Balance impairment is one of the most common symptoms in people with multiple sclerosis (MS), even found in the early stages. In this chapter, we present an advanced technique to characterize balance disorders in MS using a static force platform, called static posturography. Many linear (temporal and spectral) parameters and nonlinear indicators can be extracted from the stabilometric signals and are able to provide new diagnostic elements for the management, in particular with the possibility of predicting disability progression, and to improve the understanding of the mechanisms involved in the system for balance regulation in MS.

3.1 Introduction

3.1.1 Generalities on MS

3.1.1.1 Definition

Multiple sclerosis (MS) is a common chronic inflammatory disease of the central nervous system (CNS) that usually develops by relapses [1]. It is characterized by myelin and axon involvement (figure 3.1). This axonal damage can be primitive or secondary. The demyelination lesions are disseminated in the white matter of the CNS. The set of clinical symptoms is related to the localization of lesions, which explains their diversity. Remyelination made possible by oligodendrocytes, explains the possibility of recovery after a relapse. MS is the most common multifocal, diffuse and disability-causing neurological disorder of young people between the ages of 20 and 40 [2]. It mainly affects female subjects (sex ratio = 3 to 1). The prevalence is estimated at 95 per 100 000 and the incidence varies between 4 and 8 per 100 000 [3].

doi:10.1088/978-0-7503-1762-7ch3  3-1  © IOP Publishing Ltd 2020
3.1.1.2 Clinical forms
The disease has different clinical forms and their terminology has changed recently. Two forms of MS are currently defined in which the notion of clinical relapse or MRI activity are integrated. The concept of aggravation of disability is also taken into consideration over a given period of time (6 months, one year …) [4]. The relapsing-remitting form starts with a clinically isolated active or inactive syndrome depending on the MRI activity at the time of the clinical event, it is characterized exclusively by inflammatory events and can leave sequelae (potentially stable between two episodes) and starts usually around 30 years old. It represents 85% of the initial forms of the disease. The progressive form also includes subtypes: active with or without progression, inactive with or without progression. The secondarily progressive form is the late natural evolution of the previous form, it can affect all subjects initially remittent in a mean time of 15–20 years. The primary progressive form is characterized by an evolution present from the beginning of the disease, without relapses and affects 15% of the subjects. It starts on average around 40 years old [5].

3.1.1.3 Etiology
The etiology of MS is currently unknown but is nevertheless considered multifactorial. Genetic factors are present: Caucasian population, concordance of 30% in monozygotic twins against 2%–3% in heterozygotic twins, susceptibility genes (linked to the HLA group). Environmental factors are also advanced as well as a viral infection with EBV, smoking, vitamin D deficiency and low sunlight, obesity. Some authors argue that excessive hygiene during childhood increases the risk and that some infantile parasitic infections have a protective effect [6]. The median age in all forms is 32 for a sex ratio of 0.75 for female subjects. There is a North–South gradient and MS is more common when one moves away from the Equator (MS is twice as prevalent in the Scandinavian countries as in the Mediterranean countries).

3.1.1.4 Diagnosis
Diagnosis is based on modified McDonald’s criteria [5, 7] that associate clinical and neuroradiological criteria. It is thus demonstrated as spatial (location of lesions and

![Figure 3.1. Demyelination related to MS.](image-url)
multiple clinical symptoms) and temporal (time-onset of new symptoms or changes in lesion MRI activity) [8]. Encephalic or medullary MRI reveals the location and activity of the various lesions (figure 3.2). These lesions generally have an ovoid aspect, they sit within the white matter in different places: near the ventricles, in the cerebellum or the brainstem, in the spinal cord. These multiple localizations and their modification of appearance over time explain the variety of clinical signs observed in patients and the chronological sequence of impairments. The analysis of the cerebrospinal fluid (CSF) is not systematic but confirms the presence of inflammatory phenomena in the CNS, it is based on the abnormal presence of immunoglobulin G (IgG).

The evolution of MS is unpredictable and varies greatly from one subject to another [9]. There is a multiplicity and a polymorphism of clinical signs: patients present or associate motor, sensory, visual, cognitive, bladder and urinary disorders.

3.1.1.5 Assessment of disability in MS
The disability assessment scale that is predominantly used and specifically adapted to MS is the Expanded Disability Status Scale (EDSS) (figure 3.3). This scale is composed of two parts: a first, rated from 0 to 4, takes into account the functional parameters specified by the neurological examination, a second part rated from 4 to 10 takes into account the ambulatory capacities of the patient (perimeter of walking with or without technical assistance) [10, 11].

3.1.2 Clinical signs
3.1.2.1 Motor impairments
They are characterized by muscular deficits and gait disturbances (limitation of walking perimeter, mowing, stepping), disorders of balance, mono or paraparesis and more rarely hemiparesis. All of these signs are related to the degradation of the pyramidal pathways.
3.1.2.2 Optic neuritis
These signs reveal the disease in a quarter of the cases, especially in young adults. It leads to a decrease in visual acuity that sets in a few hours to a few days and is associated in 80% of cases to periorbital pain increased by the mobilization of eyeballs. The recovery of the visual function is complete in 80% of the cases in 6 months, nevertheless after recovery and during an effort or during the increase of body temperature, there can occur a transient decrease of the visual acuity of a few minutes (Uhthoff phenomenon).

3.1.2.3 Orthopedic disorders
The presence of orthopedic disorders is often described in MS as a compensation mechanism for balance disorders. They originate from excessive stressing of predominantly proximal tendino-muscular structures in response to distal deficits and will also lead to increased anticipatory postural adjustments [12].
3.1.2.4 Balance disorders
Balance disorders are common in MS with a prevalence of between 18% and 63% according to the authors [13–16]. These disorders are related to lesions of the central nervous system that affect the sensorimotor functions responsible for postural control [17, 18].

3.1.2.5 Fatigue and cognitive impairment
The frequency of cognitive impairment in MS ranges from 40% to 60% [19]. These disorders are found in undeveloped forms of the disease, with low levels of neurological functional impairment (EDSS < 3.5) [20], very recent evolution times [21], ‘benign’ forms [22] and in clinically isolated syndromes [23]. Fatigue and cognitive impairment (deficits in attention and concentration) affect postural balance [24, 25]. These postural disorders are reported by patients even before being detected by clinical examination [25–27].

3.1.3 Central regulation of balance in MS

3.1.3.1 General
Balance is a set of complex, referenced activities whose quality depends directly on neurophysiological and biomechanical mechanisms. Postural control regulates the position and orientation of the body in space and results from the central integration of visual, somesthetic and vestibular information [28]. The equilibration quality of a subject is related to the correlation of these three types of signals and leads to the construction of a unified reference [29]. This unification contributes to the development of internal models of spatial representation that are continuously updated according to environmental constraints [30]. These models respond to a complex, plastic stochastic neuronal process that can simulate sensorimotor behaviors through the knowledge of the physical characteristics of the body, the outside world and their interactions [31]. They make it possible to anticipate the consequences of a motor act and to determine the orders necessary to achieve performance [32]. Whatever its origin, any difficulty of central multi-sensory integration impacts the construction of these models [33]. As a motor task, posture is automatically regulated at the subcortical level by groups of spinal motoneurons and also requires the cognitive abilities of the subject [34, 35]. The level of cognitive solicitation is proportional to the complexity of the motor task performed, it involves the cortical structures involved in the motor attention within the pre-motor cortex [35] and in the 3D spatial representation of the body located in the parietal lobe [36, 37].

3.1.3.2 Neurophysiological point of view [38, 39]
Visual affiliation and ocular motricity
Gaze stabilization is ensured by reflexes of vestibular origin (vestibulo-ocular reflex and optokinetic reflex) and part of the vestibular messages reach via the posterior longitudinal strip and the thalamus to the vestibular cortex corresponding to the areas 5 and 7 located in the parietal posterior cortex. This zone ensures the conscious perception of the movements of the head in space. Movement vision
involves the detection of moving forms and objects, the perception of eye tracking, and the perception of the movement itself. The detection of moving objects is ensured by the main optical channel and is transmitted to the neurons of the V5 which encode the displacement. At the next cortical level, the upper medio-temporal area (MTS) has plurimodal neurons: visual, proprioceptive, and vestibular. They project on the posterior parietal cortex (areas 5 and 7).

The ocular pursuit of an object in motion involves the participation of the fovea and takes the main optical pathway to the parietal cortex (areas 7a and 7b), this system can detect slow movements (ranging from 0.1 to 1 Hz). The perception of one’s own movement makes use of the accessory optical system and allows the detection of a modification of the environment with respect to a stable subject, or of the subject with respect to a stable environment. This type of message merges into the cerebellum with vestibular messages, and produces the appropriate postural corrections. A copy of this ‘fusion’ is sent to the parietal cortex via the thalamus.

**Proprioceptive afferents**
These rely on the participation of proprioceptive receptors and more specifically the Muscle spindles (Ms) and the Golgi organs. Ms are placed in parallel with muscle fibers, code for stretching, and contribute to the conscious perception of movement. Their stimulation via the lemniscal pathway activates neurons of the area 3a by a double component (change of position of the limb and speed of displacement). The Golgi receptors are placed in the tendons, in series with the muscle fibers. They measure the force or its abrupt increase. The messages are then conveyed by the type 1b fibers and exert, via an inter neuron, an inhibition of α motoneurons. Joint receptors also intervene by informing the nerve centers on the static or dynamic spatial position of the segment (stereognosis).

**Vestibular afferents**
The vestibular receptors work as accelerometers and encode the second derivative of the displacements. The semi-circular channels detect the angular accelerations in the three planes of space: the horizontal (or lateral) channel is sensitive to accelerations detected in the horizontal plane, the posterior channel codes accelerations in the frontal (or transverse) plane and the upper (or anterior) channel of the sagittal plane. Otolithic organs (utricle and saccule) measure linear accelerations: the utricle detects the horizontal accelerations while the saccule detects the vertical accelerations. They constitute (especially with regard to the saccule) a gravity sensor and detect the static inclination of the head. Information from the vestibular system is transmitted via the vestibular nerve (VIII) to the vestibular nuclei of the brainstem.

Stabilization of the cervico-cephalic segment takes place via the vestibulo-spinal pathway (and its interactions with the α and γ motor neurons), to which are added information from the proprioceptive receptors of the neck muscles intended for the vestibular nuclei, the nucleus red and some reticular nuclei.
3.1.3.3 Biomechanical point of view

Mechanical model and postural strategy:
The human bipodal task has long been modeled as an inverted pendulum oscillating around its base of support [40–42]. Currently, this notion is moving towards another model: the double inverted pendulum to explain the compensatory role of the lumbo-pelvic region [43]. Various strategies are developed and controlled by the central nervous system (CNS) to stabilize the body position in orthostatic condition. The ankle strategy is the most commonly used: it is the most economical and effective solution because of the high concentration of mechanical sensors sitting in the distal muscles. The hip strategy is more expensive in terms of energy because it is less ‘reactive’. Finally, the lowering of the center of mass allows a relative stabilization when the two previous strategies prove to be ineffective [44].

Distal control, center of mass (COM) and center of pressure (COP):
Many papers emphasize the importance of distal control when the equilibrium conditions of a subject are disturbed, as such, a fundamental role played by the muscular couples: anterior tibial and soleus (which ensure stability on the axis anteroposterior) on the one hand, posterior tibial and fibular (which control the medio-lateral axis) on the other hand [43, 45]. From a biomechanical point of view, the main challenge is to ensure the concordance between the respective positions of the center of mass (COM) and the center of pressure (COP), the shift of the COM with respect to the COP generates the implementation of permanent muscular tension which leads to an increase in joint constraints. The perpetuation of these constraints leads to painful conflicts and early degenerative phenomena [42, 44].

Muscular viscoelasticity and MS:
In MS the modification of viscoelastic properties and disturbances of sensorimotor control does not allow optimal stabilization of the body in space [46]. The muscular energy demand is markedly increased, especially on pelvic stabilizing muscles, quadriceps and the tibialis anterior/soleus pair [47].

3.1.3.4 Assessment of balance disorders
Assessments of balance disorders is usually based on validated clinical tests and the most widely used in the literature are the Berg balance test (BBS), the Dynamic Gait Index (DGI), the Dizziness Handicap Inventory (DHI) and the Activities-specific balance confidence (ABC) [27]. Nevertheless, these evaluations remain subjective with inter and intra-examiner variability [24]. For a decade, instrumental analyzes have been developed that allow the oscillations of a standing subject to be accurately analyzed by recording the displacement of the Center of Pressure on a force platform [48].

3.1.4 Instrumental analysis
In recent years, posturography has attracted a great deal of interest among re-educators and neurologists, but in early-stage multiple sclerosis the literature
remains poor with regard to the instrumental study of somesthetic disorders. Two authors, Jackson [49] (concerning changes in perception of vertical and subjective horizontal in MS patients versus a control population) and Nelson [14] (about vestibular deficits and their sensory compensations highlighted on a dynamic platform) in 1995, studied the MS population on the strength platform. Some studies have analyzed postural regulation in multiple sclerosis, including Soyuer [50] in 2006. But little work has been done on proprioceptive disorders in MS, Frzosic et al [51] in 2000, Wildener et al [52, 53], more recently (2009), examined a study of this type. The existence of correlations between the posturometric signal (nonlinear analysis) and the EDSS score has been demonstrated [54]. It is clear from the literature that MS subjects experience a decrease in walking speed, step length, and increased double support time. Decrease in walking speed is very often associated with decreased hip and knee extension, plantar flexion, and propulsive force. This association evolves proportionally with the level of disability [55]. There is also an alteration of anticipated postural adjustments [56] and a significant increase in the risk of falling [57]. All of these phenomena increase fatigue in proportion to the disturbances related to insufficient motor control [58, 59]. In MS, proprioceptive disorders of the lower limbs associated with the presence of spasticity require the intervention of the paraplegral muscles to maintain the erect posture. This mode of compensation ensured by the spine results in an increase of the oscillations of the trunk along the medio-lateral axis [60]. More generally, studies carried out on subjects with low back pain, have shown a relation between lumbar pain and the increase of the amplitude of the oscillations recorded in orthostatic condition: the pain is generating postural disturbances and the converse is also true [59]. Experimentally, the pain caused by the triceps suraux influences the postural regulation and especially, the anticipated postural adjustments [61]. More generally, the compensations put in place by the CNS to maintain a stable erected posture are not limited to the pelvis and the lumbar region, in fact the intermediate joints and especially the knee will also experience a modification of the constraints. Biomechanical adaptations of the lower limb have been known for more than half a century but are still relevant [62].

3.2 Technical materials in posturography

3.2.1 Center of pressure versus center of gravity

The gravity line of the body corresponds to the vertical line going through the center of gravity (COG) of the human body or barycenter of the masses of all the segments that constitute the body. The center of mass (COM) is generally considered to be coincident with the (COG) of the human body [63]. In a standing posture, COG is located within the human body about 3 cm below the 3rd lumbar vertebrae. In static balance, the body, could be considered as a rigid solid that oscillates around the ankle joint. In this case, the body is only exposed to the actions of the gravitational force, applied at COG, and the ground reaction of the support, applied at center of pressure (COP); COP is the barycentre of the vertical forces applied to the ground (figure 3.4). Thus, the projection of the COG on the ground represents a
downwardly directed vertical force whose amplitude reflects the weight of the body. This force is opposed to an equivalent vertical upwardly directed reaction force component whose point of application to the ground is called the center of pressure (COP) [64]. Balance is achieved when the gravitational and reaction forces of the ground as well as the moments around the ankle axis are balanced. The body’s center of gravity is then projected into its sustaining polygon, which is the figure obtained by joining the most distant points of support as illustrated in Figure 3.4. For a man, its surface is the area including area of each foot completed with the area between the two feet. The COP is considered as a variable controlled by the neurological system. Indeed, the COP is proportional to the moment of force applied to the ankles and therefore to the muscular forces required to stabilize the vertical stance [65, 66]. The COM is considered by several authors as the variable controlled by the COP [67]. Thus, analysis of the temporal structure of the COP and/or the COM could give some information on the control mechanisms of the postural system and on the nature of postural oscillations. Studies, carried out on the two components COM and COP, have shown that the oscillations of the two signals of the COM and COP are in constant phase shift once the postural system is stabilized [68, 69]. But as long as the system is unstable, the COP moves faster and further to

Figure 3.4. Estimation of static balance forces, (a) assuming the points of application of ground reaction forces distributed over both feet (\(R_{\text{right}}, R_{\text{left}}\)) and gravity \(P\), (b) with a single point of application of the total ground reaction force which is the COP, the body is considered as a rigid stem whose point of support on the ground is the anchor, \(D\) distance between the COP and ankle and \(d\) distance between the COG and ankle.
the right, left, forward and backward as if it tries to bring the COM back and keep it near its average position. In fact, the COP's movements stabilize the COM. Some authors studied the difference between COM and COP signals and asserted that this difference could be associated with joint stiffness of the ankles. Force platforms measure COP variation during time.

### 3.2.2 Force platforms

Static posturography is performed using a force platform (figure 3.5), consisting of a non-deformable plate on which the subject must remain as static as possible. The force sensors are transmitting to a computer in real time, the evolution of the position of the COP is displayed as summarized in figure 3.6. This plot, the statokinesigram, allows an automated determination of the orthostatic balance parameters.

In contrast, dynamic posturography is performed using a mobile toggle platform (platform resting on a cylinder portion) equipped with an inclination sensor that analyzes the subject’s ability to maintain balance on a spontaneously unstable basis. As the platform has only one degree of freedom of movement, the antero-posterior balance (AP) and the lateral balance (ML) are analyzed successively according to the orientation of the subject in relation to the axis of rotation of the cylinder. The length of the path of the platform pivot over a given time period characterizes the dynamic balancing performance. The frequency analysis of the platform oscillations makes it possible to consider the balancing strategies used by the patient.

![Figure 3.5. Example of static force platforms: (a) [https://www.medicapteurs.com/produits/winposturo] © Medicapteurs; (b) [http://www.technoconcept.fr] © TECHNO CONCEPT; (c) [http://www.satel-posture.com] © SATEL.](image1)

![Figure 3.6. Acquisition and display of balance with a force platform.](image2)
3.2.2.1 Principle
A dynamometric force platform provides six components: three for the forces ($F_X$, $F_Y$, $F_Z$) and three for the moments of force ($M_X$, $M_Y$ and $M_Z$) resulting from the forces and moments applied to its upper plate. A force platform generally consists of two rigid, non-deformable structures connected by force sensors. The lower recessed structure serves as a rigid frame. The upper surface is a tray that supports the supports. It returns forces fully and without delay to the sensors, which are the essential elements of force platforms. They can be classified according to the sensors used to measure forces.

3.2.2.2 Types of force platforms
Strain gauge: strain gauges are sensing devices that change resistance at their output terminals when stretched or compressed. They are constituted by a length of conductor arranged in a zigzag pattern on a membrane. They offer good accuracy for a reasonable cost, but range is limited. They are therefore the most widespread:

Piezo-electric: piezo-electric are sensing devices that generate a voltage at their output terminals when stretched or compressed. Frequency and amplitude of voltage will characterize the answer of the sensor. They offer good accuracy and an important range of measure but the cost still high.
- Principal manufacturer: Kistler [https://www.kistler.com/].

Figure 3.6 summarizes the different components and their characteristics to estimate the COP.

For example, Satel platform has four constraint gauges and a 16 bit DAC with a sampling frequency of 40Hz; Stabilotest© has three constraint gauges and a 16 bit CAN with a sampling frequency in the range 5–40 Hz.

3.2.2.3 Remarks on acquisition data parameters
The choice of a 16 bit (2 bytes) resolution seems to have become the standard. The sampling frequency and acquisition duration time are the subject of a significant amount of discussion in the literature. For example, the choice of a duration of 51.4 s, with a sampling frequency of 40 Hz, parameters that are recommended in France, consists in obtaining a file of 2048 points equivalent to $2^{11}$. This choice is guided to facilitate the processing of the DAC and the acceleration of post processing too. However, one may wonder about the duration of registration and sampling frequency, which seem to be more imposed here by technical consideration than by clinical practice. The future representations of the signals, the computations performed on the basis of these measurements, and therefore the diagnostic considerations will follow from the duration time and especially the sampling frequency at which the COP is acquired. Thus, many authors have studied the breadth of information contained in the acquired data set and have discussed the influence of the number of points required to visualize and have a significant calculation [70], Satel platform, 40 Hz, 51.2 s. We can also find with the same acquisition parameters a study dealing with the Sample Entropy, but the influence of...
the number of points on the results is not discussed, this study is done on a Medicapteurs platform [71].

Some authors use a frequency data acquisition of 30 Hz to calculate the frequency parameters with a duration of 60 s of record [72], others use a duration of 30 s with a sampling of 100 Hz [73], Zebris platform, for the same parameters computed. For non-linear parameters like entropy, some authors used 1 KHz frequency [74], AMTI platform, or 100 Hz over a duration of 20 s for a dynamic task [75] on SwayStar TM platform.

Finally, a publication mentions a comparative study of estimating non-linear parameters such as Sample entropy and RQA variable with various sampling frequencies results [76], Bertec platform, acquisition frequency 100 Hz. The authors show that the sampling frequency chosen for the computations, under the experimental conditions of their study, seem to have a limited influence. However, it is practically impossible to compared objectively all these studies, because they were carried out on various machines, with various experimental conditions depending on the disease.

In fact, the problem can be summarized as follows: if we simply want to read the stabilogram or make simple calculations called linear here, the frequency does not need to be very high compared to the underlying slow dynamics of COP. In France, in addition to 40 Hz, the 100 Hz frequency is also becoming a standard sampling frequency. Several statements on the still debated issue of stabilometry standardization were agreed upon by the International Society of Posture & Gait Research Standardization Committee [73]. A set of metrological characteristics for stabilometric platforms was defined, relying both on practice and experimental verification. It was agreed that, to obtain appropriate accuracy and sensitivity, for example in the Romberg Test, the acquisition interval should not be less than 25 s, the sampling frequency should be at least 50 Hz. After careful consideration it was decided that the recommendations made in the previous Standardization proposal in 1983 regarding environmental conditions should be maintained.

The upgrade to 100 Hz allows a more accurate spectral analysis and increases the possible range of spectrum studies. The idea, that seems to be the more interesting, is based on the statement that 1 kHz sampling has become a standard for DACs, and that the explosion of memory capacities of electronic systems allows more important information to be stored. In this context, a 16 bit DAC, with \( f_e = 1 \) kHz and then under-sampling the signal to recover all the possibilities between 40 Hz and 500 Hz on the post-processing seems to be the more adapted. Thus the acquired data will allow one to validate the theoretical assumptions coming from new non-linear type analysis methods that require a lot of points and could be adapted to future other data-based investigations.

In summary, the minimum of the published standards must be respected when choosing the sampling frequency. A minimum of 100 Hz for data acquisition in the clinical setting should allow mathematically correct analyses with more advanced algorithms, especially if you want to explore frequencies above 20 Hz or use more complex filtering methods.
For research activities, the choice of manufacturers who offer custom assembly at
the level of sensor types, DAC and a sampling frequency of 1 kHz should give a finer
tune in the indicators definition.

One of the most important points that emerged from this brief study is that a
multi-machine clinical study should be carried out with a shared protocol to propose
international standards in the interpretation of posturometric measurements.

3.2.2.4 Estimated measures with platform force
Statokinesigram: this displays the sampled location of the COP in relation to a
reference frame with its origin located in the center of the platform. In figure 3.7, the
representation of the subject’s feet is on the scale of his shoe size.

Standardized representations are obtained from the statokinesigram:

- Normalized ellipse, it represents the area in which 95% of the most centered
  points of the sampling are located.
- Normalized circle, it represents the position statistically determined from the
  20% of the most frequently encountered patients (core of the Standards).
- Force histogram.

From these standardized representations, a set of measures can be deduced that are
used to establish the care. To facilitate this diagnosis, the manufacturers, in France,
propose to compare the patient’s values with the normalized values [77] defined by
the association Posture and Balance [78].

Surface
From 95% of the successive positions of the COP recorded during the whole time of
acquisition, a statistical measurement of the surface, expressed in mm$^2$, of the
confidence ellipse is performed (table 3.1). 5% of the most extreme points, resulting
from poorly controlled swings, are eliminated. Most posturologists agree that this
parameter is one of the most relevant to quantify an individual’s ability to balance
under static conditions.

![Figure 3.7.](image)

**Figure** 3.7. (a) Statokinesigram with normalized ellipse, (b) sustentation polygon with so-called
statokinesigram.
Length
The total length of the statokinesigram represents the distance travelled by the pressure centre throughout the examination (table 3.2).

LFS
The parameter LFS (Length according to Surface), reflects the amount of energy spent by a person controlling his orthostatic balance. The value of the LFS increases when the difficulty of standing upright is modifying by changing one of the inputs of the postural system (eyes closed for example) (table 3.3).

VFY:
Standard deviation of the velocity of the COP displacement as a function of the mean Y-position reflects the postural tone of certain muscles in the posterior cavity and their viscoelastic properties. In the elderly, a significant change in the VFY often indicates a change in the equilibration strategy, such as a shift from ankle to hip strategy (table 3.4).
**Romberg ratio**

It is the ratio, expressed as a percentage, of the surface with eyes closed, to the surface with eyes open. This quotient is used to assess the quality of the visual input and its relative importance compared to other inputs in the system (table 3.5).

The stabilogram: the right–left and front–back stabilograms represent the vector components of the patient’s oscillations throughout the examination. On the stabilogram there are cursors indicating the synchronisation with programmed stimulation (figure 3.8).

*Figures 3.8.*  *X*-direction (ML) and *Y*-direction (AP) stabilograms from SATEL.

**Table 3.4.** Normalized parameter (Norm 85) for VFY.

<table>
<thead>
<tr>
<th>VFY</th>
<th>Open eyes</th>
<th>Closed eyes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Limit inf.</td>
<td>−2.61</td>
<td>−4.73</td>
</tr>
<tr>
<td>Limit sup.</td>
<td>3.59</td>
<td>4.86</td>
</tr>
</tbody>
</table>

**Table 3.5.** Normalized parameter (Norm 85) for Romberg ratio.

<table>
<thead>
<tr>
<th>Romberg ratio</th>
<th>Open eyes</th>
<th>Closed eyes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>0.862</td>
<td>2.88</td>
</tr>
<tr>
<td>Limit inf.</td>
<td>0.33</td>
<td>1.12</td>
</tr>
<tr>
<td>Limit sup.</td>
<td>2.37</td>
<td>6.77</td>
</tr>
</tbody>
</table>

*Romberg ratio*

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*Figures 3.8.*  *X*-direction (ML) and *Y*-direction (AP) stabilograms from SATEL.

*Romberg ratio*

It is the ratio, expressed as a percentage, of the surface with eyes closed, to the surface with eyes open. This quotient is used to assess the quality of the visual input and its relative importance compared to other inputs in the system (table 3.5).

The stabilogram: the right–left and front–back stabilograms represent the vector components of the patient’s oscillations throughout the examination. On the stabilogram there are cursors indicating the synchronisation with programmed stimulation (figure 3.8).

*Figures 3.8.*  *X*-direction (ML) and *Y*-direction (AP) stabilograms from SATEL.
\(Y_{\text{mean}}\): projection on the \(Y\)-axis (antero-posterior axis of the subject) of the mean position of the pressure centre expressed in mm. It indicates the average value of the forward/backward balancing movements.

When these values exceed certain standard values, there is an asymmetry in postural tonicity that can lead to a postural deficiency syndrome. When these values exceed certain standard values, there is an asymmetry in postural tonicity that can lead to a postural deficiency syndrome. In particular, it is known that tonicity changes with age. For example, a young adult would normally stand in forward positions, while at about 60, the average \(Y\) would first move back, then move forward depending on the degree of inclination of the trunk.

FFT (fast Fourier transform): to assess the proportion of the different frequency bands of postural oscillations in the statokinesigram, a frequency analysis can be performed. Each of these bands involves the use of a specific postural control loop. The slow frequencies correspond to control loops with a visual or vestibular starting point. The higher frequencies correspond to regulation loops with a plantar or proprioceptive muscle skin starting point.

In figure 3.9, three frequency bands are delimited by the two vertical lines. Those cursors could be moved manually with the mouse. Spectral energies in each band could be estimated in percentages too.

**Correlations**

The inter-correlation function compares the antero-posterior oscillations with the right–left oscillations. If the shape of the curve representing this function is clearly sinusoidal, the right–left and forward–back oscillations are no longer independent since they share a common periodicity.

### 3.3 Analysis methods in posturography

As explained in section 3.1, MS patients experience balance deficits in the ML and/or AP direction(s) in quiet standing [17, 46, 73]. The directional control impairment has been further observed in the right side and backward diagonal (backward-right and backward-left) directions in individuals with MS [79]. In recent years,
posturography has become a popular and advanced technique to evaluated balance impairment in people with MS. Moreover, numerous linear and non-linear analysis methods have been proposed to explore in depth characteristics of the stabilograms of MS patients.

3.3.1 Linear analysis

3.3.1.1 Time domain

Time-domain measures extracted from the stabilograms are associated with the displacement of the COP in the ML and AP directions. In addition to the surface of the confidence ellipse (or the sway area) and the total length of the COP path (or the total excursion) indicated previously in the section 3.2, several other parameters can be found in the literature [80–82], such as:

- the mean velocity (or the sway rate): defined as the total length of the COP path divided by the total testing time;
- the ML and AP ranges: defined as the differences between the maximum and the minimum COP values along the ML and AP axes, respectively;
- the root-mean-square (RMS) distances from the mean COP in the ML and AP directions: defined as the statistical standard deviations of all COP values along the ML and AP axes, respectively;
- the total excursions in the ML and AP directions: defined as the total distances that the COP traveled along the AP and ML axes, respectively;
- the mean velocities in the ML and AP directions: defined as the total excursions in the ML and AP directions, respectively, divided by the total testing time.

Numerous studies have shown that the amplitude and the velocity of postural sway were significantly greater in MS patients compared to healthy subjects under the condition of EO or EC [26, 46, 73]. In addition, some studies have found greater postural sway in patients with a greater EDSS score compared to those with a smaller EDSS score [83, 84], although differences in some temporal measures were not significant.

3.3.1.2 Frequency domain

In addition to analysis of the ML and AP sway in time domain, several studies have focused on their frequency content and spectral characteristics [85, 86]. For this, the power spectrum, describing the distribution of power into the signal’s frequency components, needs to be calculated for the COP signal in the ML or AP direction by FFT. As a few investigations of the body sway using frequency analysis approach have reported that different frequencies are associated with different regulations in MS [87], the COP power spectrum could be divided into several frequency bands in order to be further explored [88]. Kanekar et al have reported [89] that the MS group showed a significant decrease in the magnitude of COP power spectrum in the low frequency band and a pattern of increase in the medium and high frequency bands in the ML direction.
Furthermore, many spectral parameters are used to characterize the postural stability for the ML and AP directions \([82, 90]\), such as:

- the total power: defined as the integrated area of the power spectrum;
- the median power frequency: defined as the frequency at which the power spectrum is divided into two equal energy regions;
- the 95% power frequency: defined as the frequency below which 95% of the total power is present;
- the centroidal frequency (or the zero crossing frequency): defined as the square root of the ratio of the second to the zeroth spectral moments.

### 3.3.2 Nonlinear analysis

In addition to the classical parameters indicated previously, many nonlinear methods have been applied to the postural signals in order to better analyze human static stability.

#### 3.3.2.1 Methods used to analyze postural stability in MS

**Entropy analysis**

Approximate entropy (ApEn) is a nonlinear dynamic parameter used to quantify the amount of regularity and the unpredictability of fluctuations in a time series \([74]\). As a non-negative number, ApEn reflects the occurrence of new information in the time series. Since the presence of repetitive fluctuation patterns renders a time series more predictable than the one in which such patterns are absent, a time series containing many repetitive patterns has a relatively smaller ApEn and a more complex (i.e. less predictable) process has a higher ApEn.

The algorithm for computing ApEn has been published \([91, 92]\). Given a sequence \(S_N\), consisting of \(N\) measurements equally spaced in time, its ApEn is defined as follows:

\[
ApEn(S_N, m, r) = \ln \left[ \frac{C_m(r)}{C_{m+1}(r)} \right],
\]

where \(m\) specifies the pattern length and \(r\) defines the similarity criterion. Two subsequences (or patterns) of \(m\) measurements, beginning at different intervals within \(S_N\), are considered similar if the difference between any pair of corresponding measurements in the patterns is less than the tolerance \(r\). The quantities \(C_m(r)\) and \(C_{m+1}(r)\) indicate the prevalence of repetitive patterns of length \(m\) and that of length \(m + 1\), respectively.

Therefore, smaller values of ApEn reflect a greater likelihood that similar patterns of measurements will be followed by additional similar measurements. On the other hand, if the time series is highly irregular, the occurrence of similar patterns will not be predictive for the following measurements, and ApEn will be relatively large. It should be noted that ApEn is not well suited for analysis of the short and noisy datasets and may lead to inconsistent results. For this reason, the sample entropy (SampEn) has been introduced to avoid bias due to the shortening of the data.
SampEn is a measure basically quantifying the irregularity of a time series. For a given embedding dimension \((m)\), tolerance \((r)\) and number of data points \((N)\), we take the negative logarithm of the probability that if the distance between two template vectors of length \(m\) is less than \(r\) then the distance between two template vectors of length \(m + 1\) is also less than \(r\).

\[
\text{SampEn}(m, r, N) = - \log(A(r)/B(r)) \tag{3.2}
\]

where \(A(r)\) is the total number of template matches in a \((m + 1)\)-dimensional phase space within a distance tolerance \(r\), and \(B(r)\) is the one in a \(m\)-dimensional phase space [71]. An increase in SampEn implies a higher level of disorder and unpredictability in a time series.

Manor \textit{et al.} studied the SampEn associated with the COP displacements in older adults during quiet standing [93]. They related the parameter SampEn to the complexity of postural sway, and consequently to the adaptive capacity of the postural control system to cognitive and other stressors.

Huisinga \textit{et al.} found that patients with MS exhibit increased regularity (decreased ApEn) during standing compared to healthy controls [94], while we observed a significant increase in SampEn between the healthy subjects and the MS patients in EO and EC [95]. Christopher \textit{et al} reported that the ApEn and the SampEn (algorithms typically used to quantify the entropy of COP) might yield very different results, particularly when sampling frequency and noise are different [74].

\textit{Recurrence quantification analysis}

Recurrence quantification analysis (RQA), developed by Zbilut and Webber [96, 97], is a method of nonlinear analysis to investigate and characterize the recurrence behavior (e.g. the number and duration of recurrences) of the phase space trajectory of dynamical systems, based on the recurrence plot (RP).

The RP is a black and white plot showing the times when a phase space trajectory of the system visits roughly the same region in the phase space [98]. As shown in figure 3.10, an RP revealing a behavior of the phase space trajectory is composed of single dots and lines which can be horizontal, vertical, or parallel to the mean diagonal (also known as line of identity, LOI) [99]. Generally, each black dot in such a plot represents a recurrent point. Among the lines in the RP, the diagonal lines (lines parallel to the LOI) represent periodic recurrent structures of the dynamical system, whereas the horizontal and vertical lines represent the segments of the phase space trajectory which remain in the same phase space area for a while. Since the RP is usually symmetric with respect to the LOI, each horizontal line corresponds to a certain vertical line. For this reason, the horizontal lines are often ignored and only the vertical lines are considered in the RQA.

The RQA quantifies the small-scale structures in RPs of dynamical systems, and can provide useful information even for short non-stationary data. To analyze a dynamical system, represented by a time series, using the RQA, a reconstructed phase space is first required and usually established by means of a time delay...
embedding where two embedding parameters (the embedding dimension and the time delay) have to be chosen appropriately \[96, 97, 98\]. Because the information about the original data series is transmitted to the vectors in the reconstructed phase space, the recurrence of states of the dynamical system can be identified by comparing the states at any two different times so that an RP can be constructed for the system. With the help of the RP, several measures of complexity can be estimated as follows \[98\].

The recurrence rate (RR) or the percentage of recurrence (%Rec), is the simplest RQA measure, which is the density of recurrence points in an RP:

\[
RR = \frac{1}{N^2} \sum_{i,j=1}^{N} R(i, j),
\]

where \(N\) represents the number of considered states and \(R(i, j)\) is equal to 0 or 1. If the states of a system at two different times \(i\) and \(j\) are similar, \(R(i, j) = 1\). Otherwise, \(R(i, j) = 0\). This measure reflects the probability that a specific state recurs in the phase space, and corresponds to the correlation sum, where the LOI is excluded during the computation.

In order to explore the distribution of recurrence points in the RP, two RQA measures called determinism (DET) and laminarity (LAM) have been further proposed to reflect the numbers of recurrence points which form diagonal lines and vertical lines, respectively.

Figure 3.10. Recurrence plot of the COP signal of a MS participant with EDSS = 2.0 (black dot: recurrent point).
\[
\text{DET} = \frac{\sum_{l=l_{\text{min}}}^{l_{\text{max}}} l \cdot P(l)}{\sum_{l=l_{\text{min}}}^{l_{\text{max}}} l \cdot P(l)}, \tag{3.4}
\]

\[
\text{LAM} = \frac{\sum_{v=v_{\text{min}}}^{v_{\text{max}}} v \cdot P(v)}{\sum_{v=v_{\text{min}}}^{v_{\text{max}}} v \cdot P(v)}, \tag{3.5}
\]

where \(P(l)\) represents the frequency distribution of the lengths \(l\) of the diagonal lines (with the minimal length \(l_{\text{min}}\)) and \(P(v)\) represents the frequency distribution of the lengths \(v\) of the vertical lines (with the minimal length \(v_{\text{min}}\)). The determinism is related to the predictability of the dynamical system, whereas the laminarity is related to the number of laminar phases in the system.

In addition, the averaged diagonal line length \((L)\) and the average length of the vertical lines (known as the trapping time, \(TT\)) in the RP can be also determined from the RP.

\[
L = \frac{\sum_{l=l_{\text{min}}}^{l_{\text{max}}} l \cdot P(l)}{\sum_{l=l_{\text{min}}}^{l_{\text{max}}} P(l)} \tag{3.6}
\]

\[
TT = \frac{\sum_{v=v_{\text{min}}}^{v_{\text{max}}} v \cdot P(v)}{\sum_{v=v_{\text{min}}}^{v_{\text{max}}} P(v)} \tag{3.7}
\]

The averaged diagonal line length reflects the predictability time of the dynamical system, while the trapping time reflects the laminarity time of the system.

The maximal diagonal line length \((L_{\text{max}})\) and its inverse, called divergence (DIV)

\[
\text{DIV} = \frac{1}{L_{\text{max}}} \tag{3.8}
\]

are two RQA measures as well. \(L_{\text{max}}\) is the length of the longest diagonal in the RP. The smaller \(L_{\text{max}}\) the more divergent the trajectories. Although there is a relationship between the largest positive Lyapunov exponent and \(L_{\text{max}}\)\cite{99}, this relationship is not as simple as stated in the literature, but even more complex.

The Shannon entropy (ShanEn) represents the probability of finding a diagonal of a given length

\[
\text{ShanEn} = - \sum_{l=l_{\text{min}}}^{l_{\text{max}}} p(l) \cdot \ln(p(l)), \tag{3.9}
\]

where \(l_{\text{min}}\) represents the minimal diagonal length, and \(p(l)\) represents the probability of a diagonal line of length \(l\) in the RP. This entropy can be estimated from the frequency distribution \(P(l)\) with
and reflects the complexity of deterministic structures in the system. However, this parameter is sensitive to the bin number of the processor and may differ for different data preparations or different realizations of a process.

The trend is another RQA measure, which is a linear regression coefficient of the relationship between the recurrence point density in a line parallel to the LOI and its distance to the LOI. Considering the recurrence rate in a diagonal line parallel to LOI of distance \( k \) (\( RR_k \)):

\[
RR_k = \frac{1}{N - k} \sum_{j=1}^{N-k} R(i, j),
\]

the trend (TND) is defined by

\[
TND = \frac{\sum_{i=1}^{N}(i - \bar{N}/2)(RR_i - \langle RR_i \rangle)}{\sum_{i=1}^{N}(i - \bar{N}/2)^2},
\]

where \( \langle \cdot \rangle \) gives the average value and \( \bar{N} < N \). The edges of the RP should be excluded during the TND computation because recurrence point densities are too low in the edges. This measure provides information about the stationarity of the dynamical system.

RQA has been widely used in biomedical research and applied to different kinds of clinical data, including the posturographic signal. Negahban et al have observed [76] that as the postural conditions became more difficult, COP time series of both MS and control groups became less regular (lower recurrence rate), less complex (lower RQA entropy), and less nonstationary (lower trend). In addition, when cognitive conditions became more difficult (from a single postural task to a dual postural-cognitive task), COP time series became less regular (lower recurrence rate in the AP direction and lower determinism in both directions), less complex (lower RQA entropy in the AP direction), and less nonstationary (lower trend in the AP direction). Their results have shown that, although the MS patients and the control group had a similar dynamical structure, their nonlinear behavior was different under some experimental conditions.

In our previous study [100], the EDSS score was estimated from two linear parameters, the length and the surface, and four RQA parameters: percentage of recurrence, Shannon entropy, mean diagonal line length and trapping time. Moreover, all four RQA parameters were calculated for position, instantaneous velocity and acceleration of the COP in order to select the most accurate method for estimating the EDSS. The results demonstrated that estimations of EDSS from the surface, the percentage of recurrence and the mean diagonal line length of the position, best agreed with clinical scores. Then, this EDSS modeling strategy was evaluated using both mono- and multi-dimensional RQAs [101]. These studies have
emphasized the possibility of distinguishing EDSS scores using postural sway and RQA parameters, and suggested that the posturographic signal’s mono-dimensional RQA is a more pertinent method to quantify disability in MS than the multi-dimensional RQA.

3.3.2.2 Other methods in the literature
Some other non-linear analysis methods can be also found in the literature to analyze the COP signal. Although they have not yet been used to analyze postural stability in MS, they could be able to provide some other useful information linked to MS in the future.

Fractal dimension approach
Fractal dimension analysis (FDA) is used to quantify the complexity of a system. When the COP trajectory is analyzed during a quiet stance, a change in fractal dimension (FD) may reflect a change in postural control strategies for maintaining body balance. Previous studies [102, 103] reported that FDA is a reliable method to provide us with specific characteristics of human postural control.

FD of COP signal can be computed using the box-counting algorithm [104]. To calculate the FD for a given set, we first cover the set with a grid and count how many boxes of the grid are covering part of the set. Then we do the same thing but using a finer grid with smaller boxes. By shrinking the size of the grid repeatedly, we end up more accurately capturing the structure of the pattern.

If \( N(\epsilon) \) represents the number of boxes (of grid size \( \epsilon \)) needed to fully cover the set, then the box-counting dimension is defined as follows:

\[
FD = \lim_{\epsilon \to 0} \frac{\log (N(\epsilon))}{\log (1/\epsilon)}.
\]

Thus, FD is the slope of the plot \( \log(N(\epsilon)) \) versus \( \log(1/\epsilon) \). In a two-dimensional picture, the FD value ranges from 0 to 2 and is higher when the set (or picture) is more complex [105].

Empirical mode decomposition processing method
Empirical mode decomposition (EMD) is an adaptive time–frequency analysis method. The principle of this method is to decompose a signal into a set of band-limited elementary signals, called intrinsic mode functions (IMFs), which represent the oscillatory modes embedded in the signal [106]. This technique allows extracting from the signal all IMFs with different frequencies. Breaking down biomedical signals into various components, EMD can be compared with other analysis methods such as Fourier transform and wavelet transform. However, these two methods need some predefined basis functions to decompose a signal, while the EMD method does not require a prior known basis. Since the decomposition is based on the local characteristic time scale of the data, it can be applied to nonlinear and nonstationary processes. EMD obtains much better temporal and frequency resolutions compared to Fourier and wavelet analyses [107, 108].
Detrended fluctuation analysis

Detrended fluctuation analysis (DFA) is a method to determine the statistical self-affinity of a signal. It is useful to analyze time series that appear to be long-memory processes or 1/f noise [109]. Briefly, the integrated time series of length $N$ is divided into intervals of equal length $n$ without overlapping. In each interval of length $n$, a least squares line fitted to the data is subtracted. Next, the root-mean-square fluctuation of this integrated and detrended time series is calculated by

$$F(n) = \sqrt{\frac{1}{N} \sum_{k=1}^{N}[y(k) - y_n(k)]^2} .$$

(3.14)

A linear relationship on a log–log plot indicates the presence of power law (fractal) scaling. Under such conditions, the fluctuations can be characterized by a scaling exponent $\alpha$, the slope of the line relating log ($F(n)$) to log($n$) [110]. When the DFA coefficients $\alpha$ are $> 0.5$, they indicate a more structured signal with long-term correlations, and thus low variability. When $\alpha < 0.5$, the signal has negative correlations, and $\alpha = 0.5$ indicates a non-correlated random series.

3.4 Conclusion

In this chapter, we presented an advanced technique to characterize balance disorders in MS using a static force platform, called static posturography, including the introduction to this technique, the machines used in the clinic, the linear (temporal and spectral) parameters and the new nonlinear indicators extracted from the stabilometric signals, as well as the links with the clinic in the context of MS. The data from the posturographic analysis inform clinicians about the postural control strategies developed by MS patients.

The advantage of posturography lies in its simplicity of implementation for clinicians and its character with very little restriction for MS patients (short duration, non-invasive, ...) regarding its clinically proven performance. The use of new indicators opens up new perspectives for posturography in MS. It would be able to provide new diagnostic elements for the management, in particular with the possibility of predicting the evolution of the EDSS score, and thus improve the understanding of the mechanisms involved in the system for balance regulation in MS.

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