How proprioceptive impairments affect quiet standing in patients with multiple sclerosis

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Abstract
To assess if multiple sclerosis patients with proprioceptive impairment are specifically affected during quiet standing with eyes open and how they can develop motor compensatory processes, 56 patients, classified from sensory clinical tests as ataxo-spastic (MS-AS) or only having spasticity (MS-S), were compared to 23 healthy adults matched for age. The postural strategies were assessed from the centre-of-pressure trajectories (CP), measured from a force platform in the eyes open standing condition for a single trial lasting 51.2 s. The vertical projection of the centre of gravity (CGv) and its vertical difference from the CP (CP-CGv) were then estimated through a biomechanical relationship. These two movements permit the characterization of the postural performance and the horizontal acceleration communicated to the CG and from that, the global energy expenditure, respectively. Both MS-AS and MS-S groups demonstrate larger CGv and CP-CGv movements than healthy individuals of the same age. Whilst similar CGv values are noticed in both MS subgroups, suggesting similar postural performances, statistically significant differences are observed for the CP-CGv component. Biomechanically, this feature expresses the necessity for the MS-AS group to develop augmented neuro-muscular means to control their body movements, as compared to the MS-S group. By demonstrating for both groups of patients similar postural performance accompanied by a varying degree of energy expenditure to maintain undisturbed upright stance, this study reveals that MS-AS patients which are affected by proprioceptive loss can compensate for this deficit with more efficient control strategies, when standing still with their eyes open.

Keywords: Multiple sclerosis, postural control, centre of pressure, centre of gravity, undisturbed upright standing

Introduction
Over decades, many studies have been carried out to assess the role of sensory information in regulating motor activities. Although ballistic movements can be performed without feedback, more precise activities involving either upper or lower limbs such as postural control (Horak 2001) do require sensory feedback. In situations of experimental or clinical somatosensory impairment, compensatory mechanisms have been described and related to either sensory (Horak et al. 1990) or motor strategies (Bloem et al. 2002). In most cases, somatosensory loss constitutes the unique neurological impairment in these patients.

By contrast, multiple sclerosis (MS) is a classical situation where several factors, including somatosensory loss, vision trouble, cerebellum and motor impairments increase the risk of falls (Cattaneo et al. 2002). As a result, different subgroups in patients with MS according to clinical features can be constituted. Interestingly, when motor command is altered mainly due to myelin loss then the axonal deterioration of motor pathways, the sensory system, is not systematically affected. This allows us to assess both the performance of the whole population of patients with MS and to determine the compensatory sensory involvement by comparing the clinical subgroups. A similar, previously proposed, approach...
was to evaluate gait parameters in MS (Thoumie and Mevellec 2002) and could be applied to balance evaluation through a sensorimotor experimental task such as the undisturbed upright standing paradigm.

In healthy individuals, maintaining a balanced upright stance requires very precise capacities to detect body movements and ad hoc programmed motor sequences aimed at correcting these body movements in order to recover equilibrium. A thorough biomechanical analysis reveals that the reaction muscular forces, exerted at the level of the feet in order to counteract the gravity acceleration exerted upon the centre of gravity (CG), do not develop a constant force output (De Luca et al. 1982). The main consequence of this feature is that the centre of pressure (CP), the point of application of the resultant reaction forces exerted at a given time, cannot be maintained constant either. Finally, the huge inertia which characterizes the erect posture prevents the CG from accurately following the CP displacements aimed at controlling it. In other words, most of the time there is a gap between the vertical projection of the CG (CGv) and the CP. This gap has been previously demonstrated as being the necessary condition for a horizontal acceleration (and thus a movement) to be communicated to the CG. If this organization is appropriate for eliciting movement such as step initiation (Brenière et al. 1987), it largely complicates our ability to stand still over an appreciable duration. Lastly, since standing perfectly still is, by nature, an impossible task, one can only therefore strive to limit our body movements as much as possible. At this stage, an efficient sensory system for the detection of the movements and a precise motor system for the setting up of the appropriate command, together warrant good postural performance.

Curiously, the undisturbed upright stance paradigm has been poorly investigated for patients suffering from MS. Frzovic et al. (2000), on clinical tests of balance, and Nelson et al. (1995), through dynamic platform posturography, are indeed the only studies, to our knowledge, conducted on this topic. The aims of the present study are thus manifold. Firstly, our goal is to characterize the postural behaviour of MS with eyes open through the undisturbed upright stance paradigm. Indeed, testing patients in the closed eyes condition would have contributed to selecting patients with somatosensory loss but not to evaluating their compensatory strategy in quiet stance with eyes open, a more usual everyday situation. Secondly, by enrolling various symptomatologies including ataxo-spastic (MS-AS) or only patients with spasticity (MS-S), as deduced from sensory clinical tests, our aim is to determine whether these two symptomatologies can be differentiated through this task. For this purpose, a method of analysis is used consisting as a first step in splitting up the CP trajectories, recorded through a force platform on which the subjects stand, into CGv movements and their difference in the plane of support (CP-CGv). By the former, the postural performance can be assessed whereas some valuable data such as the energy expenditure required for performing the task can be estimated from the latter. The second step consists in modeling these various trajectories through the fractional Brownian motion (fBm) framework in order to obtain supplementary insight such as the degree of control of the movements and their spatio-temporal linkage. In particular, one may wonder whether the slower conduction of the ascending and descending tracts, as much as occurs with somatosensory evoked potentials (Diener et al. 1984), may alter the time delay with which the initial control mechanism is over. This method has been previously used to analyze upright stance for various goals and also involved both healthy and disabled patients (Rougier and Farenc 2000; Rougier et al. 2001).

Methods

Experimental procedure

Overall, 79 subjects were included in this protocol. According to their symptomatologies (through sensory clinical tests), 56 multiple sclerosis patients were divided in two subgroups and compared to 23 healthy (HEA) subjects with no known visual or balance pathology (12 men and 11 women ranging in age between 26 and 57; height: 1.69 m ± 0.1 (mean ± SD); weight: 65 kg ± 11). The ataxo-spastic (MS-AS) group included 34 patients (18 men and 16 women ranging in age between 32 and 57; height: 1.69 m ± 0.09; weight: 68 kg ± 12) whereas those having spasticity (MS-S) included 22 patients (15 men and 7 women ranging in age between 34 and 66; height: 1.71 m ± 0.09; weight: 69 kg ± 14). All of the subjects were informed of the aims of the study and gave their consent in accordance with the Declaration of Helsinki II.

Inclusion criteria were clinical features of the pyramidal tract and the ability to walk alone for a distance of at least 100 m with or without a walking aid, that is, a score of less than 6.5 on the expanded disability status scale (EDSS).

Exclusion criteria were:

- History of visual involvement (ophthalmoplegia or optic neuritis).
- Cerebellar involvement assessed through both its static component with trunk ataxia in the sitting position and its dynamic component with dysmetria on one segment.
- A too high level of spasticity (Ashworth scale equal to 3 or 4 measured at both ankle and knee joint level).
- Somatosensory involvement, and thus their inclusion either in the MS-AS or MS-S groups, was assessed through either a decreased perceived sensation consecutive to vibration (tuning fork with 256 Hz frequency) in at least one part of the legs (big toe, lateral malleolus) or a loss in the joint sense at the level of the big toe (blinded perception of a 30° passive mobilization).

Undisturbed upright stance evaluation

The subjects stood on a force platform (Satel, Toulouse, France) in a natural position (feet abducted at 30°, heels separated by 6 cm). The signals issued from the load cells, on which the plate lays, were amplified and converted from analogue to digital form before being recorded on a personal computer with a 40 Hz sampling frequency. As seen below, the CP trajectory was then processed in a number of different ways. In the coordinate system used, ML and AP mean medio-lateral and antero-posterior axes, respectively. The posturographic measures consisted in a single trial, performed with the eyes open, lasting 51.2 s. MS patients being characterized by a high level of fatigability, recording a single trial over a rather long period was in our mind preferable than recording several trials lasting a shorter duration. To avoid disturbing effects due to eye movements over postural control, the subjects were required, during the trial, to stare at a target, positioned 0.9 m in front of them.

CGv and CP-CGv movement estimation

Swaying movements of the body being considerably reduced, undisturbed stance maintenance infers a regularity of the moment of inertia of the body. As seen through Figure 1, CGv and CP-CGv movements can be, in that case, estimated from the CP trajectories. To be more precise, a relationship between the amplitude ratio of the vertical projection of the centre of gravity (CGv) and CP movements (CGv/CP) and sway frequencies can be used to determine CGv and consequently CP-CGv movements. This method represents a generalization of the concept initially developed by Brenière (1996) for more dynamic conditions. The hypothesis is that the body constitutes a low-pass filter, which would explain the loss of amplitude observed between CP and CGv as the sway frequency increases. In fact, the principle consists of multiplying the data, transformed in the frequency domain, through a Fast Fourier Transform (FFT), by the filter mathematically defined by the ratio

$$\frac{\text{CGv}}{\text{CP}} = \frac{\Omega^2_0}{\Omega^2_0 + \Omega^2}$$

and then, to recover the temporal domain by processing an inverse FFT. In this formula, $\Omega_0 = \sqrt{\frac{mgh}{(I_G + mh^2)}}$ and $\Omega = 2\pi f$ is the pulsation (rad/s). Because the moment of inertia is known to be different according to the axis of the swaying movements of the body, two distinct

![Figure 1. A CP trajectory can be advantageously decomposed into two basic components: the vertical projection of the centre of gravity (CGv) and its difference from the CP (CP-CGv). As seen, a modulation of the territory covered by the CP may involve either a single basic movement or both of them.](image)
relationships, for the ML and AP axes, were used to compute the subjects’ moment of inertia taking into account their body weight and height (Ledebt and Brenière 1994).

This method is justified because of the regularity of the moment of inertia of the subjects over the trial duration. From this CGv/CP relationship, displayed graphically in Figure 2, it can be logically deduced that CP displacements operating over too high frequencies would not incur appreciable CG movements. This ratio appears maximal for the lower frequencies (CGv and CP are characterized by similar positions at 0 Hz) and tends towards zero above 3 Hz. The CGv estimation consists in multiplying the data, transformed in the frequency domain through a FFT, by the above-mentioned low-pass filter and recovering to the time domain by processing an inverse FFT. All of this data processing was automatically performed through the Equi+-PROG01 software.

**Signal processing**

Two approaches were adopted to study the CP-CGv and CGv movements: (i) a classical method based on parameters such as the surface of an ellipse calculated with a confidence interval (Tagaki et al. 1985), the variances along both ML and AP axes and mean velocity and (ii) a mathematical model termed fractional Brownian motion (Mandelbrot and Van Ness 1968). The classical parameters allow us to assess the position of the subjects over the platform (level of body weight asymmetry distribution over the two legs, relative forward leaning), and a global quantification of the trajectories. In addition, in order to highlight the deadening capacities of the postural system (by taking into account the energy expenditure, i.e., amplitudes of the CP-CGv movements, relative to the postural performance, i.e., the amplitudes of the CGv movements), a specific index, based on the ratio between variances of CP-CGv and CGv movements, was computed for each ML \( R_{ML} \) and AP \( R_{AP} \) axis. To put it briefly, the larger the ratio, the more deadening the postural strategy. For instance, an increased ratio means that, despite increased horizontal accelerations (as expressed through increased amplitudes of CP-CGv movements), the CGv movements do not increase in comparable proportions or, even, decrease. The fractional Brownian motion (fBm) modelling allows us to specify the degree to which a trajectory is controlled and the spatio-temporal limits of the successive control mechanisms. Its use has been validated for the CP trajectories (Riley et al. 1998).

The general principle is that the aspect of a trajectory, expressed as a function of time, may be quantified by a fractional, that is, a non-finite integer space dimension. The latter thus provides a quantitative measurement of evenness in the trajectory in a single direction. This fractional dimension \( D \), in a single axis, is in fact linked to the Hurst scaling exponent \( H \) since \( D = 1 - H \) for the present case. This scaling regime graphically corresponds to the half slope of the line portions constituting a variogram depicted bi-logarithmically. The latter in fact expresses the link between the mean square displacements \( \langle \Delta x^2 \rangle \) and the increasing time intervals \( 1/64 \, s < \Delta t < 10 \, s \) and is given by

\[
\langle \Delta x^2 \rangle = \Delta t^{2H}.
\]

Note that the squared distances are simply used to prevent a null mean displacement. A major feature to extract from the variogram analysis is the knowledge of the scaling regimes \( H \) which indicate the level of correlation between past and future increments and from that, the degree of control of the trajectory over these time intervals. A median value of 0.5 for \( H \) indicates a linear relationship between the two variables and thus a lack of correlation between past and future increments, hence suggesting that the trajectory is totally uncontrolled. On the other hand, that is, if \( H \) differs from 0.5, positive (0.5 < \( H \) or

Figure 2. Amplitude ratio between CGv and CP movements as a function of sway frequency. This filter shows that CGv and CP have similar positions at 0 Hz while CGv movements relative to CP become smaller, thus determining increased CP-CGv amplitudes, as sway frequency increases.
negative \((H<0.5)\) correlation can be inferred, which is indicative of a given part of determinism in the control. In addition, depending on how \(H\) is positioned with respect to the median value 0.5, it can be inferred that the trajectory is more or less controlled, that is, endowed with more or less stochastic processes: the closer the regimes are to 0.5, the larger the contribution of stochastic processes. In addition, depending on whether \(H\) is superior or inferior to the 0.5 threshold, persistent (the point is drifting away) or anti-persistent behaviours (the point retraces its steps) can be revealed, respectively.

Since two straight line portions generally characterize variograms relative to undisturbed upright stance maintenance (a quite flat line preceding or succeeding a steeper one), a final step consists in the determination of the transition point for both axes, that is, the point corresponding to the slope inflection. \(CP\) and \(CG_v\) displacements being, by definition, in phase in the inverted pendulum model, the temporal coordinate of the transition points on the variograms characterizing the \(CP\) trajectories will also be that of the \(CG_v\) and \(CP-CG_v\) movements (Rougier and Caron 2000). The method used for this purpose is based on the evolution, as a function of increasing \(\Delta t\), of the distance between the \(CP\) variogram and a completely stochastic process characterized by a slope of 1 (inferring, in that case, a value of 0.5 for \(H\)). The retained principle is that the \(\Delta t\) for which this distance is maximal is the \(\Delta t\) of the transition point (Rougier 1999), in contrast with the less objective method initially used by the pioneering study of Collins and De Luca (1993). However, it should be pointed out that the stochastic behaviour, taken as a reference, is itself modified by the low- or high-pass filters used for the computation of \(CG_v\) and \(CP-CG_v\) movements. As seen through the dashed curves of the upper part of Figure 3, the filter effect leads in fact to curvilinear functions moving progressively away from or closer to the slope of 1 mentioned above (since \(2 \times (H = 0.5) = 1\)).

Scaling regimes relative to “average stochastic variograms” over the same \(\Delta t\) must therefore be taken as a reference in such a way that

\[
H_{\text{cal}} = (H_{\text{exp}} - H_{\text{sto}}) + 0.5
\]

where \(H_{\text{cal}}\), \(H_{\text{exp}}\), and \(H_{\text{sto}}\) represent the calculated, experimental, and stochastic scaling regimes, respectively. Thus, for each of the two movements investigated and each ML and AP axis, two scaling exponents (indexed as short and long latencies: \(H_{\text{sL}}\) and \(H_{\text{lL}}\)) as well as the coordinates of the transition point \((\Delta t \text{ and } \Delta x^2)\) have to be extracted. Figure 3 illustrates this procedure with an example involving \(CP\), \(CG_v\), and \(CP-CG_v\) movements.

Figure 3. Method used to determine the transition between successive scaling regimes for the \(CP\), \(CG_v\), and \(CP-CG_v\) movements from the data of one subject. The upper part represents the variograms for one axis (ML or AP), that is, the mean square displacements as a function of increasing time intervals. Those relative to the \(CP\) are represented by grey lines while those resulting from the decomposition are black. The tilted or curvilinear dashed curves which pass through each variogram at the point with the shortest \(\Delta t\) theoretically express a pure stochastic process. The lower part displays the distances, in arbitrary units, between variograms and these dashed curves. The maximal distance relative to \(CP\) trajectories are taken to be the transition points’ \(\Delta t\) coordinates. Thus the dotted horizontal and vertical lines correspond to the mean square displacement and \(\Delta t\) coordinates of the different transitions between successive regimes involved in standing still control. Note in the lower part that the \(CG_v\) and \(CP-CG_v\) are characterized by a horizontal initial or final portion, indicating that a random-walk process mainly operates during these \(\Delta t\) (from Rougier and Caron 2000).
To assess the postural behaviours of healthy and MS patients, non-parametric tests, based on the ranks, were performed, the first level of significance being set at $p < 0.05$. This way to analyse the data is justified by the low panel of subjects in all groups. An analysis of variance (ANOVA) of Kruskal–Wallis, with repeated measures, was used to highlight the presence of a statistically significant trend across the three groups of subjects. The post hoc analysis between each group was subsequently performed through Dunn tests.

**Results**

As shown through the various results, the postural behaviour of our MS patients is characterized by a huge intra-variability in most postural parameters, as demonstrated by the standard deviations displayed on the bar charts (Figures 4 and 5). However, some statistical effects have to be emphasized for both surface and mean velocity parameters for both CGv (surface: $H = 38.623$, $p < 0.001$; velocity: $H = 37.935$, $p < 0.001$) and CP-CGv movements (surface: $H = 39.503$, $p < 0.001$; velocity: $H = 32.44$, $p < 0.001$). This feature is also observed for the variances measured along ML (CGv: $H = 37.935$, $p < 0.001$; CP-CGv: $H = 37.17$, $p < 0.001$) and AP axes (CGv: $H = 28.304$, $p < 0.001$; CP-CGv: $H = 40.388$, $p < 0.001$).

As shown by the bar charts of Figure 4, the MS patients, when compared to healthy individuals, are characterized by larger surfaces, variances, and mean velocities, all of these differences presenting huge statistical differences ($p < 0.001$). However, if a lack of effect is the common characteristic between MS-AS and MS-S groups for the CGv classical measurements, some larger differences are observed for the CP-CGv component, which sees the MS-S group displaying smaller and slower movements than the MS-AS one. To be more precise, some statistically significant effects ($p < 0.05$) are worth noting for the surfaces, variances (along the AP axis), and mean velocities.

The lack of differences for the CGv movements for the MS groups and the parallel increase of the CP-CGv movements for the MS-AS group infer effects for the ratios $R_{ML}$ and $R_{AP}$. Nevertheless, as some statistical effects have to be emphasized for both surface and mean velocity parameters for both CGv (surface: $H = 38.623$, $p < 0.001$; velocity: $H = 37.935$, $p < 0.001$) and CP-CGv movements (surface: $H = 39.503$, $p < 0.001$; velocity: $H = 32.44$, $p < 0.001$). This feature is also observed for the variances measured along ML (CGv: $H = 37.935$, $p < 0.001$; CP-CGv: $H = 37.17$, $p < 0.001$) and AP axes (CGv: $H = 28.304$, $p < 0.001$; CP-CGv: $H = 40.388$, $p < 0.001$).

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![Figure 4](image_url)
indicated by Figure 4, a significantly statistical trend is only found for the AP axis \((H = 7.472, p < 0.024)\). The post hoc analysis reveals that the effects are seen between the MS-AS and HEA or MS-S groups \((p < 0.05\) for both comparisons).

**Fractional Brownian motion modelling of the \(CG_v\) and \(CP-CG_v\) movements**

As seen from the shape of the variograms, displayed through Figure 5 (left part), the various differences between the three groups, mentioned above through the classical analysis, can be further explained. A first major effect concerns the spatial coordinate of the transition point \((\Delta x^2)\) which expresses the mean square distance covered by the elementary trajectory at the onset of the corrective process. This is true for both \(CP-CG_v\) (ML: \(H = 36.531, p < 0.001\); AP: \(H = 40.309, p < 0.001\)) and \(CG_v\) movements (ML: \(H = 24.800, p < 0.001\); AP: \(H = 18.040, p < 0.001\)). As it can be observed on the bar charts (Figure 5, right part), these distances are increased...
for the MS groups, and more specifically for the MS-AS, when compared to the HEA one ($p < 0.001$ for all paired comparisons). Interestingly, some statistically significant differences were noticed between the two MS groups, but solely for the spatial coordinates ($\Delta x^2$) measured along the AP axis. On the other hand, the temporal coordinates $\Delta t$ appear to be unchanged for all groups, signifying that the initial control mechanisms are over after a similar delay.

The other main insight is the degree to which the various trajectories are controlled, that is, how far their varigrams differ from those with a slope of 1 characterizing the stochastic or random behaviour (i.e., ordinary Brownian motion). The scaling regimes $H_{d2}$ computed in order to assess these levels, indicate that the CP-CG$_v$ movements, over the shortest time intervals $\Delta t$, are similarly controlled for all groups along the ML axis (Figure 5). On the other hand, some differences occur along the AP axis ($H = 12.872$, $p < 0.002$). The post hoc analysis highlights some effects between the MS-AS and the HEA ($p < 0.001$) or the MS-S groups ($p < 0.05$). The longer distances ($\Delta x^2$) measured for the CG$_v$ movements constitute the main explanation for the decreased parameters $H_{fl}$ observed for the MS groups, when compared to the HEA one ($H = 6.156$, $p < 0.046$). Indeed, it is generally observed within this framework that the longer the mean covered distance $\langle \Delta x^2 \rangle$, the smaller the scaling regime $H_{fl}$ and thus the better the control. As revealed by the post hoc analysis, the only significant trend is found between the HEA and MS-S groups ($p < 0.05$).

**Discussion**

As expected, the MS patients display larger CG$_v$ and CP-CG$_v$ movements when compared to the HEA taken as reference. Since the CP trajectory is the algebraic summation of these two elementary movements, one can therefore conclude that this increase should also have been seen with these complex trajectories. The larger CG$_v$ territories observed for the MS patients are the consequence of an impaired postural control. At this stage, the impairment could stem either from the afferent messages, the integrative process, the motor planning, and/or the motor activity. Concerning the motor output, a recent study (Thoumie et al. 2005) had identified a profound strength reduction in the lower limb muscles in MS patients. This deficiency could thus account for the decreased stability, as pointed out by the augmented CG$_v$ territories. Nevertheless, other avenues should be explored since the sensory impairment is quite differently affected depending on the symptomatology of the MS disease. The most striking result of our method of analysis is that the postural performance, assessed through the amplitudes of the CG$_v$ movements, is identical for both MS subgroups but is associated with a low or high energy expenditure, as revealed by the amplitudes of the CP-CG$_v$ movements, depending on whether the sensory system is impaired or not. In other words, the MS-AS group develop compensatory mechanisms consisting in a larger muscular involvement. Since the facility with which the CG movements can be controlled depends, for the most part, on the magnitude of the horizontal accelerations it undergoes (Brenière et al. 1987), it follows that postural control should be easier for the MS-S subgroup, which is characterized by the lowest CP-CG$_v$ amplitudes (variances). Because of the physical properties of the motor units' recruitment principle (Henneman et al. 1965), which sees the faster motor units being recruited to increase the muscular force output, the amplitudes of the CP-CG$_v$ movements are in fact linked to the level of energy expenditure spent in the lower limbs, as pointed out previously through the leaning posture paradigm (Rougier et al. 2001). The origin of these exaggerated CP-CG$_v$ movements for the MS-AS group could stem from the reinforcement of other sensory modalities such as those issued from the vestibular system. As shown recently in patients with somatosensory loss due to a diabetic peripheral neuropathy (Horak and Hlavacka 2001), an increase in the sensitivity of the postural system to vestibular stimulation can be noticed. This increased central vestibular gain could in turn induce a facilitation of the descending motor commands originating from the vestibular nuclei, which are known to activate predominantly the anti-gravity muscles of the lower limbs.

On the other hand, the larger the CG horizontal accelerations (assessed through CP-CG$_v$ amplitudes), the more difficult the handling of the CG. Therefore, because of the lack of differences between the MS subgroups regarding the CG$_v$ movements observed for classical parameters such as surface or variances along each ML or AP axis, it has to be said that the control of the CG is better performed by the MS-AS group than for the MS-S one. In other words, other things being equal, the larger horizontal acceleration communicated to the CG of the MS-AS group, due to the increased CP-CG$_v$ movements, should have induced larger CG displacements. Since the CG movements of the two subgroups are of similar amplitudes, one can therefore conclude that the control is better for the MS-AS group, as compared to the MS-S one. The differentiated
effects seen along the ML and AP axes have to be studied according to the biomechanical principles of the bipedal stance maintenance. Some differences are indeed observed for the control of body movement along these two axes because of the various joints and muscular groups involved. If the AP movements are mainly controlled through the ankle by the plantar flexors muscle without a concomitant activation of the antagonistic muscles (Okada and Fujiwara 1984), the significance of the ML displacements involves both the ML displacements of the pressure distribution under each foot and, for the most part, the capacity of the subject to distribute his body weight upon his two limbs constantly over time. Consequently, as pointed out by Winter (1995), the control along this ML axis is mainly performed through the abductors and adductors of the hip. Thus, it might hold true that the control of all these postural muscles could be impaired for the MS-AS group. The various postural strategies observed in healthy and impaired groups gain further insight from the fBm framework.

A first interesting result is the constancy of the mean time interval $\Delta t$ for all healthy and MS groups. This indicates that the initial control mechanisms are over in all cases after a similar period of time. This feature could be viewed as contradictory to the hypothesis that one of the cardinal signs of MS disease is the slower central conducting velocity due to the impaired sheath surrounding the axon. In addition, this result can be viewed as contradictory to the decreased cortical relay time estimated in MS patients through latencies of somatosensory and motor evoked potentials and long latency reflexes (Diener et al. 1984; Tataroglu et al. 2004). Nonetheless, one should bear in mind that this time interval comprises both the time needed for action potential conductance and motor planning. Therefore, if we nonetheless consider the former as being increased, especially for patients suffering from both sensorial and motor impairments, this would signify that most MS patients initiate their motor command through shorter delays. This “hasty” strategy could in turn explain the lesser appropriate induced CG displacements and the larger energy expenditure due to the augmented force generated. One should bear in mind that the CP displacements, over the shortest time intervals, are aimed, in this task, at decreasing postural perturbation as much as possible, that is, to minimize the gap between CP and CG. It has been suggested that this control operates through an open loop control (Collins and De Luca 1993) even though other possibilities have since been proposed for this process (Peterka 2000). The “hasty” strategy of the MS patients would infer that the motor output would be engaged despite a precise knowledge of the ongoing perturbation at the central nervous system (CNS) level. An alternative strategy at this level could be to delay the postural correction. However, in that case, the CG acceleration inferring increased body sways would largely incur a devastating effect upon postural control. This feature has been observed recently, for instance, amongst the elderly who have no previous history of falls (Berger et al. 2005). A direct consequence of such a strategy is to drastically increase the neuro-muscular demand, something most of the MS patients are unable to develop. Consequently, one may say that the observed strategy constitutes a compromise between an overly large energy expenditure and an approximate sensory integration.

These increased horizontal accelerations observed for the MS patients, as deduced from the larger amplitudes of CP-CG$_x$ movements, because of the constancy of the mean $\Delta t$, in turn determine increased spatial coordinates ($\Delta x^2$). This is true for both CP-CG$_x$ and CG$_x$ movements. However, some discrepancies are observed according to the MS groups. The MS-AS group, as shown by the results, display huge spatial coordinates for the CP-CG$_x$ movements, especially along the AP axis. This observation has to be linked to the increased control measured through the scaling regimes $H_d$ which are well above those computed for the HEA and MS-S groups. In that particular case, the larger the contribution of deterministic processes, the larger the number of motor units recruited and the higher the muscular activation (Rougier et al. 2001). Interestingly, when comparing the two MS subgroups, it appears that this MS-AS group is also the one that is characterized by the shortest covered distances ($\langle \Delta x^2 \rangle$) by the CG$_x$ movements at the end of the initial control mechanisms. This feature, even though a non-statistical trend was found, thus highlights the capacity of the MS-AS group to better constrain their body movements in a bearable territory despite larger accelerations.

This data is relevant for a better understanding of postural changes occurring in MS. In an extensive evaluation including different clinical tests (Frzovic et al. 2000), no change was obvious in the two legs standing condition between MS patients and controls. Changes in maintaining stance during dynamic posturography were related to sensory interactions in these patients (Nelson et al. 1995) but no change in stable conditions has yet been reported.

This data has demonstrated that the MS-AS patients are able to counteract their sensorial deficit by eliciting larger deadening postural capacities, also...
emphasized by the $R_{ML}$ and $R_{AP}$ ratios between CP-CGv and CGv movements, by displaying in fine similar postural performances than the MS-S group. Even though the postural strategies cannot be specified, these $R_{ML}$ and $R_{AP}$ ratios constitute an attractive tool in the assessment of the symptomatology of the disease. Consequently, in accordance with a recent study (Reid et al. 2002), the use of a force platform should be viewed as an alternative, rapid, and non-invasive way to test the balance strategies of the MS patients and from that to determine their precise sensorial involvement. However, it is conceivable that most of this adaptation could be built on strategies developed upon visual cues. Numerous studies in the past have indeed emphasized the predominant contribution of visual information in the adapted strategies encountered for instance in patients suffering from a vestibular disfunctioning (Hufschmidt et al. 1980) for whom a non-visual condition induces, in most cases, a loss of balance. Finally, it appears that these MS-AS patients are not only impaired when they are instructed to close their eyes. Further studies involving MS patients with visual and cerebellar impairment are therefore needed to assess the place of this paradigm as a standard tool to evaluate and follow-up intervention studies in MS patients. Because of the frequency of the proprioceptive impairment in multiple sclerosis patients, it seems interesting to characterize the strategies used to control their balance with the eyes open. Such a knowledge can allow us to assess the compensatory mechanisms and thus to propose ad hoc rehabilitation protocols aimed at reducing the postural control impairments and lessening the risk of falling. As shown by our results, the compensatory mechanisms mainly involve the CP-CG movements. A better understanding of the effects induced by the rehabilitation protocols upon this component is thus needed.

References


