they were too much instable at that time, so they were tested later when possible.

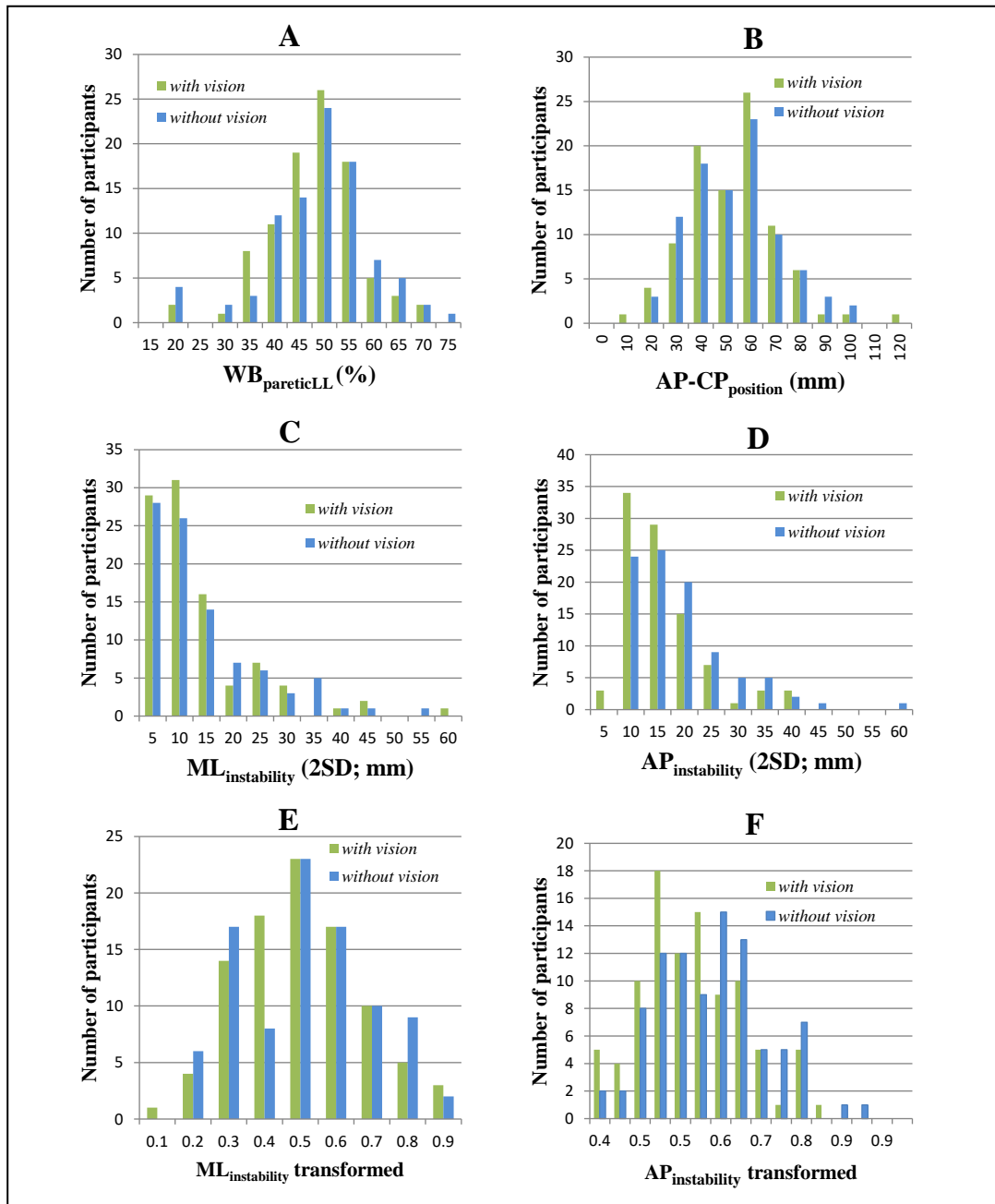


Figure 3. Histograms showing the distribution of position and instability indices with and without vision

A, B- Distribution of weight bearing on the paretic lower limb and the mean CP position along the AP axis

C, D- Distribution of postural instability along the ML and the AP axis

E, F- Distribution of postural instability along the ML and the AP axis after transformation

Influence of vision on position and instability indices

Table 1 presents posturographic data along ML and AP axes, with and without vision. Vision had no influence on position indices, patients spontaneously loading the paretic lower limb in average at 45.8 (9.3) % of BW with vision, and 46.5 (10.4) % without vision. In contrast, vision greatly influenced instability indices, decreased with vision by a large effect size on the AP axis (small effect size on the ML axis). The postural oscillations were greater on the AP axis than on the ML axis in both visual conditions.

Table 1. Effects of vision on postural control

| | with vision | without vision | | |
|--|------------------------------|------------------------------|---------------------|---------|
| <i>Position indices</i> | | | | |
| WB _{pareticLL} | 45.8 (9.3) | 46.5 (10.4) | p= 0.115 | |
| AP-CP _{position} | 47.8 (17.7) | 48.7 (17.6) | p= 0.367 | |
| <i>Instability indices</i> | | | | |
| ML _{instability} | 6.9 (4.7 – 13.4) | 8.9 (4.0 – 15.2) | p= 0.007 | r= 0.28 |
| AP _{instability} | 11.5 (8.5 – 16.5) | 14.8 (9.9 – 20.2) | p< 10 ⁻⁶ | r= 0.54 |
| <i>ML_{instability} vs AP_{instability}</i> | p < 10 ⁻⁵ r= 0.48 | p < 10 ⁻⁸ r= 0.60 | | |

Data are mean (SD) or median (Q1 – Q3).

WB= Weight Bearing, LL= Lower Limb, AP= Antero-Posterior, ML= Medio-Lateral.

WB_{pareticLL}: percentage of total body weight loaded on the paretic lower limb

AP-CP_{position}: average position (mm) of the CP along the AP axis

Instability is defined by the dispersion of the CP on each axis and is represented by 2SD.

Effect size “r” was calculated by using the Z values of the Mann-Whitney U test where:

0.10 ≤ r < 0.30 = small effect, 0.30 ≤ r < 0.50 = medium effect and r ≥ 0.50 = large effect.

Relationships between the four posturographic indices

These relationships were tested, for each visual condition. Bonferroni corrections were applied, and the significance was set at $\frac{0.05}{12} = 0.004$. The correlation matrix is shown in Table 2. Overall, we found a strong correlation between the instability on ML and AP axis, in both visual conditions. In contrast, no correlation was found between position indices on both axes. We also found the ML_{instability} increased inversely with the decrease of WB on the paretic lower limb, both with vision and without vision. In contrast, the AP_{instability} was only influenced by the WB on the paretic lower limb, in the condition without vision.

Table 2. Correlation matrix between posturography parameters with vision and without vision

| A) <u>With vision</u> | | | | | B) <u>Without vision</u> | | | | |
|---------------------------------|-------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|-------------------------------|---------------------------------|---------------------------------|---------------------------------|
| | WB_{pareticLL} | ML_{instability} | AP-CP_{position} | AP_{instability} | | WB_{pareticLL} | ML_{instability} | AP-CP_{position} | AP_{instability} |
| WB_{pareticLL} | | | | | WB_{pareticLL} | | | | |
| ML_{instability} | -0.330 p= 0.001 | | | | ML_{instability} | -0.325 p= 0.002 | | | |
| AP-CP_{position} | 0.129 p= 0.213 | 0.246 p= 0.016 | | | AP-CP_{position} | 0.136 p= 0.197 | 0.196 p= 0.061 | | |
| AP_{instability} | -0.253 p= 0.013 | 0.790 p< 10 ⁻⁶ | 0.187 p= 0.069 | | AP_{instability} | -0.303 p= 0.003 | 0.787 p< 10 ⁻⁶ | 0.136 p= 0.198 | |

WB= Weight Bearing, LL= Lower Limb, AP= Antero-Posterior, ML= Medio-Lateral
 WB_{pareticLL}: percentage of total body weight loaded on the paretic lower limb
 AP-CP_{position}: average position (mm) of the CP along the AP axis
 Instability is defined by the dispersion of the CP on each axis and is represented by 2SD .

Instability data were transformed as “log√x”.

Bonferroni corrections were applied, and the significance was set at corrected p-value = 0.05/12=0.004.

The posturographic data set was then further explored by a principal component analysis combining all 4 posturographic indices in both visual conditions. Table 3 showed that the instability (either on ML or AP axis) was the most important information encountering alone for almost half of the posturographic behavior in standing. WB was only a secondary index adding 26% of information. A three component model adding the CP_{position} explained 88.4% of the total information contained in the postural data set (Table 3 and Figure 4). This model was supported roughly equally by instability indices (either on ML or AP axis) and position indices (both axes required). This finding means that describing post-stroke standing behavior using posturography requires an optimal data set of three variables: one instability index on either axis, and both position indices on each axis, just in one visual condition. Considering each factor loading, trials without vision which are more difficult to achieve are not mandatory.

Table 3. Principal Component Analysis of posturographic behavior (with a varimax rotation)

| | Principal component | | |
|--|---------------------|--------|-------|
| | 1 | 2 | 3 |
| With vision | | | |
| WB _{pareticLL} | -0.177 | 0.961 | 0.085 |
| ML _{instability} | 0.870 | -0.227 | 0.126 |
| AP-CP _{position} | 0.156 | 0.075 | 0.945 |
| AP _{instability} | 0.903 | -0.100 | 0.021 |
| Without vision | | | |
| WB _{pareticLL} | -0.219 | 0.951 | 0.073 |
| ML _{instability} | 0.892 | -0.181 | 0.138 |
| AP-CP _{position} | 0.080 | 0.072 | 0.958 |
| AP _{instability} | 0.883 | -0.115 | 0.100 |
| Percentage explained of variance (%) | 47.5 | 26.2 | 14.7 |
| Percentage explained of cumulative variance (%) | 47.5 | 73.7 | 88.4 |

The table shows the factor loading matrix for the posturographic variables of position and instability on each axis with and without vision. Instability data were transformed as “log√x”. Three principal components were extracted, together explaining 88.4% of the variation in the data.

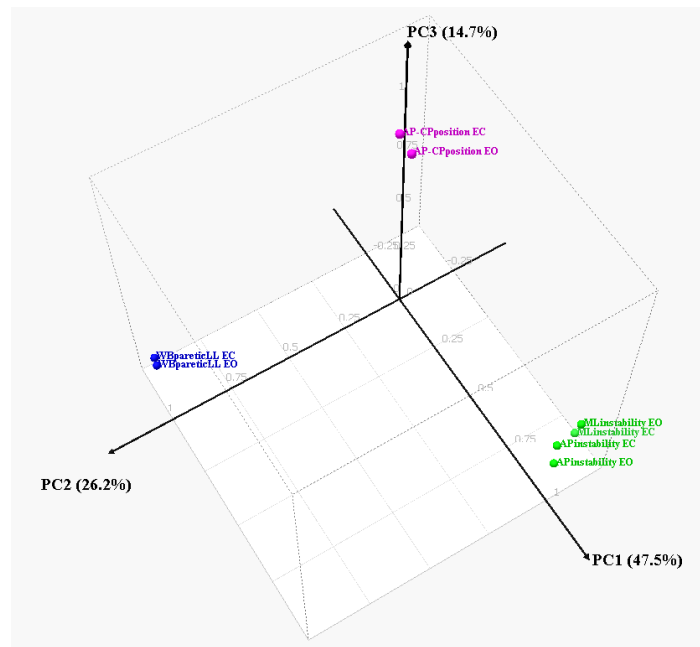


Figure 4. 3D Principal Component Analysis plot

Determinants of the global posturographic behavior in standing

We analyzed the determinants of the global posturographic behavior in standing using a MANOVA (stepwise backward procedure) combining the three independent indices explaining the greatest piece of information in the condition with vision: $WB_{\text{pareticLL}}$, AP_{position} , $AP_{\text{instability}}$). This procedure showed that the best model explaining the postural behavior of stroke patients in standing combined spatial neglect ($F(3,89)=5.3$, $p=0.002$; $\eta^2=0.152$ [large effect size]) and motor weakness ($F(3,89)=4.6$, $p=0.005$; $\eta^2=0.134$ [moderate effect size]). The model was valid given the lack of interaction between both variables ($F(3,89)=1.2$, $p=0.305$).

Posturographic behavior in the frontal plane

Data have been partly presented in Figure 3A and B, and in Tables 1 and 2, showing that position and instability indices were moderately correlated on the ML axis, and that the visual suppression condition was not crucial to understand the posturographic behavior of subacute stroke patients. In this section, we will only analyze the visual condition.

Clinical determinants of WBA

On the basis of a systematic review with meta-analysis (49) having calculated the cut-off values for symmetrical WB (41-59%), 63/95 (66%) could be considered as having a symmetrical WB. It also appeared that 26/95 (27%) patients of our series could be categorized having an abnormal spontaneous underloading of the paretic leg whereas 6/95 (6%) could be categorized as having an abnormal spontaneous overloading of the paretic leg.

To analyze the determinants of the WBA, we first compared in the whole series the $WB_{\text{pareticLL}}$ of patients presenting or not a given deficit (Table 5). Several clinical features influenced the % of WB loaded on the paretic lower limb. According to a decreasing order of

effect size, they were: motor weakness (only with a large effect size), spasticity, lateropulsion and spatial neglect (all three with a moderate effect size). Interestingly, the influence of lateropulsion was counterintuitive because the side overloaded was not the side of the body tilt which should have been mechanically loaded, but the opposite. Indeed, the average $WB_{\text{pareticLL}}$ was 41.8 (10) % of BW in patients showing lateropulsion vs 48.1 (8) % of BW in those without lateropulsion. The multivariate analysis by GLM showed that only motor weakness independently influenced the $WB_{\text{pareticLL}}$, the paretic leg being less spontaneously loaded in patients with moderate or severe weakness.

We then conducted a qualitative analysis of the six patients of the series (6%) who abnormally overloaded the paretic leg ($\geq 59\%$, see methods).

Figure 5 shows the CP displacement along the ML axis for each trial of these six patients, whose features are presented in Table 4. All presented a spatial neglect with a clear body neglect in three patients, and most of them had a mild motor deficit capable to support an increased BW. Three patients also showed a lateropulsion, severe in one. These six patients were characterized by two main postural behaviors. On the one hand, some patients (P2 and P5) had a low dispersion of the CP position and thus used their overloaded paretic lower limb as a “pillar” with nevertheless a gradual shift towards the paretic side. This postural strategy seemed rather associated with lateropulsion. The overloading of the paretic lower limb might simply mechanically result from a whole-body tilt to this side. On the other hand, other patients (P3 and P4) presented a high dispersion which reflected lateral swerves towards the paretic side secondary to the loading-unloading mechanism involved in stabilization along the ML axis. This postural behavior seemed to be associated with spatial neglect. One may wonder if they might need to overload the paretic neglected side to better feel and master its contribution to the standing posture by reproducing the weight shifting exercises learned in rehabilitation. This strategy would be a compensatory strategy. A mixed postural strategy (P6)

could be the expression of the pusher behavior characterized by actively pushing away from the non-paretic leg. Two patients who had an aphasia might have misunderstood the instructions for this specific posturographic assessment, different from those given during rehabilitation sessions dedicated to the WBA.

The univariate analysis studying the determinants of WBA was performed again after removing these six patients who presented an atypical postural strategy. Effect sizes were greater for the four variables that explained the WBA with a large effect size for three of them and with the following result ranked in a decreasing order: motor weakness ($p < 10^{-6}$; $d = 1.20$), spasticity ($p < 10^{-4}$; $d = 1.18$), lateropulsion ($p < 0.001$; $d = 0.86$) and spatial neglect ($p = 0.004$; $d = 0.66$).

Table 4. Characteristics of patients with WBA in favor of the paretic lower limb at D30

| Patients | Sex/Age | Etiology | | Posturo- graphy date | WB _{pareticLL} | ML _{instability} | Aphasia | Motor weakness LL | SCP | Hypoesthesia | PASS | mGait-FM | Bell test | Line bisection | Fluff test | CBS |
|-----------|---------|----------|---|-------------------------|-------------------------|---------------------------|---------|----------------------|------|--------------|------|----------|-----------|-------------------|------------|-----|
| | year | | | | | | | | | | | | | | | |
| P1 | M/65 | H | L | D60 | 63.4 | 6.8 | yes (4) | 32 | 0 | moderate | 34 | 6 | 2 | -0.5 | - | 3 |
| P2 | F/71 | I | R | D60 | 60.0 | 3.2 | no | 30 | 0.75 | no | 30 | 5 | 11 | 18.5 | 5 | 8 |
| P3 | F/72 | I | L | D30 | 69.1 | 25 | no | 40 | 0 | moderate | 36 | 6 | 7 | -3.5 | 0 | 14 |
| P4 | M/67 | I | R | D60 | 69.1 | 13.8 | no | 33 | 0 | - | 36 | 6 | 4 | -0.5 | 5 | 11 |
| P5 | M/54 | I | L | D30 | 63.8 | 3 | yes (4) | 32 | 0.25 | no | 36 | 6 | 2 | 1 | 0 | 5 |
| P6 | M/69 | I | R | D90 | 64.9 | 10.6 | no | 23 | 4.25 | severe | 25 | 2 | 12 | 6.5 | 9 | 19 |

WB= Weight Bearing, LL= Lower Limb, SCP= Scale for Contraversive Pushing, PASS= Postural Assessment Scale for Stroke, mGait-FM = modified Gait Fugl-Meyer, CBS= Catherine Bergego Scale, I= ischemia, H= hematoma
Clinical impairments were evaluated on D30 with standardized tools and functional disabilities were evaluated around the posturography date with the PASS and the mGait-FM (see methods).

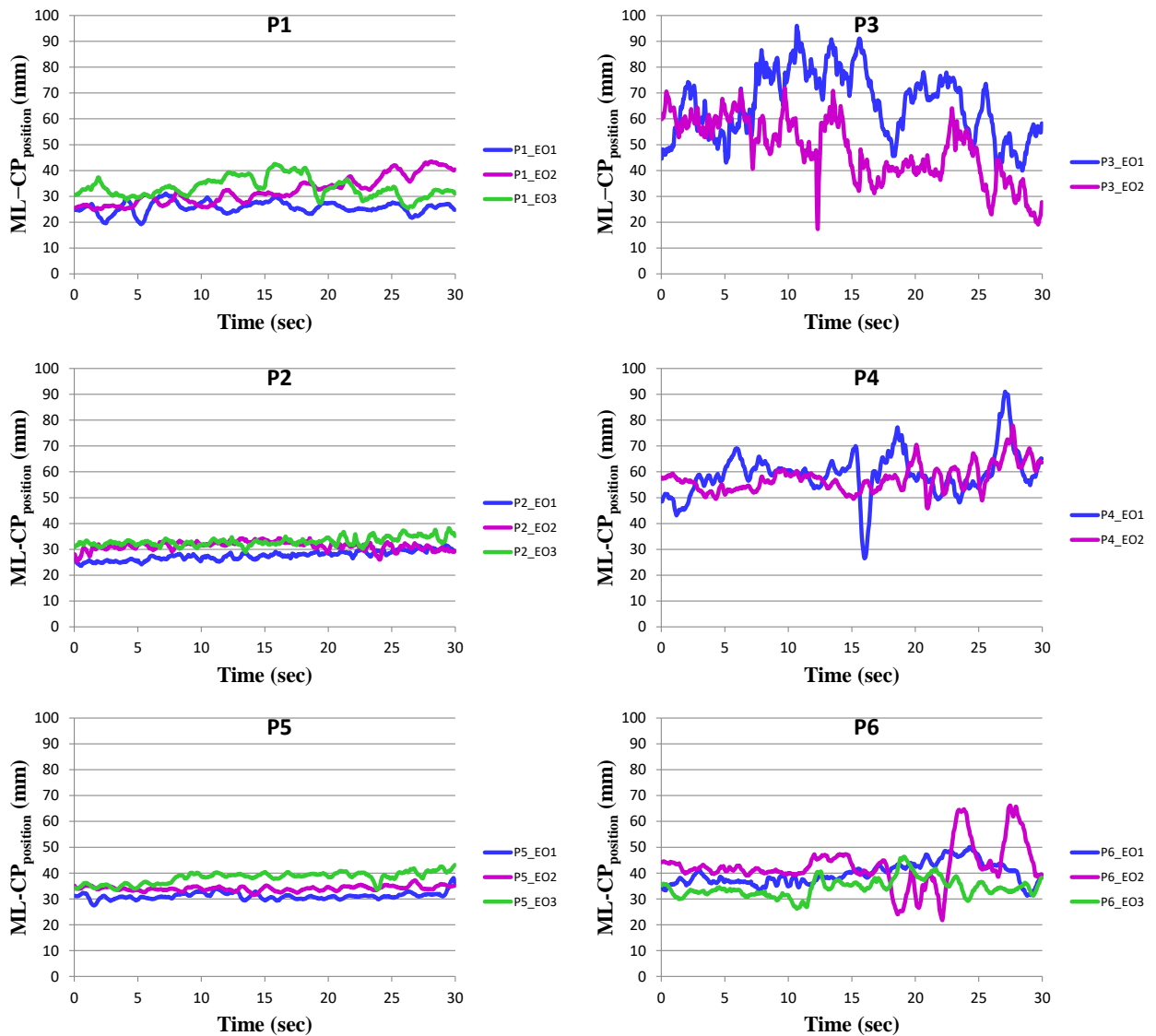


Figure 5. CP displacements along the ML axis for patients with WBA in favor of the paretic lower limb

Clinical determinants of lateral instability

To analyze the determinants of lateral instability, we compared the $ML_{instability}$ of patients presenting or not a given deficit (Table 5). Several clinical features influenced the $ML_{instability}$. Ranked on the base of a decreasing order of moderate effect size, they were: lateropulsion, spatial neglect, hypoesthesia, and motor weakness. A small effect size was found for spasticity and hemianopia. Interestingly, no influence of hemianopia was found on the

ML_{instability} without vision (p=0.270). The multivariate analysis by GLM showed that the best model explaining the ML_{instability} combined spatial neglect (F(1,91)=14.5, p<0.001; η^2 =0.138 [moderate effect size]) and motor weakness (F(1,91)=10.5, p=0.002; η^2 =0.103 [moderate effect size]).

Table 5. Clinical determinants of position and instability indices along ML axis

| | WB _{pareticLL} (%) | | ML _{instability} (mm) | |
|----------------------------------|-----------------------------|-------------------------------|--------------------------------|-------------------------------|
| Posturography date | | | | |
| D30 (n=59, 62%) | 47.2 (7.9) | p= 0.066 | 6.2 (3.8 – 10.8) | p< 0.001; r= 0.36 |
| D60 or after (n=36, 38%) | 43.7 (10.7) | | 12.4 (6.5 – 22.0) | |
| Deficits | | | | |
| Lower limb motor weakness | | | | |
| No or light (n=45, 47%) | 49.7 (6.6) | p< 10 ⁻⁴ ; d= 0.86 | 5.8 (3.5 – 8.5) | p< 10 ⁻⁴ ; r= 0.41 |
| Moderate or Severe (n=50, 53%) | 42.5 (9.9) | | 11.9 (6.3 – 21.2) | |
| Lower limb spasticity | | | | |
| No or light (n=71, 75%) | 47.4 (8.0) | p= 0.001; d=0.76 | 6.4 (4.0 – 12.2) | p= 0.005; r= 0.29 |
| Moderate or Severe (n=21, 22%) | 40.3 (10.5) | | 12.6 (6.5 – 23.6) | |
| Hypoesthesia | | | | |
| No or light (n=20, 21%) | 48.6 (7.5) | p= 0.090 | 4.4 (2.9 – 6.4) | p< 10 ⁻⁴ ; r= 0.41 |
| Moderate or Severe (n=74, 78%) | 44.8 (9.1) | | 9.0 (5.6 – 15.4) | |
| Homonymous hemianopia | | | | |
| No (n=65, 68%) | 46.6 (8.8) | p= 0.281 | 6.4 (4.4 – 12.9) | p= 0.039; r= 0.21 |
| Yes (n=30, 32%) | 44.4 (10.0) | | 9.1 (5.7 – 25.1) | |
| Spatial neglect | | | | |
| No or light (n=41, 43%) | 48.7 (7.8) | p= 0.009; d= 0.56 | 5.6 (3.7 – 6.9) | p< 10 ⁻⁴ ; r= 0.44 |
| Moderate or Severe (n=54, 57%) | 43.8 (9.7) | | 12.0 (6.3 – 19.2) | |
| Lateropulsion | | | | |
| No (n=62, 65%) | 48.1 (7.9) | p= 0.001; d= 0.69 | 6.0 (3.8 – 9.2) | p< 10 ⁻⁵ ; r= 0.45 |
| Yes (n=33, 35%) | 41.8 (10.1) | | 13.2 (7.6 – 25.0) | |
| Executive functions | | | | |
| No or Light (n=29, 31%) | 45.7 (8.2) | p= 0.936 | 6.4 (4.2 – 12.3) | p= 0.161 |
| Moderate or Severe (n=60, 63%) | 45.5 (9.7) | | 7.7 (4.9 – 14.8) | |
| Apraxia | | | | |
| No (n=78, 82%) | 46.2 (9.0) | p= 0.440 | 6.9 (4.2 – 13.3) | p= 0.214 |
| Yes (n=17, 18%) | 44.3 (10.2) | | 8.4 (6.4 – 20.2) | |
| Aphasia | | | | |
| No (n=68, 72%) | 45.4 (9.6) | p= 0.408 | 7.4 (4.3 – 13.8) | p= 0.785 |
| Yes (n=27, 28%) | 47.1 (8.1) | | 6.4 (4.8 – 12.6) | |

Data are mean (SD) or median (Q1 – Q3).

WB= Weight Bearing, LL= Lower Limb, CP= Center of Pressure, AP= Antero-Posterior, ML= Medio-Lateral, D30= Day 30

Effect size was calculated for significant results.

For the student's t-test, d = Cohen's d statistic with d < 0.20 = small effect, 0.50 ≤ d < 0.80 = moderate effect and d > 0.80 = large effect.

For the Mann-Whitney U test, 0.10 ≤ r < 0.30 = small effect, 0.30 ≤ r < 0.50 = medium effect and r ≥ 0.50 = large effect.

Missing data: lower limb spasticity (n=3,3%), hypoesthesia (n= 1,1%), executive functions (n=6,6%).

Postural behavior in the sagittal plane

Data have been partly presented in Figures 3B and 3D, and in Tables 1 and 2, showing that position and instability indices were not correlated on the AP axis, and that the visual suppression condition was not crucial to understand the posturographic behavior on this axis either. In this section, we will only analyze the visual condition.

Clinical determinants of AP-CP_{position}

We compared the AP-CP_{position} of patients presenting or not a given deficit (Table 6). No deficit influenced the AP-CP_{position} with at least a moderate effect size, and the GLM was inconclusive. Finally, the great variations of the AP-CP_{position} in our series (Figure 3A) remained unexplained.

Clinical determinants of sagittal instability

We compared the AP_{instability} of patients presenting or not a given deficit (Table 6). Several clinical features influenced the AP_{instability}. Ranked on the base of a decreasing order of moderate effect size, they were: spatial neglect, lateropulsion, hypoesthesia, and motor weakness. The multivariate analysis by GLM showed that only spatial neglect was independently associated with the AP instability.

Table 6. Clinical determinants of position and instability indices along AP axis

| | AP-CP _{position} (mm) | | AP _{instability} (mm) | |
|----------------------------------|--------------------------------|-------------------|--------------------------------|-------------------------------|
| Posturography date | | | | |
| D30 (n=59, 62%) | 48.1 (17.4) | p= 0.987 | 10.4 (8.0 – 13.0) | p= 0.001; r= 0.35 |
| D60 or after (n=36, 38%) | 48.2 (18.0) | | 16.1 (9.9 – 18.9) | |
| Deficits | | | | |
| Lower limb motor weakness | | | | |
| No or light (n=45, 47%) | 49.5 (16.8) | p= 0.468 | 10.0 (8.0 – 13.6) | p= 0.003; r= 0.30 |
| Moderate or Severe (n=50, 53%) | 46.9 (18.2) | | 13.0 (9.6 – 18.8) | |
| Lower limb spasticity | | | | |
| No or light (n=71, 75%) | 47.1 (17.7) | p= 0.374 | 10.8 (8.2 – 15.6) | p= 0.043; r= 0.21 |
| Moderate or Severe (n=21, 22%) | 51.0 (17.3) | | 13.0 (10.4 – 18.8) | |
| Hypoesthesia | | | | |
| No or light (n=20, 21%) | 42.2 (15.6) | p= 0.099 | 8.5 (7.2 – 11.4) | p= 0.002; r= 0.31 |
| Moderate or Severe (n=74, 78%) | 49.5 (17.8) | | 12.6 (9.3 – 18.2) | |
| Homonymous hemianopia | | | | |
| No (n=65, 68%) | 46.5 (17.4) | p= 0.179 | 10.8 (8.5 – 15.6) | p= 0.064 |
| Yes (n=30, 32%) | 51.7 (17.5) | | 12.9 (8.4 – 20.3) | |
| Spatial neglect | | | | |
| No or light (n=41, 43%) | 46.9 (19.5) | p= 0.552 | 9.6 (8.0 – 12.1) | p< 10 ⁻⁴ ; r= 0.44 |
| Moderate or Severe (n=54, 57%) | 49.1 (16.0) | | 14.5 (10.5 – 19.0) | |
| Lateropulsion | | | | |
| No (n=62, 65%) | 45.5 (17.1) | p= 0.048; d= 0.44 | 10.4 (8.4 – 13.6) | p= 0.001; r= 0.35 |
| Yes (n=33, 35%) | 53.0 (17.6) | | 16.4 (11.3 – 19.8) | |
| Executive functions | | | | |
| No or Light (n=29, 31%) | 48.2 (16.7) | p= 0.957 | 11.0 (8.5 – 15.6) | p= 0.446 |
| Moderate or Severe (n=60, 63%) | 48.5 (18.5) | | 12.3 (8.5 – 16.9) | |
| Apraxia | | | | |
| No (n=78, 82%) | 48.8 (18.0) | p= 0.437 | 11.4 (8.4 – 16.4) | p= 0.168 |
| Yes (n=17, 18%) | 45.1 (15.5) | | 13.4 (9.6 – 20.4) | |
| Aphasia | | | | |
| No (n=68, 72%) | 50.4 (17.3) | p= 0.046; d= 0.46 | 11.3 (8.6 – 16.4) | p= 0.738 |
| Yes (n=27, 28%) | 42.4 (17.2) | | 13.0 (8.0 – 18.8) | |

Data are mean (SD) or median (Q1 – Q3).

WB= Weight Bearing, LL= Lower Limb, CP= Center of Pressure, AP= Antero-Posterior, ML= Medio-Lateral, D30= Day 30

Effect size was calculated for significant results.

For the student's t-test, d = Cohen's d statistic with d < 0.20 = small effect, 0.50 ≤ d < 0.80 = moderate effect and d > 0.80 = large effect.

For the Mann-Whitney U test, 0.10 ≤ r < 0.30 = small effect, 0.30 ≤ r < 0.50 = medium effect and r ≥ 0.50 = large effect.

Missing data: lower limb spasticity (n=3,3%), hypoesthesia (n= 1,1%), executive functions (n=6,6%).

Posturographic behavior and mobility in daily life

Posturographic behavior and balance abilities

We first tested relationships between posturographic indices and the PASS scores at the posturography date. A poor balance was correlated with low $WB_{\text{pareticLL}}$ ($r=0.554$, $p<10^{-9}$), and with a great instability both on the ML ($r=-0.533$; $p<10^{-7}$) and on the AP ($r=-0.431$, $p<10^{-4}$) axis. In contrast, no relationship was found between the $AP-CP_{\text{position}}$ and balance abilities at the posturography date ($r=-0.006$; $p=0.954$).

We then used a stepwise MLR model to explain balance capacities at the posturography date from postural indices. A model based on the $WB_{\text{pareticLL}}$ (coefficient $[B]=0.20$, 95%CI $[0.12-0.28]$, $p<10^{-5}$) and the $ML_{\text{instability}}$ ($B=-10.06$, 95%CI $[-14.30-5.81]$, $p<10^{-5}$) encountered 44% of the information related to balance at the posturography date. By adding SCP scores assessing lateropulsion severity ($B=-1.76$, 95%CI $[-2.19-1.33]$; $p<10^{-6}$) the model explained 22% more information (totaling 66%). This meant that lateropulsion had been poorly assessed by posturography and that the association of posturographic behavior and lateropulsion explained very well balance in daily life.

We further investigated these relationships and tested the value of WB to predict the ability to stand ($PASS \geq 28$). The area under the ROC curve (AUC) displayed in Figure 6 was 0.84 (95% CI $[0.69-0.98]$, $p<0.001$). The cut-off value of $WB_{\text{pareticLL}}$ calculated from the Youden Index was 40.7% (sensitivity=0.846, specificity=0.75, PPV=0.94, NPV=0.53). This indicated that individuals with a spontaneous $WB > 40.7\%$ on the paretic lower limb would be able to stand with good balance at the posturography date (probability 94%, 95% CI $[88-97]$).

Posturographic behavior and gait abilities

We first tested relationships between posturographic indices and the mGait-FM at the posturography date. A poor walking ability was correlated with low $WB_{\text{pareticLL}}$ ($r=0.521$; $p<10^{-8}$), and with great instability both on the ML ($r=-0.579$; $p<10^{-9}$) and on the AP ($r=-0.449$;

$p < 10^{-5}$) axis. In contrast, no relationship was found between the position of the AP-CP_{position} and walking abilities at the posturography date ($r=0.008$; $p=0.936$).

We then used a stepwise MLR model to explain walking capacities at the posturography date from postural indices. A model based on the WB_{pareticLL} (coefficient [B]=0.07, 95%CI[0.04–0.11]; $p < 10^{-4}$) and the ML_{instability} (B=-4.87, 95%CI[-6.63–-3.14]; $p < 10^{-7}$) encountered 46% of the information related to walking abilities at the posturography date. By adding SCP scores assessing lateropulsion severity (B=-0.54, 95%CI [-0.75–-0.34], $p < 10^{-6}$) the model explained 12% more information (totaling 58%).

We further investigated these relationships and tested the value of WB to predict the ability to walk independently at the posturography date ($mGait-FM \geq 5$). The AUC displayed in Figure 6 was 0.81 (95% CI [0.72–0.9], $p < 0.001$). The cut-off value of WB_{pareticLL} calculated from the Youden Index was 43.1% (sensitivity=0.906, specificity=0.683, PPV=0.74, NPV=0.89), indicating that individuals who spontaneously loaded less than 43.1% of BW on the paretic lower limb would not be able to walk independently at the posturography date (probability 89%, 95%CI[78–95]).

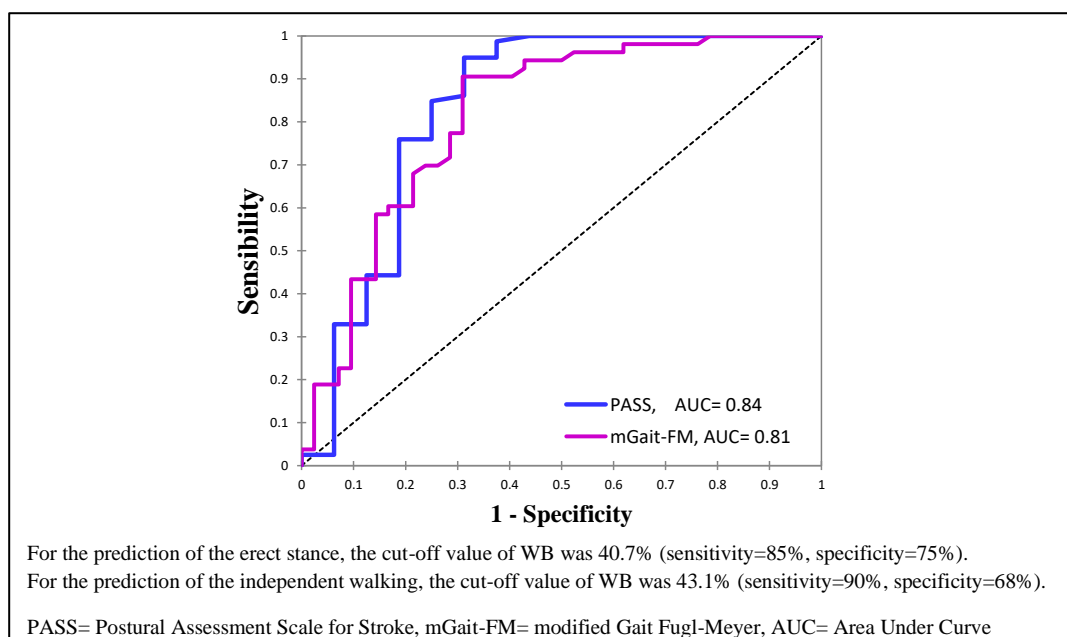


Figure 6. The receiver operating characteristic (ROC) curve of balance and gait abilities for the % of WB loaded on the paretic lower limb

DISCUSSION

Posturographic behavior in standing

The present study found that postural oscillations were greater on the AP axis than on the ML axis whatever the visual condition. Human body represents an inverted pendulum pivoting at the ankle joints which is therefore inherently unstable, and which requires the control of ankle plantarflexors and dorsiflexors to stabilize (50,51). Automatic postural responses to postural disturbances involve this ankle strategy which is the most used response during quiet stance, especially when slow and small perturbations occur on a firm and even surface (8). This stabilization mechanism includes an active feedback pathway via the central nervous system and a passive feedback pathway thanks to visco-elastic properties of tissues around the ankle joint (52). Along the AP axis, this pressure distribution mechanism is also preferred by stroke patients compared to a loading-unloading mechanism from hip despite the WBA often observed in these patients and despite the presence of a motor deficit that is often more severe for distal muscles than for proximal muscles (28).

As already conceded by de Haart et al. (53), removing vision led to a clear destabilization in both planes in subacute stroke patients, what is also observed in healthy individuals (54). Indeed, postural sway results in optical flow in the peripheral visual field and provides the central nervous system with information about the oscillations of the body relative to the environment necessary for postural stabilization (55). Postural control is achieved through the integration of visual, somatosensory and vestibular information that provides a representation of the body in space (i.e. postural body scheme) (56). Vision plays a key role especially when the afferent inputs from the other sensory systems are reduced due to stroke-related impairments. The destabilization was greater in the AP direction than in the ML direction when removing vision. This observation suggests the existence of a stronger visual dependence along the AP axis with respect to the ML axis in patients with a subacute stroke.

The visual reliance constitutes then a compensatory strategy for stroke patients to maintain a quiet standing. This adaptation could compensate for the compromised ability to integrate somatosensory information which originate from mechanoreceptors (proprioceptors) in the ankle joints, muscles, tendons, and plantar skin that provides a mapping of pressure distribution (57,58). These somatosensory information are required for the ankle control contrary to the hip strategy (59). Niam et al. (60) demonstrated that impaired proprioception was associated with a greater postural sway in the AP direction than in the ML direction in both visual conditions compared to subjects with intact ankle proprioception. Nevertheless, postural control disorders may also be caused by an impairment of vestibular input integration or by sensory organization disorders with an inability to select the pertinent sensory information (61). Moreover, rehabilitation would reinforce the excessive visual reliance by focusing on visual compensation rather than restoring the normal use of all sensory inputs (62). Lastly, future studies comparing these results with reference values from age-matched individuals are needed to explore more specifically the post-stroke postural behavior. Indeed, the visual input is also predominant in elderly people probably because of the global impairment of postural systems (63).

This study also showed that a model constituted by instability index on either axis and both position indices on each axis, just in one visual condition, were required to describe post-stroke postural control and contained 88.4% of the information provided by the posturography. The instability index was the main component. This finding reinforces the view that stabilization and orientation are independently involved in the post-stroke standing position despite their close relationship, and that WBA does not totally explain postural disorders in subacute stroke patients. In the condition with vision, the percentage of BW loaded on the paretic lower limb was associated with postural instability in the frontal plane whereas it was associated with postural instability along each plane in the condition without vision. Symmetric bipodal standing provides optimal stability requiring the least correcting

actions to maintain balance. In contrast, standing position becomes mechanically unstable when moving away from this equilibrium position due to changes in biomechanical constraints. Along the frontal plane, stability which is controlled by a weight-shifting strategy requiring more corrective hip torques (abduction/adduction) rather than ankle torques (64), seems to be jeopardized by WBA, in both visual conditions. However, it is difficult to conclude whether WBA is a cause or a consequence of postural instability because correlational studies do not allow the causal relationship to be inferred. Genthon et al. (29) found that stroke patients were more unstable compared to healthy individuals who were instructed to adopt a similar asymmetrical standing position. After stroke, patients adopt a postural strategy to limit postural instability by distributing the BW between the two lower limbs with a different optimum balance. This is a compensatory strategy which corresponds to a compromise between relieving their paretic leg and loading their non-affected limb to increase the somatosensory input and the motor output to stabilize as much as possible. Instability appears when the strong lower limb was unable to compensate the postural impairment of the paretic side, especially along the ML axis.

Nevertheless, our results showed that six patients (6%) favored their paretic lower limb rather than their strong side. Several interpretations isolated or combined may be proposed, in particular, the presence of lateropulsion behavior, spatial neglect and/or aphasia, in association with mild motor weakness preventing fall. This postural strategy seemed to be associated with stability for some patients who used the overloaded paretic lower limb as a “pillar”. For others, WBA was associated with postural instability while they showed satisfactory balance and walking abilities in daily life. In the absence of severe lateropulsion, this behavior could be considered as an adaptive process influenced by rehabilitation or related to the ability to initiate other balance reactions such as a rapid stepping with the strong lower limb (22). Further investigations are needed to clarify this issue.

Clinical determinants of postural behavior following subacute stroke

The current study showed that spatial neglect and motor weakness of the paretic lower limb strongly influenced the postural behavior of standing stroke patients.

The increase in WBA in favor of the non-paretic lower limb was related to motor weakness, in agreement with several authors (21,29,65,66). Most stroke patients prefer to load their non-paretic lower limb for biomechanical and safety reasons. Spatial cognition disorders can also disrupt BW distribution in standing. Spatial neglect and lateropulsion were associated with a discharge of the paretic lower limb. Patients with spatial neglect may display motor neglect or sensory extinction resulting in the unequal distribution of body mass. As for patients with lateropulsion, they should mechanically load their paretic side since lateropulsion implies an alignment of the erect posture with an erroneous reference of the verticality, tilted to the side opposite the lesion (10). This observed shift in the CP position towards the ipsilesional lower limb might be a compensatory strategy to prevent contralesional falling (67) but would be responsible for greater lateral and sagittal instability. Alternatively, this postural strategy might be an expression of the pusher behavior characterized by actively pushing away from the non-paretic leg. This behavior would be the extreme form of the spatial cognition disorder and would reflect a graviceptive neglect (68). The WBA would therefore represent both a direct consequence of the unilateral hemispheric lesion through the motor weakness and the spatial neglect, but also a compensatory strategy in patients with lateropulsion. Further investigations with an instrumental assessment of the perception of verticality are needed to determine if spatial cognitive deficits directly influence the WBA. Barra et al. (21) showed that a misperception of egocentric frame of reference through the biased perception of the longitudinal body axis (LBA) in relation with body neglect was a better predictor of WBA than subjective visual vertical (SVV) was. However, they had not analyzed the role of the postural vertical derived from graviceptive-somaesthetic information involved in the lateropulsion behavior.

Regarding the clinical determinants of postural sway, patients with a moderate to severe motor impairment showed a greater instability in both ML and AP directions. This finding might result from the asymmetry of lower-limb control of postural stability with a lower relative contribution of the paretic lower limb (29,64,65,69). A severe motor weakness is often accompanied by spasticity leading to varus equinus deformity of the paretic foot which modifies the area of the base of support in erect stance, and thus alters BW distribution and postural stability. Postural instability was also associated with the presence of moderate to severe hypoesthesia. Indeed, postural stabilization involves a sensory control which requires the integration of information from the somato-sensory, vestibular, and visual systems. Furthermore, lateropulsion and spatial neglect had a major impact on the stabilization along each axis, independently of motor weakness in the ML axis. Considering the determinant role of vision in postural stabilization, patients with spatial neglect may have underused visual information due to the hemi-attention characteristic of unilateral neglect. Indeed, patients had to fix a ball placed on the opposite wall in the posturographic procedure. Alternatively, these patients may also suffer from a reduced non spatial lateralized attentional capacity (70). Greater instability can be explained by the deficit of use of an allocentric referential resulting from this inattention to the environment (9). Postural stabilization consists also in adopting an egocentric frame of reference tightly related to the “body scheme” (71,72). This internal body representation involves controlling the position of body segments, with respect either to each other or to external support or to absolute space, and relying on intermediate body representations (eg, eye-head, head-shoulders, shoulders-pelvic). It might be disrupted in neglect patients, with a mismatch in the multisegmental coordination of the body in space, leading to greater postural instability (68,73). This manifestation referring to the bodily domain of neglect may be termed postural neglect (74). Further researches are needed to determine the respective roles of corporal and extra-corporal neglect in postural disability.

Posturographic behavior and mobility in daily life

Balance is one of the major issues in stroke rehabilitation because it represents one of the predictors of rehabilitation outcomes (75,76) and length of stay in rehabilitation center (77). Instability on each axis and WBA would jeopardize the standing balance in subacute stroke patients and only individuals with WB > 40.7% on the paretic leg would be able to stand with good balance. Beyond static balance assessments, the assessment of weight-shifting ability also provides crucial information about balance recovery after stroke (78).

Furthermore, we investigated the impact of postural control on locomotion. These two functions are strongly linked because they share some common organizational principles which are the control of the position of the center of body mass and the frame of reference anchored to the vertical (79). These analyses are even more clinically relevant because, of the 75% of stroke survivors who initially lose their ability to walk, only half of them will regain walking independence (80). As with standing balance, the ability to walk independently would be also affected by instability on each axis and by the WBA. The ability to load the paretic side by more than 43.1% of BW would enable an independent walking. Guillebastre et al. have already suggested that patients who do not load more than 40% of their BW on their paretic lower limb might benefit from the prescription of a walking device to compensate for the insufficient loading (81). Previous researches suggested a strong association between WBA and gait performances (82,83). The degree of WBA is a good clinical indicator of spatio-temporal gait variables which are not directly measurable with observational or timed gait analysis in routine practice (83). Hemiparetic patients walk slower, more asymmetrically and sway more laterally compared to healthy individuals, with a prolonged stance on the non-paretic lower limb (84). Conversely, the relationship between postural instability in standing position and the gait performances is less clear in the literature.

Other factors such as tilt must be also considered, in addition to WBA and postural instability. The model based on the percentage of BW on the paretic leg and the instability in the frontal

plane best explained balance and walking abilities around the posturography date. However, the posturographic assessment contained less than half of the information related to balance and gait disorders. Therefore, posturography is not sufficient for the evaluation of the functional abilities. The addition of SCP scores in the model allowed a better analysis of these capacities. This means on the one hand that lateropulsion body misorientation with respect to gravity (lateropulsion) which is the primary factor altering balance and gait during the post-stroke subacute stage (2), is poorly evaluated by posturography, and on the other hand that the standardized scales provide additional information in the evaluation of activity limitations.

Study limitations

Some limitations need to be considered when interpreting the results.

Firstly, the main limitation is the retrospective analysis of the data partly compensated by the achievement of a systematic and prospective clinical evaluation at a given time post-stroke by trained therapists using standardized scales. The sample size was also satisfactory with few missing data.

Secondly, a methodological bias can be discussed by the selection of the systematic evaluation carried out at D30 or D60 for the analysis of the clinical determinants of postural control. Indeed, the most severely impaired patients or those with medical complications arrived at the rehabilitation center more than 30 days following their stroke. Even if the first clinical evaluation in the rehabilitation center was finally retained for these patients, this does not exclude a possible spontaneous recovery that could have led to an underestimation of stroke-related impairments.

Similarly, postural control disorders could also be underestimated since patients assessed on the stabilometry platform had to be able to maintain an upright position independently. However, the patients were assessed at an early stage with a median of 35.0 (29.0-64.0) days post-stroke. Although WBA improves significantly during the first 4 weeks of rehabilitation,

some degree of asymmetry may have persisted. Postural instability also decreases in the first 12 weeks of rehabilitation (53). WB could also be analyzed before the patients were trained by the rehabilitation to perform a weight shifting to the paretic lower limb. Another point to note is the fact that this study included all stroke patients whatever the percentage of BW loaded on the paretic side.

Additionally, this paper does not explain the determinants of the CP position along the AP axis which represents one of the three essential variables in describing post-stroke postural behavior.

Finally, this is an observational study that is descriptive only. The inclusion of healthy age-matched controls would have allowed comparison of results with baseline values for a better analysis of postural behavior after stroke.

CONCLUSION

THÈSE SOUTENUE PAR : Adèle CHAUVIN

TITRE :

CONTRIBUTIONS ET DETERMINANTS DES INDICES DE POSTUROGRAPHIE
POUR COMPRENDRE LE COMPORTEMENT POSTURAL EN STATION
DEBOUT APRES UN AVC

CONTRIBUTIONS AND DETERMINANTS OF POSTUROGRAPHY INDICES
TO UNDERSTAND THE STANDING POSTURE AFTER STROKE

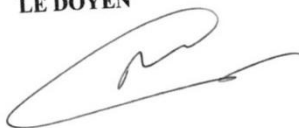
This cross-sectional observational study investigated the standing postural behavior in a large series of 95 consecutive patients at the subacute stage after a first hemispheric stroke using the first posturographic assessment performed in rehabilitation center. One instability index on either axis and both position indices on each axis, just in one visual condition, are independent and required to describe the postural control. The instability index is the primary index and explains nearly half of the information contained in the postural data set provided by a posturography assessment. The study also emphasizes the key role of spatial neglect and motor weakness in the post-stroke postural behavior.

The finding reinforces the view that despite their close relationship, postural instability and WBA are independently involved in the standing posture after stroke. The WBA should not be the main target of rehabilitation care. Lateral instability and the impaired ability to load the paretic lower limb only partly explain balance and gait disorders in daily life. In addition to postural instability and WBA, lateropulsion behavior should be more closely considered in the evaluation and the management of postural disorders in stroke patients. This study therefore provides a better understanding of the posturographic indices which underlie the postural behavior in patients after subacute hemispheric stroke, to guide their rehabilitation.

Pr Dominic PERENNOU
Médecine Physique et Réadaptation
Institut de Rééducation
Hôpital SUD - CHU de Grenoble
BP 338 - 38434 ECHIROLLES Cedex
Tél. 04 76 76 60 83
N° RPPS 10002184769

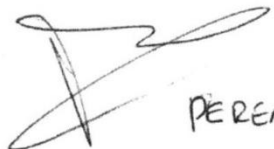
VU ET PERMIS D'IMPRIMER
Grenoble, le : 8/06/12

LE DOYEN



Pr. Patrice MORAND

Pour le Président
et par délégation
—
Le Doyen de Médecine
Pr. Patrice MORAND



PERENNOU

LE PRÉSIDENT DE LA THÈSE

Pr. Dominic PERENNOU

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ADDITIONAL MATERIALS

Table-e1
Distribution of the posturographic data

| | Kolmogorov-Smirnov test | |
|---------------------------------------|-------------------------|---------------------|
| | with vision | without vision |
| Position indices | | |
| WB _{pareticLL} | p= 0.200 | p= 0.034 |
| AP-CP _{position} | p= 0.200 | p= 0.200 |
| Instability indices | | |
| ML _{instability} | p< 10 ⁻⁸ | p< 10 ⁻⁵ |
| AP _{instability} | p< 10 ⁻⁴ | p< 0.001 |
| ML _{instability} transformed | p= 0.114 | p= 0.088 |
| AP _{instability} transformed | p= 0.200 | p= 0.200 |

WB= Weight Bearing, LL= Lower Limb, AP= Antero-Posterior. ML= Medio-Lateral

WB_{pareticLL}: percentage of total body weight loaded on the paretic lower limb

AP-CP_{position}: average position (mm) of the CP along the AP axis

Instability is defined by the dispersion of the CP on each axis and is represented by 2SD.

The data of instability were transformed as “log√x”.

Medical Research Council for muscle strength

| Grade | Ability to move |
|-------|---|
| 5 | The muscle can move the joint it crosses through a full range of motion, against gravity, and against full resistance applied by the examiner. |
| 4 | The muscle can move the joint it crosses through a full range of motion against moderate resistance. |
| 3 | The muscle can move the joint it crosses through a full range of motion against gravity but without any resistance. |
| 2 | The muscle can move the joint it crosses through a full range of motion only if the part is properly positioned so that the force of gravity is eliminated. |
| 1 | Muscle contraction is seen or identified with palpation, but it is insufficient to produce joint motion even with elimination of gravity. |
| 0 | No muscle contraction is seen or identified with palpation; paralysis. |

Modified Ashworth Scale for grading spasticity

| Grade | Description |
|-------|---|
| 0 | No increase in muscle tone |
| 1 | Slight increase in muscle tone, manifested by a catch and release or by minimal resistance at the end of the range of motion when the affected part/s is/are moved in flexion or extension. |
| 1+ | Slight increase in muscle tone, manifested by a catch, followed by minimal resistance throughout the remainder (less than half) of the ROM. |
| 2 | More marked increase in muscle tone through most of the ROM, but affected part(s) easily moved. |
| 3 | Considerable increase in muscle tone, passive movement difficult. |
| 4 | Affected part(s) rigid in flexion or extension. |

ROM, range of motion.

The ecological Catherine Bergego Scale (CBS)

| | 0 | 1 | 2 | 3 |
|---|--------------------------|--------------------------|--------------------------|--------------------------|
| 1. Forgets to groom or shave the left part of his/her face | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| 2. Experiences difficulty in adjusting his/her left sleeve or slipper | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| 3. Forgets to eat food on the left side of his/her plate | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| 4. Forgets to clean the left side of his/her mouth after eating | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| 5. Experiences difficulty in looking towards the left | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| 6. Forgets about a left part of his/her body (eg, forgets to put his/her upper limb on the armrest, or his/her left foot on the wheelchair rest, or forgets to use his/her left arm when he/she needs to) | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| 7. Has difficulty in paying attention to noise or people addressing him/her from the left | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| 8. Collides with people or objects on the left side, such as doors or furniture (either while walking or driving a wheelchair) | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| 9. Experiences difficulty in finding his/her way towards the left when traveling in familiar places or in the rehabilitation unit | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| 10. Experiences difficulty finding his/her personal belongings in the room or bathroom when they are on the left side | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| Total score (/30) | | | | |

0=no neglect; 1=mild neglect; 2=moderate neglect; 3=severe neglect

The Scale for Contraversive Pushing (SCP)

| A | Spontaneous body posture | Sitting | Standing |
|---|---|--------------------------|--------------------------|
| | 1 = severe contraversive tilt with falling to that side | <input type="checkbox"/> | <input type="checkbox"/> |
| | 0.75 = severe contraversive tilt without falling | <input type="checkbox"/> | <input type="checkbox"/> |
| | 0.25 = mild contraversive tilt without falling | <input type="checkbox"/> | <input type="checkbox"/> |
| | 0 = inconspicuous | <input type="checkbox"/> | <input type="checkbox"/> |
| | | Total (max = 2) | |
| B | Use of the nonparetic extremities (abduction &) | | |
| | 1 = performed spontaneously, already when at rest | <input type="checkbox"/> | <input type="checkbox"/> |
| | 0.5 = performed only on changing the position (e.g., on transferring from bed to wheelchair) | <input type="checkbox"/> | <input type="checkbox"/> |
| | 0 = inconspicuous | <input type="checkbox"/> | <input type="checkbox"/> |
| | | Total (max = 2) | |
| C | Resistance to passive correction of tilted posture ^a | | |
| | 1 = resistance occurs | <input type="checkbox"/> | <input type="checkbox"/> |
| | 0 = resistance does not occur | <input type="checkbox"/> | <input type="checkbox"/> |
| | | Total (max = 2) | |

a. Touch the patient at the sternum and the back. Instruction: "I will move your body sideways. Please permit this movement."

The modified Fugl-Meyer Assessment for gait (mGait-FM)

Lindmark and Hamrin Walking Scale

| | Score | Meaning |
|--------------------------------|-------|---|
| Needs a human or technical aid | 0 | Cannot walk |
| | 1 | Can take a few steps with the help of 2 persons |
| | 2 | Can take a few steps with the help of 1 person |
| | 3 | Can walk with a roller, crutches, or quadripods |
| | 4 | Can walk with one stick or one crutch |
| Walk without a technical aid | 5 | Can walk without a walking aid, but walks slowly or limps |
| | 6 | Can walk at a normal speed for his or her age |

The Postural Assessment Scale for Stroke (PASS)

Maintaining a Posture

1. Sitting without support (sitting on the edge of an 50-cm-high examination table [a Bobath plane, for instance] with the feet touching the floor)

0=cannot sit

1=can sit with slight support, for example, by 1 hand

2=can sit for more than 10 seconds without support

3=can sit for 5 minutes without support

2. Standing with support (feet position free, no other constraints)

0=cannot stand, even with support

1=can stand with strong support of 2 people

2=can stand with moderate support of 1 person

3=can stand with support of only 1 hand

3. Standing without support (feet position free, no other constraints)

0=cannot stand without support

1=can stand without support for 10 seconds or leans heavily on 1 leg

2=can stand without support for 1 minute or stands slightly asymmetrically

3=can stand without support for more than 1 minute and at the same time perform arm movements above the shoulder level

4. Standing on nonparetic leg (no other constraints)

0=cannot stand on nonparetic leg

1=can stand on nonparetic leg for a few seconds

2=can stand on nonparetic leg for more than 5 seconds

3=can stand on nonparetic leg for more than 10 seconds

5. Standing on paretic leg (no other constraints)

Same scoring as item 4

Changing Posture

Scoring of items 6 to 12 is as follows (items 6 to 11 are to be performed with a 50-cm-high examination table, like a Bobath plane; items 10 to 12 are to be performed without any support; no other constraints):

0=cannot perform the activity

1=can perform the activity with much help

2=can perform the activity with little help

3=can perform the activity without help

6. Supine to affected side lateral

7. Supine to nonaffected side lateral

8. Supine to sitting up on the edge of the table

9. Sitting on the edge of the table to supine

10. Sitting to standing up

11. Standing up to sitting down

12. Standing, picking up a pencil from the floor