Time and frequency analysis of the static balance in young adults with Down syndrome

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Abstract

The main objective of this study is to understand the differences in equilibrium control between normal subjects and those with Down syndrome. A total of 54 subjects participated voluntarily, divided into a control group and a Down syndrome group. The equilibrium of the subjects was tested under two conditions: bipedal support with eyes open and closed. The signals were analyzed in a time and frequency domain. The statistical parameters selected (i.e., RMS distance, mean velocity, mean frequency and sway area) to analyze the behavior of the center of pressures (CoP) are calculated employing the result of the combination of the time series data in both directions (i.e., resultant distance). In order to calculate the frequency bands produced by the displacements of the CoP, a Fast Fourier Transform of the data was performed. The group with Down syndrome showed poorer static equilibrium control than the control group in the time domain. In the frequency domain, we found differences between the groups in the distribution of energy in the frequency bands analyzed. In addition, we observed the existence of an interaction effect of the group and the condition tested ($p < 0.001$). These findings show that in the absence of visual information, the control group increases the energy at low frequencies, while the group with Down syndrome decreases it. Additionally, the lower amount of energy observed in this band under the 'eyes closed' condition may serve to identify abnormalities in the functioning of the vestibular apparatus of individuals with Down syndrome and/or difficulties experienced by these individuals in extracting relevant information from this route.

1. Introduction

Down syndrome (DS) is a human genetic disorder caused by the presence of all or part of an extra chromosome 21 [1]. People with DS exhibit a number of anatomical and

physiological characteristics that differentiate them from people without DS. For example, the brains of individuals with trisomy 21 are smaller and lighter than those of normal individuals [2] and exhibit a lower neuronal density; they also show synaptic irregularities due to the reduction of neurotransmitters [3] and anomalies in myelination processes [4]. Individuals with DS also show alterations in sensory modalities. They typically achieve poorer results in tests of sensitivity [5] and visual acuity [6] and show sensorineural hearing loss that affects the inner ear [7]. In addition, DS individuals seem to have difficulty integrating sensory information from various modalities, becoming more dependent on the visual [8], although this issue is not fully understood [9].

Hypotonia and joint laxity are common phenomena in DS [10,11]. Compared to unaffected subjects, DS patients show lower levels of strength [12]; this is probably partly due to the action of factors such as number and type of muscle fibers, because the percentage of fast fibers in DS individuals is smaller than in people without disabilities [13]. DS patients are also less able than normal individuals to adapt their motor action to the circumstances and to generate greater strength when necessary [14]. These characteristics affect their general mobility and increase the difficulty they experience in performing coordinated movements and maintaining equilibrium [4,15].

Although maintaining a bipedal position may appear to be simple, it requires integration of information arriving at the central nervous system (CNS) through the proprioceptive organs and senses, especially vision and the vestibular apparatus of the inner ear [9]. In recent years, study of the behavior of the center of pressure (CoP) has emerged as a way of indirectly understanding the neuromuscular control of equilibrium [16]. According to Winter [17] the CoP is the point location of the vertical ground reaction force vector. It represents a weighted average of all the pressures over the surface of the area in contact with the ground.

The analysis of the time and frequency domains of CoP data obtained from subjects on a strength platform has been used on several occasions to analyze healthy populations [18,19] as well as populations diagnosed with a pathology [20,21]. Some studies on the equilibrium of individuals with DS performed using this method conclude that this population shows deficient motor control compared to individuals without DS [16,22,23].

According to the scientific literature, in the frequency analysis of equilibrium the total spectral energy is distributed in three frequency bands depending on the type of somatic regulation: low frequencies (0–0.5 Hz) correspond to the action of the sensory systems (visual and vestibular), intermediate frequencies (0.5–2 Hz) are related to the regulation of the cerebellum, and high frequencies (>2 Hz) reflect proprioceptive regulation [24].

To our knowledge, no studies have indirectly measured the control of the nervous system in equilibrium through the comparison of frequency bands of the CoP between populations with and without DS [23]. These aspects of the postural control are related to typical features of the subjects with DS such as vestibular problems, hypotonia, ligament laxity, poor visual acuity, inter alia. Therefore, the quantification of these aspects and their comparison with those obtained from normal subjects are very important to better understand the clinical aspects that affect the postural control of DS subjects. The importance of this study lies in the novelty of presenting comparative data obtained by calculating the three frequency bands of the spectral density CoP signals in

populations with and without DS. This type of analysis can help identify potential abnormalities in equilibrium control as well as allow indirect identification of brain structures showing alterations.

The main objective of our investigation is to better understand the differences in equilibrium control between people with and without DS through time and frequency analysis of CoP signals. This analysis permits a better understanding of the possible relationship between trisomy 21 and equilibrium control.

2. Methods

2.1. Subjects

Twenty-seven subjects with Down syndrome (Down syndrome group, DSG) were recruited from four organizations in the city of Seville, in which activities are planned for people with intellectual disabilities. All subjects had been previously diagnosed with trisomy 21 by their reference doctors. The control group (CG) included 27 college students without Down syndrome. The characteristics of both groups are shown in Table 1.

The exclusion criteria for the DSG included having suffered from epilepsy, atlantoaxial instability or an Intelligence Coefficient higher than 55 or lower than 35 (according to the assessment of their medical specialist). In addition, there were exclusion criteria common to both groups, including neurological disorders, severe sensory disorders, muscular–skeletal injuries or surgeries related to the musculoskeletal system that may interfere with the motor control of equilibrium. Subjects were advised not to consume excitatory substances (e.g. coffee or soda) during the 24-h period prior to the tests. All subjects signed a voluntary consent form in which they agreed to participate in the study. In the case of the subjects in the DSG, a legal guardian signed the consent. The protocols used in the study were presented to the University of Sevilla Ethical Committee for approval; these protocols met all the requirements set out in the Declaration of Helsinki of 1975, which was later reviewed in 2008.

2.2. Static posturography

In order to measure postural stability, a force plate was used (Dinascan/IBV, Biomechanics Institute of Valencia, Valencia, Spain). The platform consisted of a 600 mm × 370 mm plate with an active area and 100 mm height with four force transducers. The platform was placed on a stable surface on the floor to avoid distortion and noise in the signal. The subjects stood barefoot and still in a relaxed manner with their arms unfolded by their sides. The same foot placement was adopted on all trials (i.e. heels separated by the width of the shoulders and toes pointing outward at an angle of 20° from the sagittal midline), according to the specifications of the manufacturer. A point of reference (5 cm in diameter) was placed opposite the subject at eye level at a distance of 2 m. All subjects were informed of the importance of maintaining this posture and were asked to attempt to minimize any abnormal movement. One 50 s attempt was made under each of two conditions: (i) bilateral stance with eyes open (EO), (ii) bilateral stance with eyes closed (EC). Due to the difficulties some subjects from the DS group experienced in keeping their eyes closed during the entire test, we chose to use an opaque mask for all subjects. All the patients did a familiarization session 48 h before

the tests with the help of a familiar or an assistant person during all the time. This familiarization session was performed with the intention of explaining the tests and also to reduce the anxiety for the use of opaque masks.

2.3. Data analysis

During each postural trial, signals were recorded at a frequency of 60 Hz using an amplified analogue-to-digital converter. Data representing the forces exerted on the platform along three axes (x, y, z) were saved on a hard disk for subsequent analysis. The CoP displacement data, both in the mediolateral (ML) and the anteroposterior (AP) directions, were obtained using the analysis software NedSVE/IBV (Biomechanics Institute of Valencia, Valencia, Spain).

The Matlab 7.0 (Mathworks Inc., Natick, USA) program was used to condition the signals and to calculate the stabilometry variables. Signals were filtered digitally using a fourth-order Butterworth low-pass filter with a 6 Hz cut-off frequency. The first and last 10 s of each attempt were eliminated whenever they appeared unstable [25,26]. The signals of the CoP were then analyzed in both the time and frequency domains.

The statistical parameters selected in this study to analyze the behavior of the CoP result from the combination of the time series in both directions (i.e., resultant distance). The measures that combine both directions are usually designated '2D' and describe the displacement of the CoP on a flat surface, as indicated by several authors [25–27]. The 2D parameters are more robust and independent than biomechanical factors (e.g., height and weight of the subjects) that describe the directions of the anteroposterior and the mediolateral separately [26].

Four parameters were calculated in the time domain, based on equations for the composite measures computed from both the anteroposterior and mediolateral time series: (i) root mean square (RMS); (ii) mean velocity (MV); (iii) rotational frequency (RF); and (iv) sway area (SA). For the calculation of these parameters, we used the equations proposed by Prieto et al. [25].

The CoP excursions were also investigated in the frequency domain to assess the preferential involvement of short or long neuronal loops in equilibrium regulation. Fast Fourier transforms were applied to the distance resultant from the combination of both directions. The spectrum was calculated between 0.15 and 6 Hz (resolution = 0.025 Hz). The lowest frequencies were eliminated from this analysis because they relate to events that are repeated in periods close to 20 s that are not a direct consequence of equilibrium control [26]. The total spectral energy (TSE) was calculated and distributed among three frequency bands: low frequencies, medium frequencies, and high frequencies. The values of each of these three frequency bands were expressed as a percentage of the total spectral energy. Representative recordings for a standard subject in the time and frequency domains are illustrated in Fig. 1.

2.4. Statistical analysis

Statistical analysis was carried out using SPSS software version 17 (SPSS Inc., Chicago, IL, USA). It was verified that all the variables complied with the assumptions of normality and homogeneity of variance. Standard statistical methods were used to

obtain the mean and the standard error of the mean (SEM). A mixed model [Group (2) × Condition (2)] MANOVA was applied to establish the effects of group and condition on the dependent variables related to the equilibrium. Follow-up of the multivariate contrast was performed through univariate contrast. Post hoc analysis with Bonferroni correction was performed in the case of significant main or interaction effects. A p-value of 0.05 (α) was accepted as the level of significance.

3. Results

Multivariate contrast revealed that there was a main effect of the Group in the dependent variables ($F_{7,40} = 41.26$, $p < 0.001$). We also found an interaction effect between Group and Condition ($F_{7,40} = 8.82$, $p < 0.001$) in the dependent variables.

Univariate contrasts showed a main effect of the Group in MV ($F_{1,46} = 47.55$, $p < 0.001$, $r = 0.71$), RF ($F_{1,46} = 44.87$, $p < 0.001$, $r = 0.7$) and TSE ($F_{1,46} = 86.37$, $p < 0.001$, $r = 0.8$). The CG showed lower MV (mean: 7.5, SEM: 0.66, $p < 0.001$), RF (mean: 0.34, SEM: 0.03, $p < 0.001$), and TSE (mean: 19083.56, SEM: 3240.21, $p < 0.001$) than the DSG (mean: 13.6, SEM: 0.58, mean: 0.64, SEM: 0.03, mean: 59235.09, SEM: 2857.59 respectively).

ANOVA also revealed a Group × Condition interaction effect in the RF ($F_{1,46} = 4.75$, $p = 0.034$, $r = 0.31$), LF ($F_{1,46} = 23.09$, $p < 0.001$, $r = 0.58$), MF ($F_{1,46} = 5.61$, $p < 0.022$, $r = 0.33$), HF ($F_{1,46} = 30.74$, $p < 0.001$, $r = 0.63$) and TSE ($F_{1,46} = 4.26$, $p = 0.045$, $r = 0.29$). The RF was higher in the DSG than in the CG in both conditions ($p < 0.001$). Furthermore, in the EC condition, this variable showed a significant increase compared to the EO condition in the DSG ($p < 0.001$). In addition, there seemed to be a trend toward an increase in the RF with EC in the CG ($p = 0.052$). On the other hand, the LF was higher in the CG (mean: 40.07, SEM: 1.48) than in the DSG (mean: 31.67, SEM: 1.78, $p = 0.001$) when subjects were blinded. The DSG achieved a higher LF with EO (mean: 37.53, SEM: 1.35) than with EC (mean: 31.67, SEM: 1.78, $p < 0.001$). However, the CG showed a lower LF in the EO condition (mean: 35.01, SEM: 1.54) than when they were blinded (mean: 40.07, SEM: 1.48, $p = 0.005$). Regarding the HF, the CG (mean: 21.4, SEM: 0.67, $p < 0.001$) showed lower values than observed in the DSG (mean: 19.82, SEM: 0.8) in the EO condition. Moreover, the mean value of this variable increased in the DSG when subjects were blinded (mean: 23.34, SEM: 1.2, $p < 0.001$) compared to the EO condition (mean: 19.82, SEM: 0.8). Finally, in the CG, the HF increased when subjects' eyes were open (mean: 21.4, SEM: 0.67, $p = 0.002$) compared to the EC condition (mean: 18.71, SEM: 0.99).

With respect to the TSE, the DSG showed a markedly higher mean value than the CG both with the EO (mean: 51541.01, SEM: 3895.14 and mean: 15050.85, SEM: 1085.32, respectively; $p < 0.001$) and EC (mean: 66929.16, SEM: 4083.64 and mean: 23116.26, SEM: 1424.08, respectively; $p < 0.001$). In both groups, TSE was lower with EO than EC ($p < 0.001$).

In Table 2 and Fig. 2, we show the results related to the differences between groups and the condition of the variables related to the time and frequency domains, respectively.

4. Discussion

Quiet standing equilibrium and postural control are often assessed by means of information obtained from CoP data collected with a force platform [16]. The analysis of CoP data in both the time and frequency domains has been used to analyze different populations [28–30]; however, this is the first time that the CoP has been studied in people with DS and the spectral energy analyzed by frequency bands.

For the variables analyzed in the time domain, the results for the control group in both the EO and EC conditions are similar to those reported in previous studies [21,26,28]. In general, DS subjects showed higher values than control subjects, except for RMS with EC. Since similar studies of DS subjects have not been reported, our results in DS subjects could not be compared directly with those of other studies; however, they resemble results obtained by others in studies of older people and those with various pathologies [29]. Although there is a tendency for the DSG to show higher values than the control group in the time domain, the differences were statistically significant only for the variables MV and RF. This might be due to the subjects' standing in a position that does not require exacting control of equilibrium; if this is the case, the test employed might not be efficient at discriminating related problems. The reason for not conducting a unipodal test was the inability of individuals with DS to remain on a single support for a sufficiently long time, an aspect that has been observed in similar studies [29]. We believe that it will be necessary in future research to use situations that require a greater involvement of the systems involved in equilibrium control. Another possible explanation for these findings is the heterogeneity in the performance of the DSG. Taking into account the characteristics of this population (i.e., nervous, anatomical, sensorial and cognitive characteristics), it is difficult to create a homogeneous study group that presents less dispersion in the results. However, the inhomogeneity of the group does not imply that the observed higher values in MV and RF did not result from the presence of an extra chromosome in the karyotype of individuals with DS.

The most striking result of this study appears when comparing the groups by frequency bands. While there were no significant differences in MF either among groups or between conditions, there were significant differences in both LF and HF between the groups. The behavior of the groups in the EO situation does not show significant differences in the LF band. However, in the EC condition, the control group shows higher values. These findings show that, in control subjects, the absence of visual information increases the energy at low frequencies, while in DS individuals, low-frequency energy is decreased. The opposite results between the two groups suggest the existence of differences in the strategies of equilibrium control used by normal and DS individuals when deprived of visual information. As mentioned above, the LF relates to the action of the sensorial system; the lower amount of energy observed in this band under the condition of EC may be indicative of anomalies in the functioning of the vestibular apparatus of patients with DS or the presence in such individuals of difficulties in extracting relevant information from this route, as indicated in other investigations [1,8,16].

In the HF band, something similar occurs; however, there the significant differences are found in the EO situation, in which the CG has the higher percentage of stored energy. This result may indicate that, with EO, control subjects use proprioceptive mechanisms to control equilibrium more often than do Down's subjects. Possible reasons for this may include the fact that people with DS have a deficient vestibular apparatus [8], as well as the possibility that the information coming from this route is not properly

interpreted by the upper centers of the central nervous system [29] or that there is a dysfunction in the capacity to integrate information from different sensorial directions [30]. Moreover, the proprioceptive system may also present deficiencies, as is suggested by the low values found in the bands of HF. A decrease in general physical activity could be the cause of these effects. It is known that people with DS tend to engage in less physical activity than people without DS [10].

Interventions conducted with the DS population show improvements in equilibrium through physical exercise programs of different kinds [13,15,29,30]. For this reason, as well as based on the experimental results reported here, we believe that interventions are needed to improve general elements of the physical condition of DS patients as well as aspects related to proprioception and sensory perception in these patients. Such interventions can be expected to improve quality of life and reduce the risk and number of falls and the incidence of degenerative processes caused by time.

5. Conclusions

The present study shows that young adults with DS have significant differences in equilibrium control compared to control subjects. These differences are particularly evident in the time and frequency domains of CoP data. Specifically, individuals with DS show poorer postural control and a different distribution of energy across frequency bands. These findings highlight the importance of developing targeted interventions to improve postural stability in this population.

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Conflict of interest statement

No commercial party having a direct financial interest in the results of the research supporting this article has conferred or will confer a benefit on the authors or on any organization with which the authors are associated.

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TABLES

Table 1

Subject characteristics.

Variable	CG ($n = 27$)	DSG ($n = 27$)
Age (years)	23.38 (1.25)	27.44 (1.26)
Weight (kg)	68.02 (2.17)	63.08 (2.14)
Height (m)	173.19 (2.01)	153.18 (1.88)
BMI (kg m^2)	22.59 (0.43)	26.99 (0.94)

Data are expressed as mean (SEM). BMI, body mass index.

Table 2

Acronym	**Description**
Time domain	
RD	Resultant distance is obtained from the following equation: $RD[n] = (AP(n^2) + ML(n^2))^{1/2}$, where ML and AP are the time series of the displacement of the CoP in the axes x, y respectively. The calculation was conducted for the entire time series, n = 1, ..., N
RMS	Root mean square of CoP time series (mm)
MV	Mean velocity (total CoP trajectory length/trial duration) (mm/s)
RF	Rotational frequency represents the revolutions per second of the CoP if it had traveled the total excursion around a circle with a radius of the mean distance (Hz)
SA	Sway area estimates the area enclosed by the CoP path per unit of time (mm^2/s)
Frequency domain	
Total spectral energy	A FFT was applied to the RD time series and then the absolute value was calculated (frequency spectrum amplitude). Total spectral energy (mm) was obtained from the summation of every point of the frequency spectrum
LF	Low frequencies represent the amount spectral energy of the frequency spectrum accumulated between 0.15 and 0.5 Hz
MF	Medium frequencies represent the amount spectral energy of the frequency spectrum accumulated between 0.5 and 2 Hz
HF	High frequencies represent the amount spectral energy of the frequency spectrum accumulated between 2 and 6 Hz

Table 3

Results of the variables calculated for CP displacement in the time domain under both tested conditions.

		RMS (mm)	MV (mm/s)	SA (mm^2/s)	RF (Hz)
DSG (n = 27)	Eyes open	4.22 (0.38)	11.76 (0.66)	13.3 (1.76)	0.57 (0.03)*,**
	Eyes closed	4.34 (0.31)	15.44 (0.85)	17.18 (1.77)	0.71 (0.04) *
CG (n = 27)	Eyes open	3.86 (0.29)	6.14 (0.38)	8.33 (1.01)	0.31 (0.02)
	Eyes closed	4.72 (0.29)	8.86 (0.64)	14.98 (1.74)	0.36 (0.03)

The data represent the mean value (SEM). DSG, Down syndrome group; CG, control group; RMS, root mean square; MV, mean velocity; SA, sway area; RF, rotational frequency.

* Significant difference between groups ($p < 0.001$).

** Significant difference between conditions ($p < 0.001$).

FIGURES

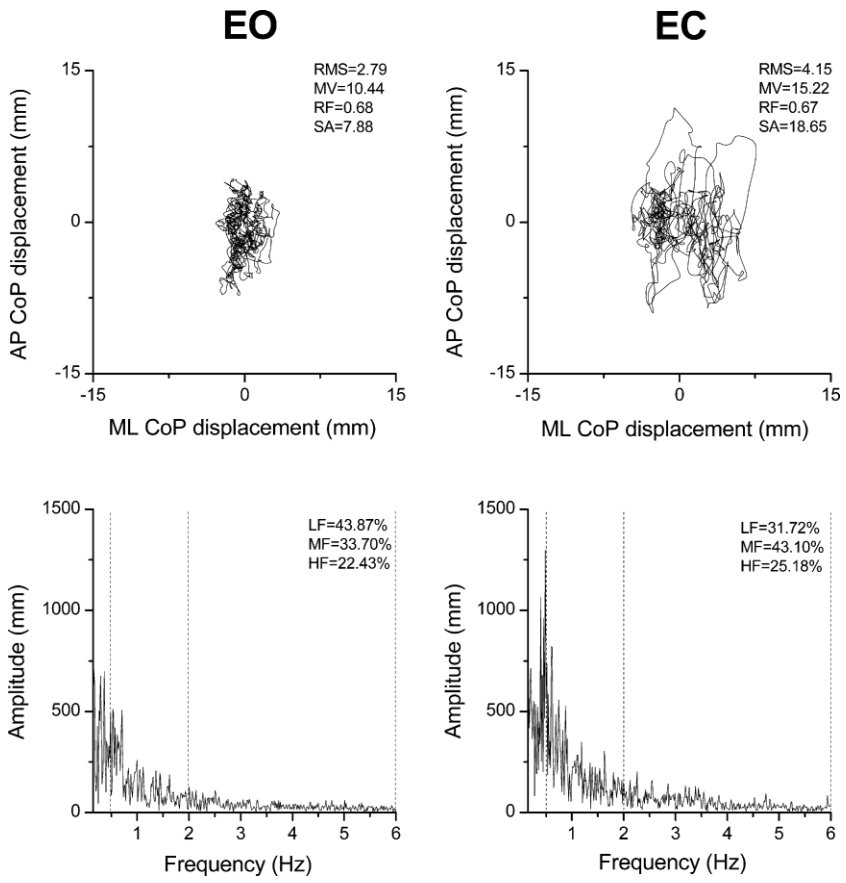

Fig. 1. Example of the signals recorded and their analysis in both time/frequency domains. The top panel shows records of the CP displacement of a subject affected by DS. In the bottom panel, the FFT of the records above is displayed. The panels on the left represent an attempt with eyes open (EO), and those on the right represent an attempt with eyes closed (EC). In the time domain, the values of the parameters root mean square (RMS), mean velocity (MV), rotational frequency (RF) and sway area (SA) for both attempts are shown. In the frequency domain, numerical values are expressed as the percentage of energy contained in each of three bands: low frequencies (LF, 0.15–0.5 Hz), medium frequencies (MF, 0.5–2 Hz), and high frequencies (HF, greater than 2 Hz). The discontinuous vertical lines separate the space of each frequency band.