

Postural control after traumatic brain injury in patients with neuro-ophthalmic deficits

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Abstract: Postural instability is a common and devastating consequence of Traumatic Brain Injury (TBI). The majority of TBI patients also suffer from neuro-ophthalmic deficits that may be an important contributing element to their sensation of vertigo and dizziness. Static posturography aims at the objective evaluation of patient balance impairment, but it is usually affected by large inter- and intra- subject variability. Here we propose a protocol based on ten randomized trials stimulating in different ways the visual and vestibular systems. Due to its completeness, our protocol highlights the specific residual difficulties of each patient in the various conditions. In this way, it was possible to evidence significant balance abnormalities in TBI patients with respect to controls. Moreover, by means of a multivariate analysis we were able to discriminate different levels of residual neuro-ophthalmic impairment.

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Postural control after traumatic brain injury in patients with neuro-ophthalmic deficits

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1 Abstract

2 Postural instability is a common and devastating consequence of Traumatic Brain Injury (TBI). The  
3 majority of TBI patients also suffer from neuro-ophthalmic deficits that may be an important  
4 contributing element to their sensation of vertigo and dizziness. Static posturography aims at the  
5 objective evaluation of patient balance impairment, but it is usually affected by large inter- and  
6 intra- subject variability. Here we propose a protocol based on ten randomized trials stimulating in  
7 different ways the visual and vestibular systems. Due to its completeness, our protocol highlights  
8 the specific residual difficulties of each patient in the various conditions. In this way, it was possible  
9 to evidence significant balance abnormalities in TBI patients with respect to controls. Moreover, by  
10 means of a multivariate analysis we were able to discriminate different levels of residual neuro-  
11 ophthalmic impairment.

12

13 1. Introduction

14 Traumatic Brain Injury (TBI) is an important cause of disability at all ages [1]. In the USA the  
15 annual incidence of emergency department visits and hospital admission are respectively 403 per  
16 100,000 and 85 per 100,000 [2]. The mean annual incidence rate of hospitalized and fatal TBI for  
17 Europe is 235 per 100,000 [3]. Approximately 80% of injuries are classified as mild, 10% as  
18 moderate, and 10% as severe [3]. Severity is usually described by the Glasgow Coma Scale (GCS)  
19 [4], evaluated when the patient enters the emergency department. However, GCS may change  
20 during hospitalization and it does not describe the nature and the entity of the residual impairments.  
21 One of the most common complaints among TBI patients is postural instability and balance  
22 impairment [5-6].

23 Neuro-ophthalmic deficits commonly follow TBI, since the afferent and efferent pathways are  
24 vulnerable to traumatic injury. Commonly described categories of oculomotor dysfunctions are  
25 anomalies of accommodation, version, vergence (nonstrabismic, as well as strabismic),

1 photosensitivity, visual field integrity, and ocular health [7]. Authors indicate different percentages  
2 of neuro-ophthalmic impairments following TBI, ranging from 39% to 90%, as described in [8-11].  
3 Neuro-ophthalmic deficits may have important consequences on balance, since postural control  
4 integrates information from the visual, vestibular, and somatosensory systems.

5 Subjective complaints of dizziness that occur in the absence of objective clinical signs are difficult  
6 to assess [12-13]. Static stabilometry may provide an objective evaluation of postural instability  
7 [14-18] by characterizing the performance of the postural control system during quiet standing.  
8 This technique is based on the study of the trajectories of the Center of Pressure (CoP) on the  
9 support surface. CoP trajectories are recorded by a force platform and analyzed using different  
10 techniques and extracting different kinds of parameters [16,18]. A possible limit of static  
11 stabilometry was highlighted by [15,19] due to the high inter-subject and intra-subject variability  
12 that many studies report.

13 Previous studies [12-13, 20-25] addressed the problem of quantifying the consequences of TBI on  
14 balance assessment using static stabilometry. None of the studies published in the past specifically  
15 considered a group of TBI patients with a significant residual visual impairment.

16 Studies on static posturography are usually based on an acquisition protocol consisting of two trials,  
17 with eyes open and closed respectively, to take into account the role of the visual system.

18 Our study differs from the previous ones for two aspects. First, we consider a group of TBI patients  
19 with residual neuro-ophthalmic deficits. Secondly, this study is based on a more complete  
20 acquisition protocol that adds to frontal open- and closed-eye trials, trials in which quiet standing of  
21 the subject is evaluated after a fast or a slow head rotation, both with eyes open and closed. In this  
22 way, it is possible to highlight the specific difficulties of each patient in various conditions that  
23 stimulate the visual and vestibular systems.

24 The aim of this study is to present a more complete acquisition protocol that allows to evaluate  
25 balance impairments in TBI patients and to demonstrate that such a protocol can discriminate

1 between controls and patients. Furthermore, we demonstrate that the presented protocol can also  
2 distinguish patients with different levels of visual impairment.

## 3 2. Materials and Methods

### 4 2.1 Subjects

5 TBI patients were recruited from the outpatients of the Clinica Oculistica “C. Sperino”, Ospedale  
6 Oftalmico (Torino), Italy, where they were referred to for a neuro-ophthalmologic examination. On  
7 the average, 73% of approximately 70 TBI patients that refer to Clinica Sperino in a year have  
8 neuro-ophthalmic impairments. The assessment of the severity of trauma was based on patient’s  
9 history and medical records obtained from the Post-traumatic Rehabilitation Centre of Caraglio  
10 (Cuneo, Italy) where they were treated after the injury. Our greater sample was formed by 50  
11 subjects. The inclusion criteria were the typology of brain injury, its localization, and the presence  
12 of visual impairment only at the time of the test. We considered patients whose injuries were  
13 localized in the frontal, fronto-temporal, and fronto-temporo-parietal lobe, to select subjects with a  
14 high probability of suffering from neuro-ophthalmic deficits caused by the trauma. We excluded  
15 patients who showed residual sensorimotor or vestibular impairments. Thus, 13 TBI patients out of  
16 50 were included in this study. These were 4 females (age 28 - 41 years, mean  $34.5\pm 6.0$  years;  
17 height 160 - 170 cm, mean  $163.0\pm 4.8$  cm; weight 53 - 85 kg, mean  $62.5\pm 15.1$  kg) and 9 males (age  
18 22 - 63 years, mean  $33.7\pm 13.9$  years; height 170 - 186 cm, mean  $181.0\pm 3.4$  cm; weight 70 - 90 kg,  
19 mean  $79.0\pm 6.4$  kg). Table 1 shows patient characteristics.

20 The control group consisted of 43 healthy subjects, 26 females and 17 males, matched for age,  
21 height and body mass index, with no orthopedic, neurological or visual problems.

22 Both TBI patients and controls underwent a neuro-ophthalmologic examination prior to the test to  
23 evaluate the visual system. They were examined for pupillary reflex, smooth pursuit, saccades and  
24 optokinetic nystagmus. The last column of Table 1 reports the clinical evaluation of the residual  
25 visual impairment at the time of the balance test. In all patients abnormal saccades were observed.  
26 In five patients global deficits of the eyes version were found. These patients were classified as

1 “severe” in the last column of Table 1. Three patients showed both saccades and smooth pursuit  
2 anomalies and were classified as “moderate”. Patients in which only abnormal saccades were  
3 observed were classified as “mild”. All the subjects belonging to the control group did not show any  
4 neuro-ophthalmologic abnormality.

5 The experimental protocol was approved by the local ethical committee and all participants gave  
6 their written informed consent to the study.

## 7 2.2 Acquisition protocol

8 Subjects were asked to stand quietly, in upright position, over a Kistler 9286A force platform. The  
9 inter-malleolar distance was fixed at 4 cm and the feet opening angle was 30°. The acquisition  
10 protocol consisted of 10 different trial conditions, five with eyes open (looking at a visual target)  
11 and five with eyes closed. The head positions were: 1) frontal: Open Eyes Frontal (OEF), Closed  
12 Eyes Frontal (CEF), 2) head rotated after a slow left rotation: Open Eyes Left slow (OELs), Closed  
13 Eyes Left slow (CELs) 3) head rotated after a slow right rotation: Open Eyes Right slow (OERs),  
14 Closed Eyes Right slow (CERs) 4) head rotated after a fast left rotation: Open Eyes Left fast  
15 (OELf), Closed Eyes Left fast (CELf), 5) head rotated after a fast right rotation: Open Eyes Right  
16 fast (OERf), Closed Eyes Right fast (CERf). At the operator order, the subject reached the requested  
17 head position and then the signal acquisition started. A biaxial accelerometer fixed on the forehead  
18 of the subject was employed for monitoring the head rotation. Each recording started at the end of  
19 the head rotation and lasted 60 s.

20 The sequence of trials was randomized to avoid learning and/or fatigue effects [26]. Every two trials  
21 the subject rested for one minute moving away from the platform.

22 The platform signal was recorded with a sampling frequency of 2 kHz and then down-sampled to 50  
23 Hz. The acquisition system was Step32 (DemItalia, Italy).

## 24 2.3 Data analysis

25 We calculated the major geometrical and time-domain parameters based on the CoP trajectory [16-  
26 17]. Table 2 describes the set of parameters we considered.

1 First, we compared TBI and controls - for each trial condition and CoP parameter - by means of a  
2 two-sample t-test, after having verified the gaussianity of the distributions.

3 Moreover, we were interested in taking into account the inter-relations among CoP parameters in  
4 the different trials, using the global information arising from the complete protocol: for each subject  
5 we have a total of 70 dependent variables (10 trials  $\times$  7 parameter values). To this purpose, we  
6 applied a multivariate analysis of variance (MANOVA) approach [27-29]. We reduced the number  
7 of CoP parameters considered, preserving those containing non-redundant information and  
8 discarding parameters highly correlated among them or with high within-group variability. To  
9 select the reduced set of parameters we used Wilks' Lambda statistic ( $\Lambda$ ) [27].  $\Lambda$  is an index of the  
10 parameters' discrimination capability. It is defined as the ratio between the within-groups  
11 generalized variability and the total generalized variability, the latter being the sum of the within-  
12 groups and between-groups generalized variability. This index takes values between zero and one,  
13 lower  $\Lambda$ -values indicating a better discrimination among groups.

14 The procedure we adopted is the following. As a first step, we calculated  $\Lambda$  for each parameter  
15 separately and sorted the parameters in  $\Lambda$  ascending order. We kept the parameter with lower  $\Lambda$ -  
16 value. Then we considered all the possible combinations of two parameters, recalculated the  
17 corresponding  $\Lambda$ -values and sorted them in ascending order, keeping the combination with lower  $\Lambda$ -  
18 value. The process was carried out iteratively adding one parameter at a time, each time  
19 recalculating the  $\Lambda$ -value and choosing the combination of parameters showing the lowest  $\Lambda$ -value.  
20 The parameter selection stopped when, adding more parameters,  $\Lambda$  did not significantly decrease  
21 [27].

22 After the selection of the reduced set of CoP parameters we summarized the information arising  
23 from the ten-trial protocol applying a canonical variate analysis (CVA) [27]. The canonical  
24 variables  $C$  are linear combinations of the original variables, chosen to maximize the separation  
25 among groups. Specifically, the first canonical variable  $C_1$  is the linear combination of the original  
26 variables that has the maximum separation among groups. This means that among all possible linear

1 combinations, it is the one with the most significant F statistic in a one-way analysis of variance.  
2 The second canonical variable C2 has the maximum separation while being orthogonal to C1, and  
3 so on. We represented the two populations of TBI and controls in the plane of the first two  
4 canonical variables.

### 5 3. Results

6 Fig. 1 shows, for each parameter, mean and standard deviation of TBI patients and controls in the  
7 ten typologies of acquisition. Differences between groups which are statistically significant (two-  
8 sample t-test,  $p \leq 0.05$ ) are indicated with an asterisk. Major and Minor Axis and the RMS values  
9 show significant differences in all of the trials. Mean Velocity highlights significant differences  
10 between TBI and controls mainly in trials after head rotation (slow or fast). On the contrary, Mean  
11 Velocity is not significantly different in trials with a frontal head position, both with eyes open and  
12 closed. Sway Area and Eccentricity do not differentiate the two groups.

13 We tested also open eyes vs. closed eyes performances: significant differences are indicated with  
14 triangles in controls and with circles in TBI patients. In controls, differences were observed in all  
15 the test conditions for the Mean Velocity. For the other parameters, statistically significant  
16 differences were observed only in a few test conditions. In TBI patients there were significant  
17 differences between open eyes and closed eyes trials only in a single test condition (Mean Velocity,  
18 OERf vs. CERf).

19 Fig. 2 shows the values of  $\Lambda$  on which we based the parameter selection. The single parameter that  
20 better differentiates the two populations is Minor Axis ( $\Lambda = 0.42$ ), the best combination of two  
21 parameters is Minor and Major Axes ( $\Lambda = 0.31$ ), that of three parameter is Minor Axis, Major Axis,  
22 and RMS AP ( $\Lambda = 0.15$ ), that of four parameters is Minor Axis, Major Axis, RMS AP, and  
23 Eccentricity ( $\Lambda = 0.076$ ), and, finally, that of five parameters is Minor Axis, Major Axis, RMS AP,  
24 Eccentricity, and Sway Area ( $\Lambda = 0.0035$ ). Therefore, the  $\Lambda$ -value decreases remarkably each time  
25 a parameter is added to the set of the best CoP parameters and it falls below 0.05 when considering  
26 the best combination of five parameters. Hence, in the rest of the analysis, we consider only these

1 five parameters. Note that Eccentricity and Sway Area do not play a role in differentiating the two  
2 populations if they are considered as standalone parameters, but they become useful if they are  
3 considered in combination with the other parameters.

4 The parameter selection procedure was performed considering all the 10 trials. The effect of  
5 considering a smaller number of trials is evidenced by Fig. 3, which shows multivariate data from  
6 TBI patients and controls plotted against the first two canonical variables C1 and C2. Fig. 3a) and  
7 3b) show the results of multivariate analysis to compare controls and TBI patients, while fig. 3c)  
8 and 3d) show the differences among the three sub-groups of TBI patients and controls. The  
9 procedure of parameter selection was not redone, while we recomputed the canonical variables for  
10 this specific case. Fig. 3a shows the results on two acquisition trials only (Open Eyes Frontal and  
11 Closed Eyes Frontal), while Fig. 3b refers to the complete set of ten trials. In Fig. 3a TBI patients  
12 and controls are partially overlapped, even if some of the TBI patients fall outside the control group  
13 cloud ( $\Lambda = 0.63$ ,  $p = 0.014$ ). In Fig. 3b the two populations are completely separated ( $\Lambda = 0.0035$ ,  $p$   
14  $= 3.3 \times 10^{-13}$ ). Therefore, considering all the ten trials, TBI patients are completely differentiated  
15 from controls.

16 Fig. 3c and Fig. 3d show controls and patients suffering from mild, moderate, and severe residual  
17 visual impairment, as reported by Table1. When only two trials are considered, the various groups  
18 are scarcely separated (Fig. 3c). On the contrary, when all the ten trials are taken into account, not  
19 only the patients are well differentiated from controls, but also the three groups are completely  
20 separated among them (Fig. 3d). Moreover, the distance between controls and the three TBI groups  
21 increases with increasing level of visual impairment.

22

#### 23 4. Discussion

24 The most widely used parameters in posturography are the total length of the CoP path (Sway Path  
25 Length) and the Mean Velocity. They are essentially the same parameter, except that Mean Velocity  
26 is normalized with respect to the test duration and hence does not depend on it. They are usually

1 evaluated with the subject in quiet stance on the platform with the head in frontal position, both  
2 with eyes open and closed. It is important to notice that velocity integrates both amplitude and  
3 frequency changes, thus a concomitant reduction in sway frequency can reduce the discriminant  
4 power of velocity. Dehail et al. [20] studied a group of sixty-eight TBI patients (60 of which with a  
5 GCS score  $< 8$ , and 33 with a residual neurological impairment) and found that Sway Path Length  
6 was significantly increased, compared to controls, both with eyes open and closed. In our sample  
7 population, we found that Mean Velocity did not separate TBI patients from controls in the trials  
8 with the head in frontal position (both with eyes open and closed), while it separated the two  
9 populations in the newly proposed test conditions (after slow or fast head rotation). The difference  
10 between our results and those reported in [20] may be explained by the fact that in our study  
11 patients reported, in general, less severe TBI and suffered from no vestibular or sensorimotor  
12 impairment.

13 We hypothesized that subjects with visual impairment rely less than controls on the information  
14 arising from the visual system. Geurts et al. [13], working with a group of TBI patients who  
15 complained of reduced gross motor skills without sensory-motor impairments, report that visual  
16 deprivation was most detrimental for TBI patients, particularly for the Medio-Lateral control. In our  
17 patients, differences between the open- and closed-eyes balance performances are almost never  
18 statistically significant, while they are significant in controls for the parameter Mean Velocity.  
19 These results are coherent with our hypothesis, since we found that visual deprivation is less  
20 detrimental for patients.

21 Among others, Visser et al. [12] pointed out that the poor discriminative ability (between health and  
22 disease) of posturography may relate to the substantial inter-subject and intra-subject variability.  
23 Given these uncertainties, many researchers record a broad range of different parameters and/or  
24 perform repeated tests in the same or in different test conditions. As a consequence, for each  
25 subject, many parameters and many test conditions are considered which are partially correlated  
26 among them.

1 To take into account all the information arising from the complete protocol, we used a multivariate  
2 approach. Multivariate analysis requires a prior variable selection, as described in [27]. The results  
3 of variables selection are often counterintuitive. In our study, we excluded from the 'best  
4 combination of five parameters' parameters that were discriminative in univariate analysis. This is  
5 not surprising, since univariate analysis does not take into consideration the correlation among  
6 parameters.

7 Thanks to the representation of subjects in the plane of the first two canonical variables, we  
8 demonstrated (see Fig. 3) that it is possible to obtain a complete separation of patients from controls  
9 when all the 10 test conditions are considered and that it is also possible to discriminate among  
10 groups of patients with different residual visual impairment. Specifically, C1 discriminates patients  
11 from controls, while C2 summarizes the information needed to separate patients according to the  
12 degree of their residual visual impairment.

## 13 5. Conclusions

14 Using the proposed 10-trial protocol it was possible to clearly distinguish balance abnormalities of  
15 TBI patients with respect to controls. Moreover, we found that the severity of the residual neuro-  
16 ophthalmic deficit is correlated to the severity of the balance impairment. This is of paramount  
17 importance from a clinical perspective since it demonstrates that static posturography, associated to  
18 the presented protocol, can be applied to objectively evaluate the balance performances of a patient  
19 enrolled in a rehabilitation program and assess his/her progresses.

20

21

## 22 Conflict of interest statement

23 None of the Authors on this manuscript had or has any financial and personal relationships with  
24 other people or organizations that could inappropriately influence (bias) this work.

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Table 1

Characteristics of Traumatic Brain Injury patients.

Patient	Age (years)	Gender (M/F)	GCS score <sup>1</sup>	CT/MRI	Time (months) <sup>2</sup>	Cause	Residual damage <sup>3</sup>
1	26	M	15	Negative	37	Violence	Mild
2	62	M	14	Positive	130	Traffic accident	Moderate
3	25	M	4	Positive	35	Fall from scaffolding	Severe
4	41	F	8	Positive	42	Traffic accident	Severe
5	28	M	8	Positive	95	Traffic accident	Severe
6	31	M	6	Positive	71	Traffic accident	Severe
7	22	M	Not available	Positive	55	Traffic accident	Mild
8	28	F	9	Positive	64	Fall from horse	Severe
9	31	F	8	Positive	38	Traffic accident	Mild
10	38	F	6	Positive	66	Traffic accident	Moderate
11	38	M	6	Positive	143	Traffic accident	Mild
12	21	M	14	Positive	15	Traffic accident	Mild
13	50	M	14	Positive	17	Fall from scaffolding	Moderate

<sup>1</sup> Lowest Glasgow Coma Scale score after hospitalization.

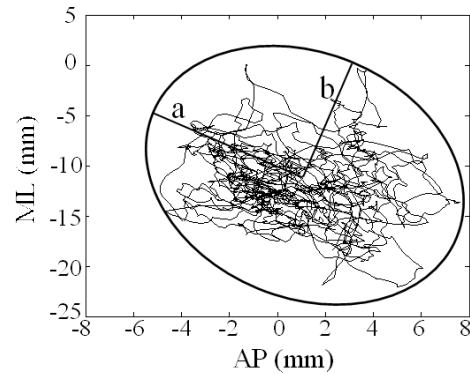
<sup>2</sup> Time elapsed from head trauma.

<sup>3</sup> Assessed from the clinical neuro-ophthalmic evaluation of the patients prior to the balance test.

Table 2

Posturographic parameters.

Parameter	Dimension	Description	Definition <sup>1</sup>
Mean velocity	mm/s	Length of CoP trajectory on the base of support in the unit of time	$\frac{1}{T} \sum_{n=1}^{N-1} \sqrt{(AP(n+1) - AP(n))^2 + (ML(n+1) - ML(n))^2}$
Sway area	mm <sup>2</sup> /s	Area of the surface enclosed by the CoP path per unit of time	$\frac{1}{2T} \sum_{n=1}^{N-1} [AP(n+1)*ML(n) - AP(n)*ML(n+1)]$
RMS AP	mm	Root mean square of the antero-posterior time series	$\sqrt{\frac{1}{N-1} \sum_{n=1}^N (AP(n) - \overline{AP})^2}$
RMS ML	mm	Root mean square of the medio-lateral time series	$\sqrt{\frac{1}{N-1} \sum_{n=1}^N (ML(n) - \overline{ML})^2}$
Major Axis	mm	Length of the major axis of the smallest ellipse containing the CoP trajectory on the base of support	2a
Minor Axis	mm	Length of the minor axis of the smallest ellipse containing the CoP trajectory on the base of support	2b
Eccentricity	adimensional	Eccentricity of the smallest ellipse containing the CoP trajectory on the base of support	$e = \sqrt{1 - \frac{b^2}{a^2}}$



<sup>1</sup>AP and ML are respectively the antero-posterior and the medio-lateral coordinates of the displacement of the CoP on the platform surface.

## Captions to illustrations

Fig. 1 – Comparison of posturographic parameters between TBI patients and controls: mean values and standard deviation are shown for each parameter and each trial condition listed in the legenda.

\* Significant difference between TBI and controls ( $p < 0.05$ )

△ Significant difference, in controls, between eyes open and closed ( $p < 0.05$ )

○ Significant difference, in TBI patients, between eyes open and closed ( $p < 0.05$ )

Fig. 2 – Wilks' Lambda ( $\Lambda$ ) as a function of the number of CoP parameters. 1. The best single parameter (Minor Axis). 2. The best combination of two parameters (Minor Axis and Major Axis). 3. The best combination of three parameters (Minor Axis, Major Axis and RMS AP). 4. The best combination of four parameters (Minor Axis, Major Axis, RMS AP and Eccentricity). 5. The best combination of five parameters (Minor Axis, Major Axis, RMS AP, Eccentricity and Sway Area).

Fig.3 – Scatter plots of the first (C1) vs. the second (C2) canonical variable for controls and TBI patients. (a) Two trials: Open Eyes Frontal (OEF) and Closed Eyes Frontal (CEF). (b) Ten trials: OEF, CEF, OELs, CELs, OERs, CERs, OELf, CELf, OERf, CERf. (c) Two trials: OEF and CEF. TBI patients with different levels of neuro-ophthalmic residual impairment (mild, moderate or severe) and controls. (d) Ten trials. TBI patients with different levels of neuro-ophthalmic residual impairment (mild, moderate or severe) and controls.

Figure 1

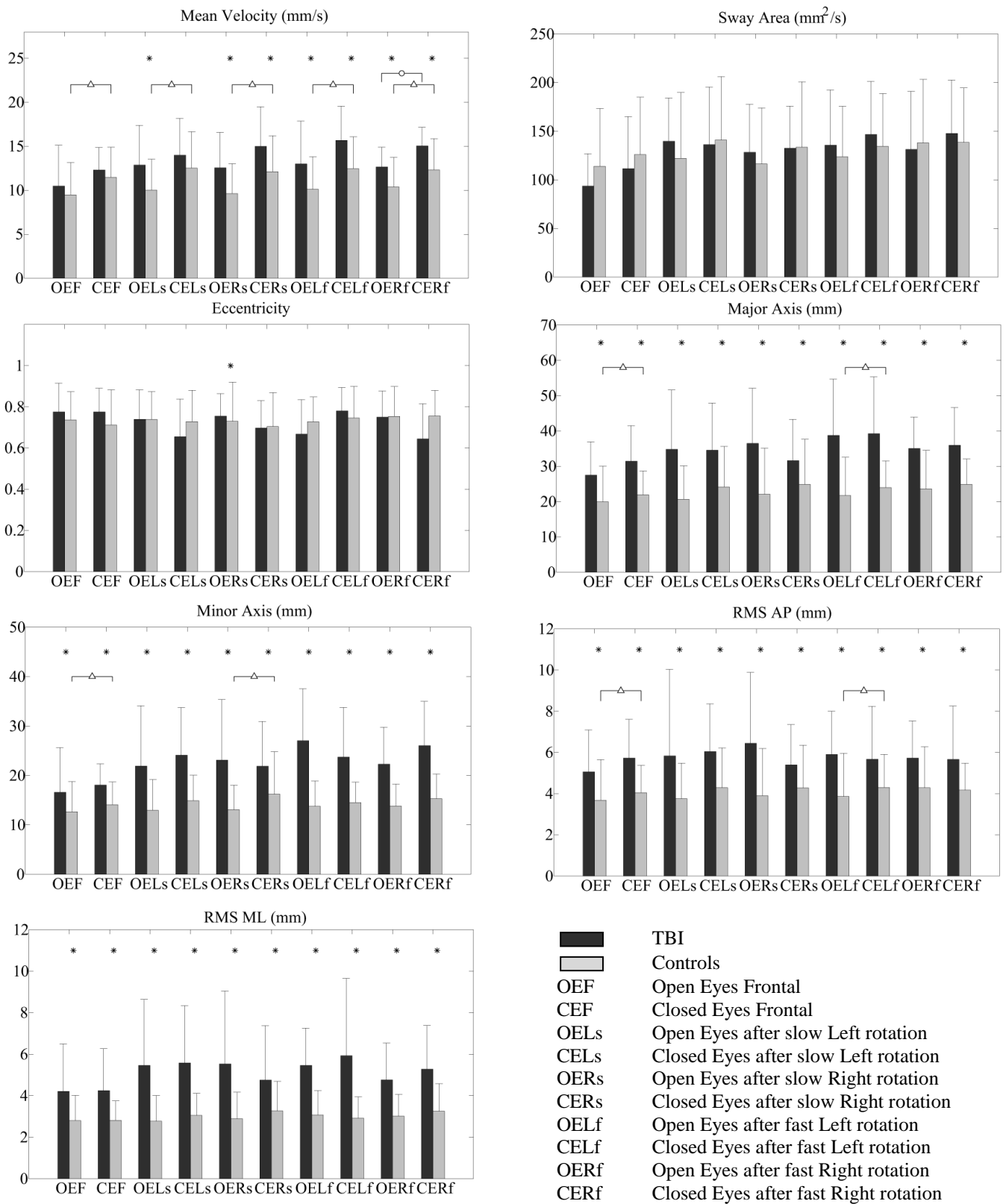


Figure 2

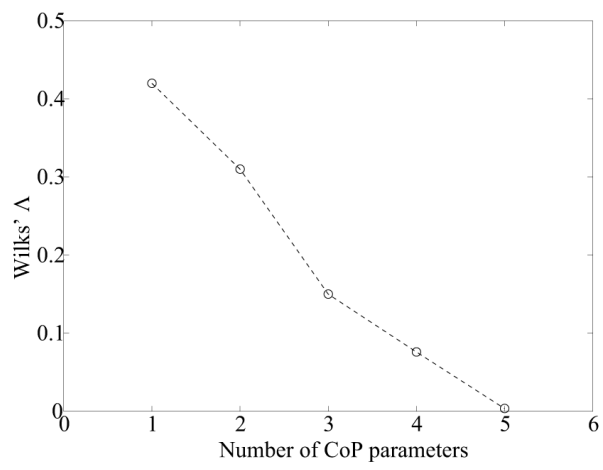


Figure 3

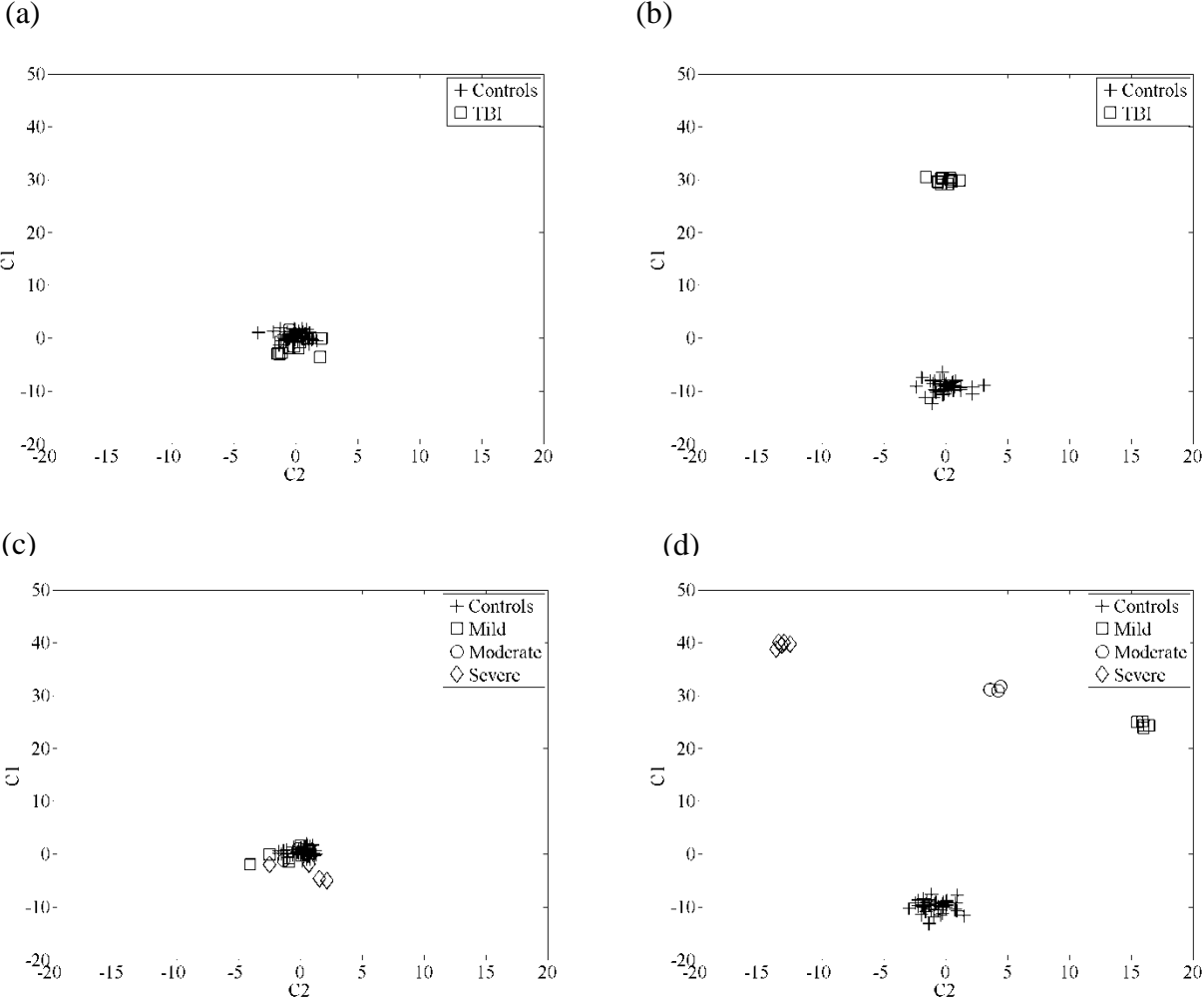


Table 1

Characteristics of Traumatic Brain Injury patients.

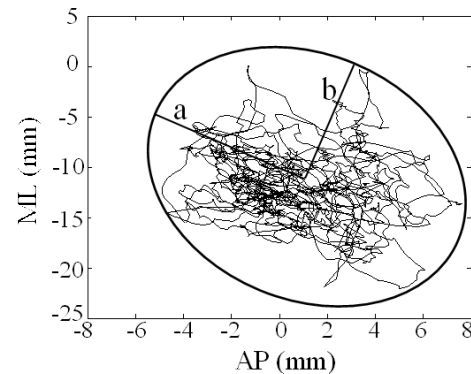
Patient	Age (years)	Gender (M/F)	GCS score <sup>1</sup>	CT/MRI	Time (months) <sup>2</sup>	Cause	Residual damage <sup>3</sup>
1	26	M	15	Negative	37	Violence	Mild
2	62	M	14	Positive	130	Traffic accident	Moderate
3	25	M	4	Positive	35	Fall from scaffolding	Severe
4	41	F	8	Positive	42	Traffic accident	Severe
5	28	M	8	Positive	95	Traffic accident	Severe
6	31	M	6	Positive	71	Traffic accident	Severe
7	22	M	Not available	Positive	55	Traffic accident	Mild
8	28	F	9	Positive	64	Fall from horse	Severe
9	31	F	8	Positive	38	Traffic accident	Mild
10	38	F	6	Positive	66	Traffic accident	Moderate
11	38	M	6	Positive	143	Traffic accident	Mild
12	21	M	14	Positive	15	Traffic accident	Mild
13	50	M	14	Positive	17	Fall from scaffolding	Moderate

<sup>1</sup> Lowest Glasgow Coma Scale score after hospitalization.<sup>2</sup> Time elapsed from head trauma.<sup>3</sup> Assessed from the clinical neuro-ophthalmic evaluation of the patients prior to the balance test.

Table 2

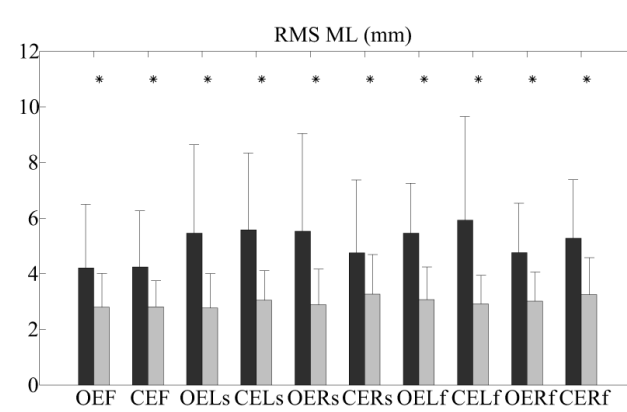
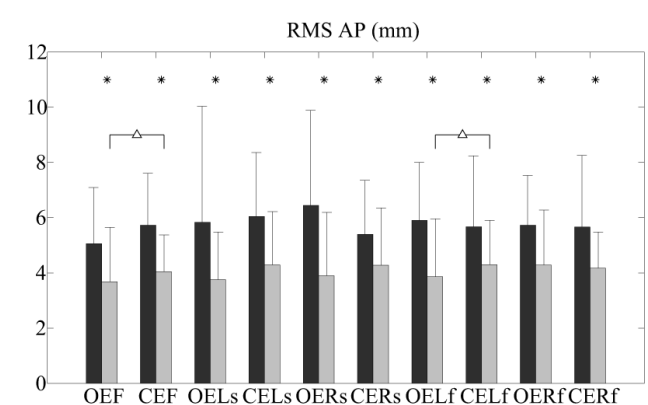
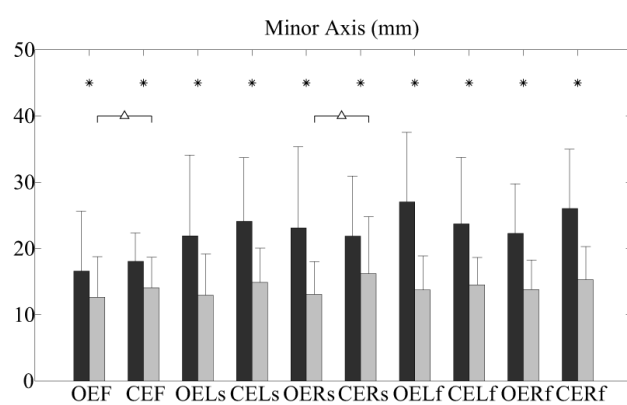
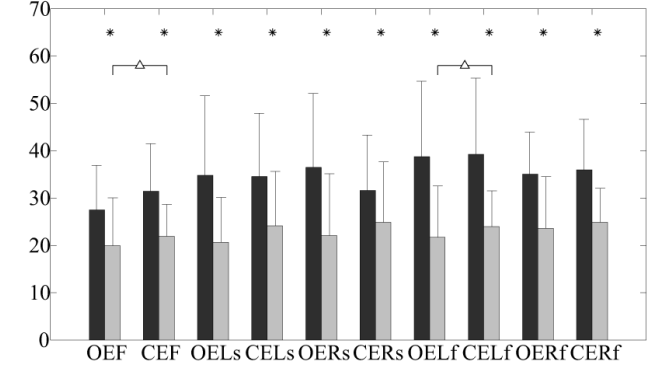
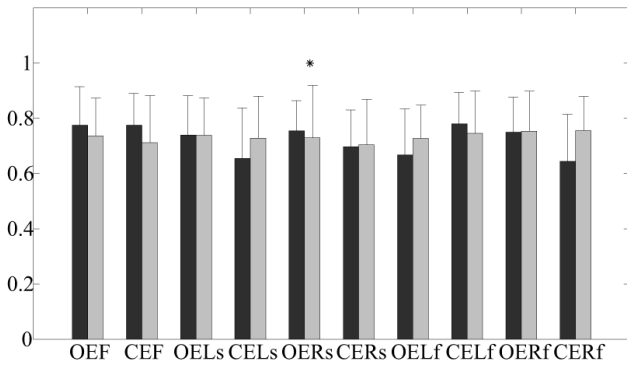
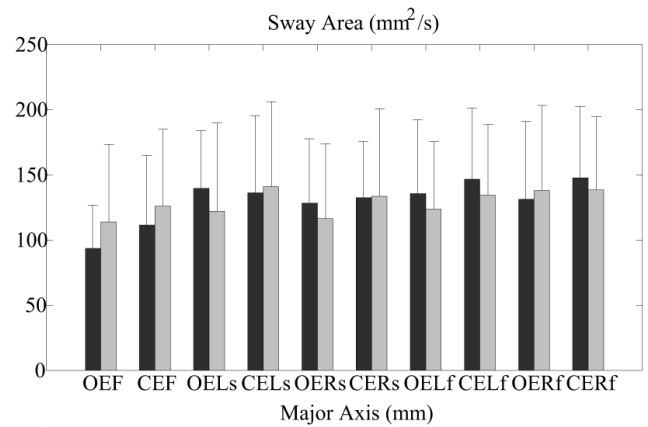
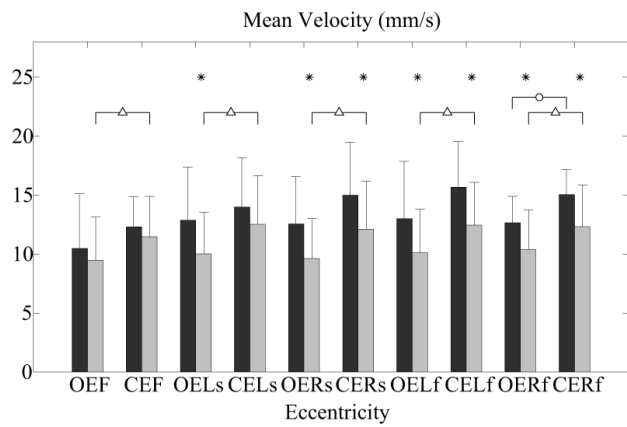
Posturographic parameters.

Parameter	Dimension	Description	Definition <sup>1</sup>
Mean velocity	mm/s	Length of CoP trajectory on the base of support in the unit of time	$\frac{1}{T} \sum_{n=1}^{N-1} \sqrt{(AP(n+1) - AP(n))^2 + (ML(n+1) - ML(n))^2}$
Sway area	mm <sup>2</sup> /s	Area of the surface enclosed by the CoP path per unit of time	$\frac{1}{2T} \sum_{n=1}^{N-1} [AP(n+1) * ML(n) - AP(n) * ML(n+1)]$
RMS AP	mm	Root mean square of the antero-posterior time series	$\sqrt{\frac{1}{N-1} \sum_{n=1}^N (AP(n) - \overline{AP})^2}$
RMS ML	mm	Root mean square of the medio-lateral time series	$\sqrt{\frac{1}{N-1} \sum_{n=1}^N (ML(n) - \overline{ML})^2}$
Major Axis	mm	Length of the major axis of the smallest ellipse containing the CoP trajectory on the base of support	2a
Minor Axis	mm	Length of the minor axis of the smallest ellipse containing the CoP trajectory on the base of support	2b
Eccentricity	adimensional	Eccentricity of the smallest ellipse containing the CoP trajectory on the base of support	$e = \sqrt{1 - \frac{b^2}{a^2}}$



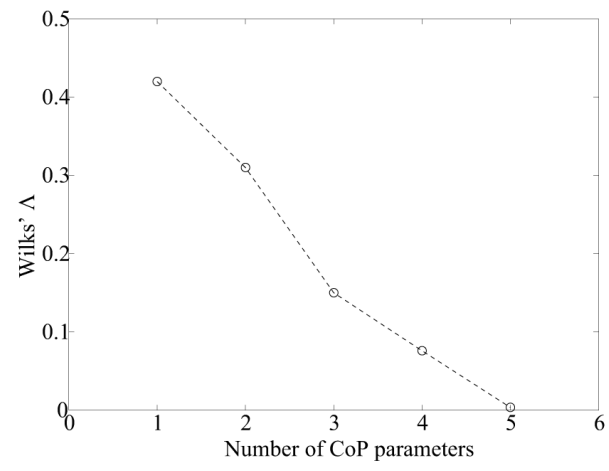
<sup>1</sup>AP and ML are respectively the antero-posterior and the medio-lateral coordinates of the displacement of the CoP on the platform surface.

# 7. Figure1

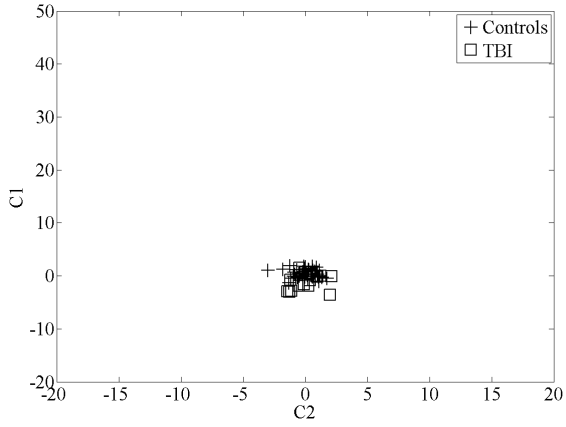


- TBI
- Controls
- OEF Open Eyes Frontal
- CEF Closed Eyes Frontal
- OELs Open Eyes after slow Left rotation
- CELs Closed Eyes after slow Left rotation
- OERs Open Eyes after slow Right rotation
- CERs Closed Eyes after slow Right rotation
- OELf Open Eyes after fast Left rotation
- CELf Closed Eyes after fast Left rotation
- OERf Open Eyes after fast Right rotation
- CERf Closed Eyes after fast Right rotation

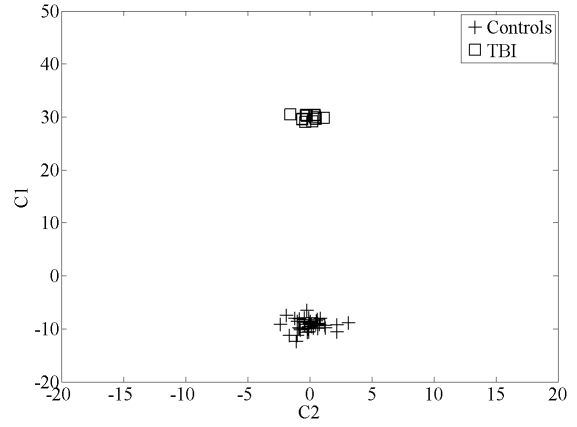
7. Figure2



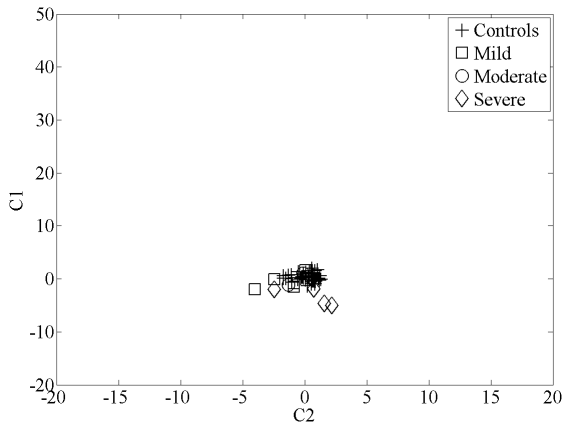
(a)



(b)



(c)



(d)

