Why and how to use the Center of Gravity in clinical Stabilometry

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Summary

Clinicians must be critical when treating patients who suffer from purely functional disturbances of the postural system — without any anatomic lesion of the central nervous system —. Stability proves to practise this criticism, both on the concept itself of stability and the means to objectify it. We must stop basing our stabilometric analysis only on the traditional 'center of pressure' which causes confusion between stability and stabilization. Many methods have been proposed to assess the position of the center of gravity starting from the center of pressure; a new method is presented here. choose one of these methods, its to confront the subject to a reference population must be taken into account. This may result in a choice different from the one made in laboratories studying the movement. Stabilometry is specified by its object, this paper deals with postural clinical stabilometry.
Why

WWI forced neurologists to consider the functional neurological disorders beyond their clinicopathological concept. Not only do they exist (Babinski and Froment, 1918) but some of them have an unquestionable objectivity when observing a cohort of patients who suffer from the same disorders «They all say the same thing, with the same words, we cannot think that they have agreed» (Marie, 1916). Intersubjectivity is the basis of the objectivity of these functional disorders.

But when a clinician observes an isolated functional patient, the criterion of intersubjectivity is blunted and the clinician needs to find other objectivity criteria behind the subjective complaints of his patient. Some neurologists have then tried to use the labyrinthine galvanic stimulation, unsuccessfully (Cestan et al., 1916, b; Cestan et al., 1916, a; Foy, 1919). As soon as they emerged in the clinical field, force platforms have raised hopes (Baron, 1964), hopes that were partially disappointed: the force platforms are unable, even today, to provide proof of the objectivity of the functional disorders presented by a patient, they are hardly able to provide a series of presumptions. This does not mean that platforms are no longer useful, they are useful and even more and more, but differently: they allow those who treat functional patients to validate the efficiency of their treatments and to access to a language whose rigor tries to rely on biomechanics.

This rigor of language has become strictly necessary since the discovery that the postural system operates as a nonlinear dynamic system (Baron, 1955; Cao et al., 1998; Firsov and Rosenbum, 1990; Fukuda, 1957; Gagey et al., 1998; Martinerie and Gagey, 1992; Micheau et al., 2001; Murata and Iwase, 1998; Myklebust et al., 1995; Peng et al., 2002; Peterka, 1999; Sasaki et al., 2001; Sasaki et al., 2006; Sasaki et al., 2002; Shimizu et al., 2002; Thomasson, 1995). The criterion of proportionality between cause and effect having disappeared, any minor event can be assumed to cause remarkable cures, for instance a few millimeters of additional thickness of the inner sole of a shoe positioned under a certain area of the footpad (Ehring and Kurzawa, 2012; Janin, 2007), for example an optical prism half a diopter in front of one eye in a given position (Baron and Fowler, 1952; Marino and Quercia, 2007), or a tiny chip stuck to the lingual surface of a certain tooth (Marino and Quercia, 2007). Mathematically, we no longer have the right to say that these astonishing effects are impossible, but in practice we still need more proofs than just the subjective complaints of patients. A critical way of thinking had then to develop around these new phenomena, moving, uncertain, even strange in some ways, particularly in their therapeutic implications (Bricot, 1996; Gagey et al., 1980; Gagey and Weber, 1995b, 1997, 2000, 2001, 2008; Vallier, 2012; Willem, 2001). In France, this criticism of Posturology originated inside the «Association Française de Posturologie» (Gagey and Weber, 1995a; Lacour, 1997), then inside the «Association Posture et Équilibre» (Lacour, 1999a, b, 2001, 2004; Lacour and Borel, 2007; Lacour and Defebvre, 2011; Lacour et al., 2003, 2009; Lacour and Hamou, 2012; Lacour and Perennou, 2006; Lacour et al., 2012; Lacour and Rougier, 2006; Lacour and Thoumie, 2008; Lacour and Weber, 2005) and the «Association Internationale de Posturologie» (Villeneuve, 1996, 1998; Weber and Villeneuve, 2000, 2003, 2007, 2010, 2012).

This critical reflection was mainly clinical, but not only. In biomechanics, this criticism has tackled first the concept of equilibrium as defined among doctors: «For there to get balance, the line of gravity must simply fall within the base of support» André Thomas said (Thomas, 1940). But in fact, we find that the line of gravity of a «normal» man standing at rest remains «within a surface that is not even a centimeter square» (Toulon, 1956). Thus, it must be acknowledged that the subject can't be said «normal» simply because the line of gravity falls within the base of support. The medical concept of balance is a wrong idea, it does not allow to think about all that can be abnormal in patients complaining of instability,
while their vertical of gravity remains inside their base of support. The physical concept of equilibrium shows that the normal man standing upright quiet is never in equilibrium, he is stable, his body returns next to its mean position when it is pushed aside from it. This concept of stability has quickly become the basic biomechanics concept of our studies. With the force platforms, we can measure the accuracy of the stability of a subject through the average deviation of his center of gravity (CoG) from its mean position, evaluate the energy spent by the system to achieve this stability, check if this energy expenditure is consistent with the resulting stability, consider the time constant of this stability.

Our critical think tank then addressed the use of the «Center of Pressure» (CoP) in stabilometry. It is not the projection of the center of mass (CoM)\(^1\) on the plane of the platform (Murray et al., 1967; Thomas and Whitney, 1959). By equating the CoP to the projection of the CoM a mistake is made that can be of importance (Gurfinkel, 1973). The analysis of the stabilometric signal shows that the CoP has two clearly identified parts, either around one Hertz in frequency analysis (Gagey et al., 1985) or around one second in temporal analysis (Collins and Luca, 1993). The CoP signal comprises two series of information, one on the controlled variable, below 1 Hz ± and the other on the controlling variable, at higher frequencies (Winter and Eng, 1995). This signal of the CoP is not suitable for a rigorous study of the stability of the standing man since it mixes up these two types of information, doing so it blurs the information on the position, speed (fig. 1) and acceleration of the CoM. Stability and stabilization are two related phenomena, but different, as already detected by Thomas (Thomas, 1940).

![Fig. 1](image_url)

**FIG. 1** — Speeds of the COP and of the CoG, from the same stabilometric recording of a rifle shooter, two seconds before and after shooting. Alone the speed of the CoG shows that the shooter controls the speed of his center of gravity at the moment of firing. (Recording on Cyber-Sabots, sampling frequency 40Hz, in firing position. The CoG has been calculated by the algorithm presented in this article).

Both these criticisms explain and justify why the use of the CoG in clinical stabilometry is required.

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\(^1\) Winter suggested to make a clear distinction in our language between the CoM «point of mass equivalent to the total mass of the body in the global reference system» and the CoG «Vertical projection of the CoM on the floor plan.» (Winter & Eng, 1995).
How

Historical

Borelli (Borelli, 1680) was the first to examine the gravity line of the «human machine» (Descartes, 1664). He situated the position of this gravity line by placing a subject on a platform resting on a knife (Murray et al., 1967). This technique was adopted by Hellebrandt (Hellebrandt, 1938) too and it helped Toulon to notice that the CoM of man is projected onto the plane of his support basis within an area of less than one inch (Toulon, 1956). But the study of the position and movements of the gravity line could not really develop until the force platforms were used.

The first force platforms were built in the mid-twentieth century (Babskii et al., 1955; Hirasawa, 1960; Soula, 1951). The first French platform was built by Lauru and Soula (1953). It measured the forces developed in response to the presence of a subject on the plateau and did so in the three directions of space (PF3D). The force sensors were piezoelectric quartz. With these sensors and electrometers without inertia, he had at hand, Lauru failed to measure the horizontal forces developed by a subject standing still on the platform; «The anteroposterior and lateral traces are silent, the layout is roughly that of a straight line» (Ranquet, 1953). Later, many authors confirmed that their PF3D, commercially available, measured incorrectly the horizontal forces (Caron et al., 1997; Hof, 2007; Karlsson, 1997; Levin and Mizrahi, 1996). Only Lafond (Lafond, 2005) seems satisfied. Since 2013, it is said that now these horizontal forces would be properly measured.

Measuring the CoG with 3D platforms

The news is interesting because these horizontal forces allow us to know immediately the horizontal acceleration of the CoM, in the direction of the force measured, by the application of the Newtonian equation:

\[ F = mG'' \]  

where F: force measured, m: mass of the subject, G'': horizontal acceleration of the CoM in the direction of the force.

The CoM horizontal accelerations concern the clinicians (Yu et al., 2008), but the position of the CoG and its speed as well. To calculate the position of the CoG from this second order differential equation, theoretically one just has to do a double integration, practically it raises two problems. Winter & Eng (Eng and Winter, 1993) noticed: «The double integration of the ground reaction forces is prone to integration error, especially during steady-state period.» Other authors, like Morasso (Morasso et al., 1999), have confirmed. To these difficulties of the numerical integration is added the fact that the differential equation (1) has an infinite number of solutions because its initial constants are not known.

Various solutions have been proposed to overcome this difficulty. Spaepen and coll. choose the initial data that produce the curve of the CoM movements which is closest to that of the movements of the CoP (Spaepen et al., 1977). Shimba (Shimba, 1984) and Levin and Mizrahi (Levin and Mizrahi, 1996) adjust by the least squares method two curves obtained by integration of two different mechanical equations. Zatsiorsky and King (Zatsiorsky and King, 1998) note that if the horizontal force \( F_h \) in a given direction is zero, then the horizontal acceleration of the CoG in this direction is zero and its velocity is constant; two observations that allow to assess approximately the conditions of position and initial velocity, of the double integral. But it is unusual that sampling instants occur exactly at a time when \( F_h = 0 \); generally, these moments must then be estimated. When \( F_h = 0 \) we know that the speed is constant, but we do not know its value. Assuming it is zero, we will have two constants of integration that allow to achieve a first integral calculus between two successive situations.
when $F_h = 0$. This calculation provides the measure of speed that allows to start again a
correct integral calculus. This calculation technique is then repeated between every moment
when $F_h = 0$. This long series of calculations makes the method difficult to use in clinical
practice (Yu et al., 2008). However, despite the approximations involved and the problems of
numerical integration, an assessment of the method by Lenzi et Coll. (Lenzi et al., 2003)
recognizes the advantages of this method over methods using the model of the inverted
pendulum.

Barbier (Barbier et al., 2003), generalizing the Karlsson's method (Karlsson, 1997) to
the three dimensions offers two smart solutions to eliminate the second derivatives of his
mechanical equations by application of Newton's second law and the theorem of angular
momentum. His solutions take into account the size of the subject.

**Measuring the CoG by averaging and filters**

It is not necessary to use the horizontal forces in order not to use the model of the
inverted pendulum. Nashner (NeuroCom International, 1989) only makes a sliding average
between successive sampled positions of the CoP, since the CoP navigates on either side of
the CoG. But the results vary according to the size of the sliding window. Benda, Levine and
Mizrahi, Brenière, Caron, Hugon propose to apply a low-pass filter to the stabilometric signal,
since the CoG movements have lower frequencies than those of the CoP (Benda et al., 1994;
Brenière, 1996; Caron et al., 1997; Hugon, 1999; Levine and Mizrahi, 1996). But the results
vary according to the cut-off frequency and the type of filter; moreover the phase of the signal
is changed. Hof (Hof, 2005) thinks that in some cases it is advisable to use the horizontal
forces rather than a low-pass filter.

**Measuring the CoG by the model of the inverted pendulum**

The methods using the model of the inverted pendulum can rely only on measuring the
vertical forces, easy to measure accurately.

Assimilate the human body to a pendulum pivoting around the ankles allows one to
write mechanical equations that relate the position of the CoP to the position of CoG through
couples and moments acting on this pendulum. The equation proposed by Winter and Eng
(Winter and Eng, 1995) is illustrated in figure 2.

**FIG. 2 — Diagram of Winter's mechanical equation**

The body weight, $W$, and the reaction, $R$, opposed to weight by the platform, are two equal forces, opposite, seldom aligned, acting respectively on the pendulum at the distance $G$ and $P$ from the ankle joint. The resulting moment of the couples $WG$ and $RP$ is equal to the moment of inertia of the pendulum, multiplied by its angular acceleration, $\alpha'$:

$$WG - PR = I \alpha'$$

$G$ expresses the distance of the CoG, and $P$ of the CoP, from the axis of the ankle joint. The oscillations of the human pendulum being of low amplitude at rest, the angle $\alpha$ is not very different from its sinus in these conditions, so the angular acceleration of the pendulum is almost equal to the horizontal acceleration of the center of gravity $G''$ divided by the distance,
h, between the axis of the ankle and the center of gravity: furthermore:

\[ R = W = mg \]

where \( m \) is the mass of the subject, \( g \): the acceleration of gravity. So the equation can be written as:

\[ G - P = \frac{I}{mgh} G'' \]

If we write

\[ \frac{I}{mgh} = k^2 \]

then

\[ P = G - k^2 G'' \quad (2) \]

You need only to solve this differential equation to determine the position of the CoG at every moment of the recording. The problem is that, on the one hand, the integration constants are not known and, on the other hand, numerical integration techniques applied to unstable systems pose problems.

Morasso (Morasso et al., 1999) gets around these problems by using the method of least squares in a standard approach of the approximate solution of overdetermined systems, with the best fitting B-spline functions. This method is of interest because it provides a function that describes the position of the CoG in relation to time. However, the error introduced by the series of approximations is unknown; moreover the anthropometric variations of the subjects being recorded does not interest Morasso.

Jacono (Jacono et al., 2004) uses the same mechanical equation of the inverted pendulum. From the Fourier transform of both sides of this equation, we can write the transfer function of a filter that lets you know the time evolution of the position of the CoG from the sampled positions of the CoP. The error of the curve obtained by this filter comes from the inverted pendulum model and is not estimated; secondly the filtering operation does not take into account the anthropometric data of the subject.

**Proposed method**

Equation (2) can be expressed best at any moment, \( j \), of measurement by a linear equation, replacing the second derivative with a finite difference approximation.

\[ P = G_j - k^2 \frac{G_{j-1} + G_{j+1} - 2G_j}{\delta t^2} \]

For \( j \) from 1 to \( n \), we can write a system of \( n \) linear equations with \( n \) unknowns, having a solution, \( G_j \), and only one, assuming \( G_0 \) and \( G_{n+1} \) are zero.

Moreover the equation (2) has an infinite number of solutions, \( \gamma_i \), but the difference between any two of these solutions for the same \( P_j \) is singular. Indeed, suppose «\( d \)» is the name of the difference between two solutions, \( \gamma_1 \) and \( \gamma_2 \), of the equation:

\[ \gamma_1 - \gamma_2 = d \]
This difference can also be written:

\[ P_j - P_j = \gamma_1 - \gamma_2 - k^2 \left( \gamma_1^* - \gamma_2^* \right) \]

or, by replacing \( \gamma_1 - \gamma_2 \) by \( d \):

\[ d = k^2 d^* \]

All the solutions of this equation can be expressed by a two parameters function:

\[ d_{a,b} = ae^{-qt} + be^{-q(F-t)} \]

\( t \) represents time, \( F \): the value of \( t \) at \( n + 1 \), \( q = 1 \/ k \)

If we choose a function of \( D = d_{a_1,b_1} \), with \( a_1 \) and \( b_1 \) such that \( G_0 = D_0 \) and \( D_{n+1} = G_{n+1} \), then the solution we are looking for is \( G + D \).

But we know neither \( G_0 \) nor \( G_{n+1} \), so no more \( a_1 \) and \( b_1 \). However, it is known that \( G_0 \) and \( G_{n+1} \) are in the support basis, that \( a_1 \) and \( b_1 \) are almost equal to \( G_0 \) and \( G_{n+1} \); based on this fact, if you look at the curve \( D \) (Figure 3 & 4), we can see that, apart from a few seconds at the beginning and end of the measurement interval, the function \( D \) is practically zero, whatever the values \( G_0 \) and \( G_{n+1} \), bounded by the support basis.

\[ \text{FIG. 3 — Evolution over time, from zero to three seconds, of the error introduced in the calculation by the arbitrary selection of } G_0 \text{ and } G_{n+1}. \]

\[ \text{FIG. 4 — Zoom on the precedent figure.} \]

This means that, apart from a few seconds at the beginning and end of the measurement interval, the resolution of the equation system gives the value of \( G \) pretty well.

Finally, the \( G \) research is therefore to build and solve the linear system of \( n \) equations — what, by now, a PC achieves in a few seconds — and to eliminate a few seconds of the measurement terminals.
The coefficient $k^2$ and anthropometry

$$k^2 = \frac{I}{mgh}$$

The coefficient $k^2$ involves specific anthropometric data for each subject under recording: moment of inertia of the body relative to the axis of the ankle ($I$), body mass ($m$), height of the CoM above the axis of the ankle joint ($h$). In clinical practice it is unthinkable to evaluate these data for each subject, or even to look for them in the anthropometric data tables, such as Winter’s (Winter, 2009) for example. Given the importance of the coefficient $k^2$ in the context of standardized clinical stabilometry, the choice of the $k^2$ values should be the result of a consensus among clinicians, based on fundamental studies.

Discussion

The peculiarity of the proposed method is to take advantage of the edge effects when solving a differential equation the variable of which is bounded, which gives it a real simplicity. But we must admit that the method is based, like many other methods, on the model of the inverted pendulum, which is far from perfect. In addition to its significant reduction of the degrees of freedom of the human pendulum, this model confuses the axis of the ankle joint and the Henke's axis. The angular deflections of the body axis are assumed to be minimal, corresponding only to the case of static stabilometry. It reckons that the feet specific muscles are not involved in controlling the position of the CoP, which is an error (Tortolero et al., 2007). It would be advisable to replace this model by a better model, the model of the broom for example (Gagey et al., 2003; Roberts., 1995). But it is not formalized biomechanically yet.

Among the methods that do not use the model of the inverted pendulum, the King-Zatsiorsky was recognized particularly interesting. But no anthropometric data appear in its mechanical equations. Now, faced with his functional patient who brings him only subjective complaints, the clinician needs «something» reminding him of the intersubjectivity of the symptoms, basis of the objectivity of the syndrome. Stabilometry provides this «something» because it allows to compare the performance of the patient to a database... provided the database takes into account the anthropometric characteristics of individuals. That is why it is better to use a method based on the inverted pendulum, which remains «an acceptable model» (Gage et al., 2004; Winter et al., 1997).

Among the methods using the model of the inverted pendulum, there is no compelling reason to choose the method presented in this paper rather than the methods of Morasso, Jacono or Barbier. However, we believe all of us must decide to use the same method with a view to standardizing clinical stabilometry. It is not clear, in fact, that the differences between the methods, however small, will not have an impact on the calculation of certain stabilometric parameters.

Some additional reasons could guide the imperative choice of a single method toward the one presented in this article. It has been used for several years to study the marksman's posture and it showed, for example, the obvious interest to compare the movements of the CoG with the movements of the weapon (Dudde et al., 2014; Dudde et al., 2012; Gagey et al., 2014; Gagey et al., 2013). It is already used to build a database of reference values of the stabilometric parameters. It first appeared within a group that has been practising stabilometric standards for 30 years (AFP, 1985; Bizzo et al., 1985). All these arguments are worth quoting, they can guide the selection, but the other three methods allow as well to work with the CoG in order to improve the analysis of the stability, its accuracy, its cost, its speed, its tonic background.
The statistical measure of the average deviation of the CoG from its mean position, by a 90% confidence ellipse for example (Takagi et al., 1985), corresponds exactly to the definition of the accuracy of this stability, once accepted the CoG may represent the body. While the average deviation of the CoP from its mean position certainly gives an idea of the accuracy of the stability of the subject but, also and above all, it shows the importance of the movements of his CoP in order to maintain his stability.

This difference between the CoP and the CoG is designated by the model of the inverted pendulum as the expression of the acceleration of the CoM in connection with the puffs of phasic muscular contractions that control the accuracy of stability. The cost of this accuracy can be assessed by the extent of the acceleration of the CoM.

The relationship between the results and the means, between the accuracy of the stability, and its cost was already possible by the ratio of the area of the ellipse that contains 90% of the sampled positions of the CoP, to the length of the displacements of the CoP (AFP, 1985; Gagey, 1986; Imaoka et al., 1997). But this comparison is more stringent between, the accuracy of the stability and the acceleration of the CoG (Gély, 2014).

As Morasso (Jacono et al., 2004) has noted, the frequency of the puffs of phasic muscular contractions is significant in relation to the time management of stability. The acceleration of the CoM is designated as a basis to calculate the time constant of the upright postural control system (Dudde et al., 2012; Gagey et al., 2012a; Gagey et al., 2012b).

The stiffness of the tissues of the posterior lodges of the legs is not enough to stabilize the body of a man (Morasso and Schieppati, 1999; Winter et al., 1998), to compensate for the inadequacy of this stiffness, muscle contractions are required (Loram et al., 2005) and the importance of these contractions changes depending on the forwards inclination of the body that changes the stiffness (Gagey and Gentaz, 1993). The acceleration of the CoM allows to evaluate the basic stiffness of the subject, provided that the inclination of the body is taken into account (Dudde et al., 2012).

**Conclusion**

The therapists who use the properties of nonlinear dynamic systems to treat functional disorders of the upright postural control system need to criticize, their work and the allegations of their patients. The concept of stability and its measurement are currently the instrumental basis for this criticism. The measure of stability in all its aspects, is improved if the analysis of the signal is achieved from CoG and not from CoP, because the CoP confuses stability and stabilization. Among the methods for evaluating the CoG from measurements of a force platform, we must focus on those reflecting the anthropometric data of the subject in order to normalize the stabilometric parameters as much as possible. Among the presented methods that meet this criterion, only one method must be chosen, this choice is not ours.

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