ORIGINAL ARTICLE

Spectrum Analysis in Postural Strategy on Static Tests in a Healthy Population

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KEYWORDS
Vertigo;
Stance;
Spectral analysis

Abstract
Introduction and objectives: The power spectral density can be used to find a hidden behaviour in a physical system. We studied postural behaviour in a healthy population, by means of power spectral density, and compared it with a situation of complete immobility.
Methods: A group of healthy volunteers carried out the modified Clinical Test for Sensory Interaction in Balance. A fibre optic gyroscope device was used to record the data. We compared the power spectral density in these tests and with another recording where the device was motionless. We looked for significant differences using the ANOVA test.
Results: A power peak appeared at 8.4 Hz in all static tests. The static group showed significant differences with all the other tests. We found no statistically significant differences when visual input discriminated between 2 tests. There were statistically significant differences for the proprioceptive input.
Conclusions: Brief movements are needed to maintain the quiet stance. The distinctive feature of these movements is a fundamental frequency at 1.4 Hz and a harmonic frequency at 8.4 Hz. Proprioceptive input is essential for balance.
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PALABRAS CLAVE
Vertigo;
Postura;
Análisis espectral

Estudio espectral de la estrategia postural de una población sana en pruebas estáticas

Resumen
Introducción y objetivos: La densidad espectral de potencia puede servir para encontrar comportamientos no evidentes en un sistema físico. Mediante la misma vamos a estudiar el...
Introduction

One of the applications of posturography systems in vestibular diagnosis is the study of sensory organisation used by patients to maintain their position, which is achieved by selectively altering visual and somatosensory information, and then measuring the ability of patients to maintain their balance. This alteration is obtained with the method known as sway-referencing, tilting the support base or the visual environment, so that both always remain constant relative to the centre of gravity of the patient. Thus, even if the patient continues to receive visual and somatosensory information, under these conditions it will be of no use for balance. One of the most commonly used protocols is the Sensory Organisation Test (SOT). It consists of a set of 6 tests in which visual and somatosensory information is altered. Conducting this test requires a system with a movable platform and visual environment.

An alternative clinical trial which follows the same philosophy as the SOT was developed due to the high cost of these platforms. This test was called the Clinical Test for Sensory Interaction in Balance (CTSIB) and aimed to obtain the same conditions as the SOT, but in a clinical environment: the mobile platform was replaced by a foam mattress and the moving visual environment by a "dome", a type of helmet which only allows patients to see an environment that moves at the same time as them. This test is also known as "foam-and-dome test" or "sensory conflict posture test". Some studies have shown that the CTSIB test has a good correlation with the SOT in identifying patients with vestibular alterations. Other studies suggest that using a foam surface represents a greater challenge for the maintenance of balance than a mobile platform.

The manufacturers of posturography devices assimilated these findings and created cheaper, static platform models, which incorporated into their protocols the modified Sensory Organisation Test (mSOT) and the modified Clinical Test for Sensory Interaction in Balance (mCTSIB). The mSOT eliminates the mobile visual environment, maintaining a dynamic platform. The mCTSIB also substitutes the mobile platform by a static platform and a foam mattress, that is, it uses conditions 1, 2, 4 and 5 of the SOT, eliminating the PREF ratio from sensory analysis whilst using simpler and cheaper apparatus. At present, there are some posturography devices available which are not based on a pressure platform. Some of these devices are based on gyroscopes or devices that detect the movement of an object. Among other uses, they have been applied for inertial navigation, as artificial horizons in aircraft, etc. One of the most sensitive types of gyroscope is the fibre optic gyroscope. Abundant information on the operation of the fibre optic gyroscope can be found through the references of this work.

The interesting work by Thurner et al. considered swinging movements of the body as fractal processes. These authors concluded that the fractal pattern was most regular when the visual system was excluded and somatosensory information was reduced. Therefore, a highly complex pattern must be associated with a completely healthy balance. The oscillations of a body can be considered as a stochastic process. As such, the signal generated by a posturography device is susceptible to analysis by spectral density.

Stochastic analysis is the branch of mathematics which studies the evolution of highly complex phenomena, resulting from varied interactions between numerous components in nature. From a stochastic perspective, a time series is considered as the performance of a theoretical process consisting of random variables relating to points in time. The stochastic analysis of the time series consists of performing a statistical inference on the properties of a theoretical process based on the information contained in the observed series. Therefore, there is a high degree of parallelism between stochastic analysis and general statistical analysis.

In mathematics and physics, the spectral density of the power of a signal informs us about the power distribution of the signal throughout the frequencies which form it. It is often used as an equivalent to the "frequency spectrum". Although strictly speaking, they are different concepts. The spectrum is the graph showing how a waveform signal is decomposed. Intuitively, the power spectral density captures the frequency content of a signal and helps to identify periodicities. It can also be defined as a variable frequency function associated with a stationary stochastic process. Spectral density cannot be known with absolute precision, since the signal being processed is a stochastic process. The
only accurate way to know it would be to have an infinite record of the signal, which is not possible. Therefore, we resort to spectral density estimation. There are several estimation methods:

- Nonparametric methods: always based on the calculation of the periodogram. The most commonly employed technique is the Fourier transform.
- Parametric methods: they consist of assuming a particular model for the stochastic process (autoregressive moving average models [ARMA]) and estimating the parameters using various techniques.

Spectral analysis is the method used to represent any signal in the frequency domain. It enables us to know various characteristics of a signal, which would not be evident when represented in the time domain.

Among the applications of power spectral density we can include:

- Intuitively, spectral density is used to identify hidden periodicities within a continuous variable or discrete variable function (sequence of numbers).
- The estimation of entropy in a random process. The flatter the power spectral density, the more entropy it contains.
- Obtaining valuable information on the internal dynamics of various physical systems. It serves to identify chemical compounds or elements (spectroscopy). It also serves to identify linear mathematical models in control theory.

In fact, relating it to the exploration of balance, the most significant concept for the quantification of the Romberg test results is the measurement of the energy in the power spectral density of the trajectories of the centre of gravity while an individual maintains a straight posture.

We recommend consulting the bibliography for further information on this topic.

In this work we studied the postural strategy in static tests of a healthy and young population by analysing their power spectral density. This was compared with a situation where the recording device remained completely still. Subsequently, we studied the influence of the visual system (comparing tests with open and closed eyes) and the somatosensory system (comparing tests on firm ground and on foam) on the maintenance of static balance or silent stance.

Materials and Methods

We selected healthy volunteers under 40 years of age and with no history of balance alterations. All patients underwent the tests included in the mCTSIB, as described below. To be included in this study, participants had to present normal results in the tests mentioned according to the limits of normality for their age and gender included in the recording device of the test. These records represented the young group.

For comparison purposes, we placed the recording device leaning against a wall, so as to maintain it fully upright and motionless. We obtained 4 recordings for 20 s in this position. These records represented the static group.

Test recording was done using a fibre optic gyroscope. The specific model was the Sway Star (Balance International Innovations GmbH, Switzerland). In the young group, the device was placed in the lumbar area of each individual. The device recorded the oscillations (posturogram) in the sagittal plane (pitch) and frontal plane (roll). The software included with the device analysed the power spectral density corresponding to each of the planes at frequencies of 1.4, 2.5, 3.7, 4.9, 6.1, 7.2, 8.4, 9.6, 10.7, 11.9, 13.1, 14.3, 15.4, 16.8, 18.2 and 19.3 Hz.

In order to perform the various tests we used a square, foam mattress, measuring 1 m on each side, with a thickness of 10 cm and a density of 25 kg/m³.

The mCTSIB was comprised of the following tests:

- s2eo: standing on 2 legs with eyes open and on a firm surface.
- s2ec: standing on 2 legs with eyes closed and on a firm surface.
- s2eof: standing on 2 legs with eyes open and on a foam mattress.
- s2ecf: standing on 2 legs with eyes closed and on a foam mattress.

In summary, we had 2 study groups: static and young. In the static group we only conducted a single test. In the young group we conducted 4 tests: s2eo, s2ec, s2eof and s2ecf.

For each test we obtained a record in the pitch plane and another in the roll plane. All tests had a duration of 20 s. We then obtained the power spectral densities in the pitch plane and in the roll plane. We calculated the main descriptive statistics for each frequency, plane and test. Next, we sought significant differences through the ANOVA test. We separated the results in the pitch and roll planes. Previously, we applied the Levene test of variance analysis. In case of equal variances, we applied the Bonferroni post hoc contrast. In cases where the variances were different, we applied the Tamhane method.

We set the level of statistical significance at $P = .05$ in all tests. We used the software package SPSS v.15.0 for Windows® and Microsoft Excel® 2007 to perform the statistical analysis.

Results

The young group was composed of 20 individuals, 50% males and 50% females. The ages ranged from 23 to 37 years, with a mean value of 27.75 years.

Tables 1 and 2 show the results of the ANOVA test after applying the Tamhane or Bonferroni post hoc contrast, according to the previous results of the Levene contrast.

Figs. 1 and 2 are box diagrams of the power spectral densities in all tests conducted in both planes. Figs. 3 and 4 represent the arithmetic mean of all the power spectral densities for all tests conducted in both planes.

Fig. 1 shows a box plot for all the frequencies in each test and in the pitch plane. It is immediately striking that the static group had very low values, especially compared to the other tests. Indeed when verified in Table 1, at 5 the static group variance was 0 at all frequencies. The remaining
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Values of $P$ after applying the corresponding post hoc contrast in the ANOVA test.
Freq1.4: frequency of 1.4 Hz; Freq2.5: frequency of 2.5 Hz, and so on.
* Significant values ($P<.05$).
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Values of P after applying the corresponding post hoc contrast in the ANOVA test.  
Freq1: frequency of 1.4 Hz; Freq2: frequency of 2.5 Hz, and so on.  
* Significant values (P<0.05).
Spectrum Analysis in Postural Strategy on Static Tests in a Healthy Population

Figure 1  Box plot for the static group and the s2eo, s2ec, s2eof and s2ecf tests in the pitch plane at all frequencies. The lowest frequencies in each test are on the left. The highest frequencies are on the right.

tests had a higher variance. This indicates that the static group obtained much more homogeneous results.

Fig. 1 also shows that the power spectral densities of the s2eo, s2ec and s2eof tests were very similar and with significantly higher values than the static group. The s2ecf test had apparently superior values to all others.

Fig. 3 represents the arithmetic mean of the power spectral densities for all groups. It shows that the static group produced a horizontal curve. The remaining tests followed a descending profile, showing 2 main peaks. The first one was located at the lowest frequency, 1.4Hz, whilst the other peak was centred around the frequency of 8.4Hz.

Figure 2  Box plot for the static group and the s2eo, s2ec, s2eof and s2ecf tests in the roll plane at all frequencies. The lowest frequencies in each test are on the left. The highest frequencies are on the right.

Figure 3  Graphical comparison of the arithmetic mean of the power spectral densities in all tests in the pitch plane. The vertical axis is in log scale. On the horizontal axis, the number "1" corresponds to the frequency 1.4Hz, the number "2" to the frequency 2.5Hz, and so on up to "16", which corresponds to 19.3Hz.

Figure 4  Graphical comparison of the arithmetic mean of the power spectral densities in all tests in the roll plane. The vertical axis is in log scale. On the horizontal axis, the number "1" corresponds to the frequency 1.4Hz, the number "2" to the frequency 2.5Hz, and so on up to "16", which corresponds to 19.3Hz.
We can also observe that the power spectral densities of the s2eo and s2ec tests were almost identical. The s2eof test offered higher figures and the s2ecf test even more so. We verified the results of the ANOVA test for the pitch plane in Table 1, and observed the following points of interest:

- The static group presented statistically significant differences in most frequencies, except for the highest, with the s2eo and s2ec tests. The number of frequencies with significant differences increased in the s2eof test. Finally, it presented significant differences at all frequencies with the s2ecf test.
- When analysing potential differences regarding the influence of vision (keeping eyes open or closed) we observed that:
  o The s2eo and s2ec tests did not present significant differences at any frequency.
  o The s2eof and s2ecf tests did not present significant differences at any frequency either.
- When assessing the influence of the somatosensory system (testing on solid ground or foam) we observed that:
  o The s2eo and s2eof tests presented significant differences at 2 frequencies, 2.5 and 3.7 Hz.
  o The s2ec and s2ecf tests presented differences at the 4 lowest frequencies.

Fig. 2 shows the data relating to the roll plane. Once again, the static group obtained a variance of 0 at all frequencies. The remaining tests obtained lower values than the pitch plane, as can be seen in the corresponding tables. Moreover, the power spectral densities of the s2eo and s2ec tests were very similar.

Fig. 4 shows that the static group had an almost horizontal power spectral density. The rest of the tests had a descending profile, without the peak at 8.4 Hz which could be observed in the pitch plane. The s2eo and s2ec tests were still almost identical and presented lower values than the s2eof and s2ecf tests.

When verifying the ANOVA results in the roll plane, we observed that:

- The static group showed significant differences at almost all frequencies with almost all the tests.
- Regarding the influence of vision:
  o The s2eo and s2ec tests did not present significant differences at any frequency.
  o The s2eof and s2ecf tests did not present significant differences at any frequency either.
- Regarding the influence of the somatosensory system:
  o The s2eo and s2eof tests presented significant differences at most frequencies.
  o The s2ec and s2ecf tests presented significant differences at almost all frequencies.

Discussion

The first point to discuss is whether, in the light of these data, a young and healthy individual is incapable of standing completely still on 2 feet. The static group presented significant differences with the other tests in both the pitch and roll planes. This fact was already known through other previous studies. Nasher even stated that it is impossible to maintain the centre of gravity completely motionless, since upright standing is an inherently unstable task which requires periodic corrections to compensate the influence of gravity.

We believe that a small oscillation of the centre of gravity may be necessary to maintain balance. We know that the peripheral vestibular organ is only stimulated through accelerations. If there were a small acceleration at all times, that is, if the body were constantly moving, then there would also be permanent vestibular information for the maintenance of balance. In the same way, a continuous oscillation of the body would also serve to stimulate the myotatic reflexes. Thus, there would be a double source of information: vestibular and somatosensory.

The peak found regularly at a frequency of 8.4 Hz in the pitch plane in all tests conducted on the young group was also striking. Given that the lowest frequency analysed was 1.4 Hz (where there was a power maximum), and that multiplying this frequency by 6 gives exactly 8.4, it is conceivable that this power peak corresponds to a harmonic of the main frequency.

In other words, the young group presented a body movement in the pitch plane in all tests, characterised by a main frequency of 1.4 Hz and a harmonic at 8.4 Hz.

This fact suggests that the frequency of 8.4 Hz may have an important role in maintaining balance. As seen in Figs. 3 and 4, the power of the 8.4 Hz frequency was between 35% and 39% of the power at the 1.4 Hz frequency. This phenomenon could be explained by stochastic resonance. This stochastic resonance appears when the addition of an optimal amount of noise improves the performance of the system. It must be clarified that the term "noise" does not refer to an "inaudible and generally unpleasant sound" (as defined by the Royal Academy of the Spanish Language), but to the concept of "noise" in a physical signal, that is, a random variation in the signal. In the case of the balance system, the studies of Priplata et al. showed that the addition of a random vibration at 90% intensity of the perception threshold of a patient, significantly decreased oscillations during standing with eyes closed among elderly patients.

When analysing the influence of sensory systems on the maintenance of balance we observed the following:

- Regarding the pitch plane (Table 1), when we analysed the influence of visual afferents we could find no significant differences when comparing the s2eo and s2ec tests. The same held true for the s2eof and s2ecf tests. In other words, there was no statistically significant difference between keeping eyes open or closed.
- When comparing the s2eo and s2eof tests we could only observe significant differences at 2 frequencies. Moreover, when comparing the s2ec and s2ecf tests we only observed differences at 4 frequencies, all in the lower range. Therefore, somatosensory afferents may play an important role in maintaining balance in young and healthy individuals.
- When performing the same analysis in the roll plane (Table 2), comparing the s2eo and s2ec tests revealed no significant differences at any frequency. The same held
true when comparing s2eof and s2ecf tests. Therefore, closing the eyes did not induce any difference in the movements made in this plane.

- However, when testing somatosensory influences, we observed that there were differences at almost all frequencies when comparing the s2ec and s2ecf tests on the one hand, and the s2eo and s2eof tests on the other. Therefore, somatosensory afferents seem to play an important role in the control of movements in this plane.

Studies like that by Peterka35 established that, under normal conditions, a person depends primarily on somatosensory information from the supporting surface for the maintenance of balance. Furthermore, as reported by the aforementioned study by Allum et al.,6 a foam surface represents a greater challenge to the maintenance of balance than a mobile platform.

Conclusions

Healthy individuals cannot remain completely still when standing on 2 ft, they need to make small movements to maintain balance. This motion is characterised by a fundamental frequency of 1.4 Hz and a harmonic of 8.4 Hz.

Among our population of young and healthy individuals, somatosensory afferents were more important than visual afferents in maintaining standing balance.

Conflict of Interests

The authors have no conflict of interests to declare.

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