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Cross-Correlation Between Head Acceleration and Stabilograms in Humans in Orthostatic Posture

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Abstract— **This work aims at evaluating the role of the vestibular system in the postural sway control using the cross correlation function. A sample of 19 young, healthy male adults was monitored with a three axial accelerometer placed over the head during a stabilometric test, standing on a force platform during 3 min in four conditions: eyes closed and open, and feet apart and together. The normalized cross correlation (NCCF) function and the Monte Carlo simulation were used to correlate changes in body sway with head accelerations. Significant NCCF was rarely observed in conditions with opened eyes, and occurred in six subjects with eyes closed and reduced support basis. These results are inconclusive. As no delayed response was observed, the classical negative feedback appears to be absent, and either phasic displacements of the center of pressure and the head or anticipatory control could be occurring.**

I. INTRODUCTION

The orthostatic postural control involves a complex system where the central nervous system integrates sensorial information from the visual, vestibular, proprioceptive, tactile, and muscular systems to promote the stabilization process [1]-[5]. A major problem for human standing posture is to maintain a body with high center of mass over a relatively small base of support [6]. For this control, deviations in body position are identified by each sensory branch in a particular way: the vestibular system is particularly sensible to head orientation deviations, while the visual system relates these head orientation deviations to the surround environment and the proprioceptive system detects changes in leg and foot orientation relative to the support surface [4], [7].

The role of vestibular input and its interaction with visual and somatosensory cues for human postural control is still not well understood [8]. To investigate this interaction Nashner *et al.* [5] developed a formal approach that incorporated the mechanics of body sway and the threshold and dynamic characteristics of the vestibular organs. In this model, the postural movements were limited to the ankle and hip strategy, to simplify analysis. The mechanical constraints related to each control strategy were associated with the vestibular system structures. The utricular otoliths were associated with the ankle strategy by the higher degree of center of mass movement and low frequency of oscillation. On the other hand, the semicircular channels have been associated with hip strategy by its lower degree of center of mass movement and higher frequency of oscillation. This approach differs from Winter *et al.* [9], who considered that experimental oscillations in the body, using an inverted pendulum model in stable condition, does not cause head accelerations above the excitability threshold.

Various models have been proposed for the control of body movements during standing posture. According to the stiffness theory [9]-[11], the postural control system is passive, with adjustments of muscular tension independent of the sensory inputs. These authors consider that ankle muscles control the anterior-posterior displacements by setting the stiffness, and support this hypothesis with the inverted pendulum model, by showing that center of mass (COM) and center of pressure (COP) signals are in-phase with a strong correlation between the acceleration of the COM and COM-COP difference. However, various studies proposed that the central nervous system applies a feedforward control that anticipates the body position, changing the activity of the gastrocnemius in advance to regulate balance during quiet stance [1], [6]-[14]. This control mechanism was considered [1], [14] as a compensation for the inevitable transmission delay in the neural process. However, few studies evaluated the feedback sensory control mechanism from the vestibular system in response to COP displacement.

Although the vestibular system is assumed as one input in postural control, few studies presented experimental setups designed to relate acceleration of the head to the body movements. Some studies [9], [15] evaluated the position of the head by kinematics methods. Since the sensory mechanisms of the vestibular system only respond to the head acceleration, it would be necessary to perform the first and second derivative of these data to obtain head velocity and acceleration, respectively. However, the use of analog differential circuits requires taking care not only on the offset voltages of operational amplifiers, but also with respect to the inherent noise introduced by position or velocity transducers [16]. Thus, the use of accelerometers becomes more adequate to measure the effects of shock, vibration and acceleration over the head [16].

Given the importance of the feedback mechanisms of the controls systems in the assessment of the body movements during standing posture, it is necessary to use methods for analyzing the signal in the time domain. An important tool is the normalized cross-correlation function (NCCF), which allows estimating how similar two different signals are and the time shift that produces the greatest similarity [17].

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This work aims at developing a method to evaluate the role of the vestibular system components in quiet standing control. This method was based on the comparison of the head acceleration and the COP position to identify their similarity and if this two signals have time shift using NCCF estimations.

II. Materials and Methods

A. Subjects

Participated in this study 19 young male subjects, with age 25 ± 6 years (mean ± standard deviation), body mass 79.7 ± 8.7 kg and height 1.77 ± 0.05 m, with no history of neurological disorders or orthopedic diseases. The experimental protocol was approved by the Ethical Human Research Committee of the Federal University of Rio de Janeiro [CAAE – 0034.0.239.000-10], and all subjects were voluntary and signed a free informed consent before inclusion in the study.

B. Accelerometric and Stabilometric Data Recording

The head oscillation was measured by a capacitive triaxial accelerometer MMA7260Q (Breakout, USA) with an analogical input module MP150 (Biopac Systems, USA) for data acquisition. Signals were digitized with 2 kHz frequency sample by an analog-to-digital converter with 16 bits resolution and ± 10 V dynamic range. The COP oscillations were measured by a force platform AccuSwayPlus (AMTI, USA) at a sample rate of 200 Hz. The force plate was automatically reseted by the program Balance Clinic (AMTI, USA) before each stabilometric test. A tailor made trigger system was employed to synchronize the recording of accelerometric and stabilometric data. The signals were saved and exported in text format for further processing with programs whiten in MATLAB version 7.0 (The Mathworks, USA).

C. Balance Assessment

After the application of an anamnesis and anthropometric measurements, the subjects were guided about the objective and test protocol. Then, the instruments calibration and accelerometer fixation was performed.

The accelerometer was fixed at the midpoint of the external occipital protuberance to the glabella and between the leading edges of both ears, that corresponds to the Cz point from 10-20 international system for electroencephalography [7]. A cap was employed for better fixation of the head accelerometer. The cable was adjusted below the cap, in order to adjust the accelerometer axis in the mediolateral (x), anterior-posterior (y) and vertical (z) directions.

After the accelerometer fixation and the platform calibration, each subject was oriented to stay on the force platform, in the quiet standing position, barefoot and with arms relaxed. The test protocol consisted of four randomized conditions: eyes open and feet in a comfortable, open position (EOFO), eyes open and feet in a close position, according to the Association Française de Posturologie [18] (EOFC), eyes closed and feet open (ECFO) and eyes closed and feet closed (ECFC). When the subjects stood in the platform with eyes open they should focus at a fixed point positioned at a distance of 1.5 m. The subjects remained on the platform for a period of three minutes in each condition, interspersed by two minutes interval between them.

D. Pre-Processing

The voltage values correspondent to ± 1 g (gravity acceleration = 9.8 m/s^2) and 0 g were taken from the accelerometer datasheet, to be used as a reference for conversion of raw data values in Volts to values in gravity acceleration, by linear regression. Both accelerometric and stabilometric signals were pre-processed by a 2nd order digital Butterworth low-pass filter with cutoff frequency 2 Hz, applied in direct and reverse directions to avoid phase shifts. Then, both signals were decimated to 5 Hz.

E. Data Processing

Initially, a linear detrend procedure [17] was applied on COP displacement signals in the anterior-posterior (COPy) and mediolateral (COPx) axis, as well as on head acceleration in the anterior-posterior (ACy) and mediolateral (ACx) axis.

The NCCF was estimated between accelerometric and stabilometric signals in both anterior-posterior and mediolateral axis. To this end, the cross-covariance function (CCVF) was calculated, given by [17]:

$$C_{uz}[k] = \begin{cases} \frac{1}{N} \cdot \sum_{n=0}^{N-k-1} \left(u[n] - m_u\right) \cdot \left(z[n+k] - m_z\right), & k \geq 0 \\ \frac{1}{N} \cdot \sum_{n=0}^{N-k-1} \left(u[n+k] - \hat{m}_u\right) \cdot \left(z[n] - \hat{m}_z\right), & k \leq 0 \end{cases} \tag{1}$$

where $C_{uz}[k]$ is the estimator of CCVF, $u[n]$ and $z[n]$ are the signals, m_u and m_z are their averages, N is the number of samples in each signal and k is the time delay. As the means of the signals have been removed, the cross-covariance function is equal to the cross-correlation function. Therefore, the NCCF is defined by [17]:

$$\rho_{uz}[k] = \frac{C_{uz}[k]}{s_u \cdot s_z} \tag{2}$$

$$-1 \leq \rho_{uz}[k] \leq 1$$

where $\rho_{uz}[k]$ is the estimator of the NCCF, s_u and s_z are the signals standard deviations.

F. Statistical Analysis

Monte Carlo simulation [19] was applied to determine the critical value of the NCCF, by simulating an ensemble of 1000 accelerometric and stabilometric signals pairs with equal spectral magnitude and random odd phase with uniform probability density function in the range from $-\pi$ to π. The simulated NCCF was thus obtained as previously described for real data. The critical value for the significance level of 0.05 was then determined corresponding to the 950th largest value of the simulated NCCF peaks.

Student's t-test was applied to test the presence of delays between the accelerometric and stabilometric signals ($\alpha = 0.05$).

III. Results

One example of COP displacement, head acceleration and the respective significant NCCF is shown in Fig. 1, for subject #13.

The NCCF employed for measuring latency between head acceleration and body sway showed few cases with significant correlation peak (Table I). In both y and x axes the conditions with eyes closed showed more subjects with significant NCCF. The correlation values and respective lags are depicted in Tables II and III.

Most of significant correlations were observed with no delay between accelerometric and stabilometric signals, thus leading to a no significant overall delay.

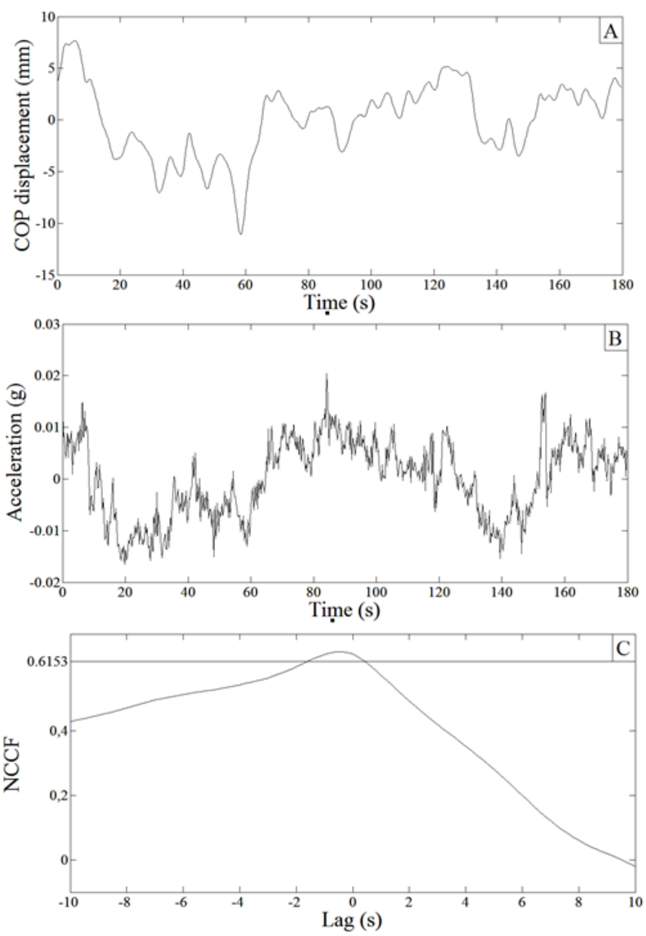

Fig. 1 (A) Anterior-posterior COP displacement (subject # 13). (B) Anterior-posterior acceleration (subject # 13). (C) NCCF between signals shown in (A) and (B).

TABLE I. Number of Subjects with Significant NCCF in Each Condition and Each Axis

Condition	y axis	x axis
EOFC	2 subjects	2 subjects
ECFC	6 subjects	6 subjects
EOFO	1 subject	3 subjects
ECFO	4 subjects	5 subjects

TABLE II. Subjects (SUBJ) with Significant Correlations (S.C.) and Respective Time Lags (LAG) in the Anterior-Posterior Direction

	EOFC		**ECFC**		**EOFO**		**ECFO**	
SUBJ	**S.C.**	**LAG**	**S.C.**	**LAG**	**S.C.**	**LAG**	**S.C.**	**LAG**
4					0.61	-0.2	0.70	-0.2
5			0.78	0.0			0.44	0.2
6	0.53	-1.8	0.58	-0.4				
7							0.52	0.0
9			0.60	-0.2				
11							0.89	0.0
12			0.47	0.0				
13	0.42	-0.2	0.87	0.4				
16			0.86	0.0				

TABLE III. Subjects (SUBJ) with Significant Correlations (S.C.) and Respective Time Lags (LAG) in the Mediolateral Direction

	EOFC		**ECFC**		**EOFO**		**ECFO**	
SUBJ	**S.C.**	**LAG**	**S.C.**	**LAG**	**S.C.**	**LAG**	**S.C.**	**LAG**
7					0.57	-3.0		
9	0.57	0.0	0.49	0.0				
12	0.81	0.0	0.60	0.0	0.69	0.0	0.93	0.0
13			0.80	0.0			0.78	0.0
14			0.43	-0.2	0.51	-0.2	0.76	0.0
15			0.79	0.0			0.68	-0.4
16			0.76	0.0			0.62	-0.2

IV. Discussion

The NCCF between head acceleration and stabilograms was proposed for assessing the contribution of the vestibular system in the control of quiet standing position. To estimate this contribution, the number of significant NCCF was accounted in each condition. The reduced number of significant correlation are in accordance with Winter *et al.* [9], which suggested that acceleration of the head performed during postural control did not reach the excitability threshold of the vestibular system. However, when submitting the body to conditions related to increased postural balance, as closing the eyes and reducing the support basis, more subjects presented significant NCCF. As the body sway control is based on multiple sensorial inputs, the limited occurrence of significant correlations between head accelerations and stabilograms may be expected a priori, since it is affected by changes in other (unmeasured) control inputs. Thus, a readjustment in load of the sensory inputs [4] would be required when subjects closed their eyes and/or reduced the support basis, thus potentially increasing the role of the vestibular system in maintaining quiet standing position. However, it was not possible with NCCF to find significant results in all subjects, neither differ the relative participation of utricular otoliths and semicircular canals.

Among the subjects with significant NCCF there was not delay between signals. Thus, there is no delayed response to accelerometric signal, as would be expected in classical feedback control systems. Therefore, the observed in phase results may lead to two opposite hypothesis: (1) the positive correlations, when observed, may be a result of the phasic movement of COP and head, as expected by the inverted pendulum model; or (2) it corroborate the occurrence of an anticipatory component in the postural control, which could cause an approximately phasic response. In this rationale, the feedback is not used to correct a past disturbance, but to calculate and anticipate the future disorder, which is prevented by the controller. Similar events occurred in studies in which the feedforward mechanism was identified by the early gastrocnemius muscular activity in relation to the COP displacement [1], [6], [13], [14].

The NCCF function was no sensitive enough to identify the role of the vestibular system on body sway control in most of subjects. This can be explained by structural differences in time domain between accelerometric signal and stabilogram. However, even with no similarity in time domain between these two signals, they may have correlated frequency components that can be observed using the magnitude squared coherence function [17], taking into account the different frequency range of actuation of each sensorial system [3].

The triaxial accelerometer was showed as a promising transducer for monitoring the head accelerations with some confidence. Its use together with the already proven functionality of the force platform [20] allows a more objective assessment of vestibular system as a sensory input in body sway control.

V. Conclusion

The presented founds suggest that the NCCF function was partly capable for analyzing the behavior of vestibular system in postural control. It was possible to identify correlations between head acceleration and COP displacement in some subjects with sensory suppression and mechanical constrain.

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