TIME-FREQUENCY ANALYSIS OF POSTURAL SWAY

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Abstract

Maintaining upright balance is a dynamic process in humans, dependent upon sensory input from the visual, vestibular (i.e., inner ear) and somatosensory systems. Deficiencies in one of these sensory systems often result in abnormal postural responses to external disturbances. Studying these responses, via measurement and analysis of postural sway, can yield insight into the nature of the system deficiency. Past efforts have utilized spectral analysis to study postural sway. However, recent work has shown that the frequencies of postural sway change over time; hence, spectral analysis provides an incomplete description of the system. We present results from our work in time-frequency analysis of postural sway, and discuss its potential as a clinical tool for assessing balance disorders.

1 Introduction

Upright balance is maintained in humans through the interplay of sensory information provided by vision, the balance organs of the inner ears (the vestibular system), and the somatosensory system [10], [21]. If one of these systems fails, the person becomes more reliant upon the other two systems for maintaining balance. Sensory conflicts are less efficiently resolved in such patients; for example, patients with vestibular deficits often complain of sensitivity to moving visual environments, and experience symptoms of dizziness and imbalance [22].

Studying and analyzing the human ability to maintain balance, or postural stability, is important because disequilibrium contributes to falling, which is responsible for hundreds of thousands of injuries a year, costing billions of dollars in health care [3], [18], [21], [24]. Clinicians rely on a battery of tests to diagnose and assess balance disorders, but many patients, especially those with symptoms of inner ear problems, have normal clinical tests [10], [25].

Postural stability has been assessed by studying postural sway, often measured via center-of-pressure (COP) recordings from a force platform (e.g., [22]). Spectral analysis is a common technique used for studying postural sway, as it reveals the frequencies present in the signal. The spectral density, however, does not reveal *when* the frequencies occurred, only that they did. This fact is not a limitation if the frequency content of the signal is constant over the duration of the signal.

Recent studies have shown that the frequency content of postural sway changes over time; that is, postural sway is a "nonstationary," or time-varying, process [4], [8]. Thus, the standard Fourier spectrum gives an incomplete description of postural sway and the postural control system. *Time-frequency analysis*, however, provides a means for studying the changing spectral content of postural sway. Time-frequency analysis identifies not only *what* frequencies were present, but also *when* they were present and their intensities at each time. Analyzing the time-varying properties of postural control should further our understanding of the mechanisms of postural stability in humans, and provide additional information for many of the patients with normal clinical tests despite symptoms of vestibular abnormalities.

2 Background

2.1 Time-frequency analysis

In the past decade, there has been dramatic development in our understanding of time-varying spectra, and methods of application (e.g., [5], [7], [17]). There have been a number of review articles on time-frequency analysis, perhaps the most comprehensive one by Cohen [7]. Time-frequency analysis has been successfully applied in a variety of fields, particularly the analysis of biological signals (e.g., [1], [19], [26], [28]).

Perhaps the most straightforward and readily understood approach for time-frequency analysis is the short-time Fourier transform, the magnitude-squared of which is called a "spectrogram" [15]. Developed in the 1940s, the basic idea behind the spectrogram is simple yet powerful: to measure the changing spectral content of a signal, successive short intervals of the signal are isolated via multiplication with a window, and then Fourier transformed. The squared-magnitude is taken to obtain an energy density. Mathematically, we have

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$$P_{sp}(t,\omega) = \left|\int s(\tau)\, w^*(\tau - t)\, e^{-j\omega\tau} d\tau\right|^2 \qquad (1)$$

where $P_{sp}(t,\omega)$ is the spectrogram of signal $s(t)$, $w(t)$ is the window, and $*$ denotes complex conjugation.

While simple and effective for many applications, the spectrogram has limitations. Principally, the window distorts and sometimes obscures the time-frequency structure of the signal (see [7], [17], [19], [27], [28] for examples).

New methods of time-frequency analysis that overcome this limitation of the spectrogram have been developed in recent years. These new time-frequency distributions (TFDs) are obtained by specifying a particular "kernel" $\phi(\theta,\tau)$ in Cohen's general formulation [6], [7]:

$$P(t,\omega) =$$
$$\iiint s\left(u+\frac{\tau}{2}\right)s^*\left(u-\frac{\tau}{2}\right)\phi(\theta,\tau)\, e^{-j\theta(t-u)-j\tau\omega}du\,d\tau\,d\theta\ .(2)$$

The kernel dictates properties of the distribution. For example, summing up the spectral content over all time in the TFD should yield the total spectral content of the signal, given by $|S(\omega)|^2$, which is the squared-magnitude of the Fourier transform of the signal. Likewise, the sum over frequency should yield the total temporal content, or instantaneous power, $|s(t)|^2$. Formally, these summations are done by integrating the TFD over time and frequency, respectively. To ensure that the TFD yields these results, the kernel should be chosen such that [6]

$$\phi(\theta,0) = \phi(0,\tau) = 1 \quad . \qquad (3)$$

The quantities $|s(t)|^2$ and $|S(\omega)|^2$ are called the "marginals" of the joint density function; TFDs whose kernels satisfy equation (3) are said to "satisfy the marginals." The spectrogram does not satisfy this condition. The significance of this condition is that it ensures the accuracy of measurements from the TFD such as duration and bandwidth (calculated as the standard deviation in time and frequency, respectively). The spectrogram overestimates these quantities [7]. Significant progress has been made in designing kernels to obtain accurate and informative TFDs (e.g., [5], [11], [16], [17]).

Another alternative to the spectrogram is the "evolutionary spectrum" defined by Priestley [20]. The basic idea is to describe a nonstationary stochastic signal as a sum of amplitude modulated tones,

$$s(t) = \int A(t,\omega)\, e^{j\omega t} dZ(\omega) \qquad (4)$$

where $dZ(\omega)$ is an orthogonal process that accounts for the stochastic nature of the signal. The variance of (4) is given by

$$E|s(t)|^2 = \frac{1}{2\pi}\int |A(t,\omega)|^2 d\omega \qquad (5)$$

and the "evolutionary spectrum" of the process is therefore defined as $\frac{1}{2\pi}|A(t,\omega)|^2$. Methods for estimating the evolutionary spectrum from the given signal have been developed (e.g., [12], [13]). The evolutionary spectrum and Cohen-class TFDs provide complementary (and related) approaches to time-frequency analysis [19].

2.2 Postural sway

A common approach to the study of postural stability is to analyze the postural sway of a subject during quiet stance. A second common approach is to analyze postural sway in response to external disturbances. Visually perceived motion ("optic flow") is often used as the system disturbance, as are somatosensory perturbations such as movement of the force platform [2], [9], [14], [21], [22].

Optic flow is typically induced via one of two methods: moving surrounds or projected scenes. With moving surrounds, the environment about the subject is physically moved in a prescribed manner (e.g., sinusoidally). Thus, the perceived motion is genuine. With projected scenes, the illusion of movement is created by projecting specific images on a screen viewed by the subject.

In analyses of postural sway data, it is generally assumed that postural sway is a stationary process. However, recent studies have shown that postural sway is nonstationary [4], [8]. In an investigation of three healthy subjects, Carroll and Freedman [4] experimentally demonstrated that the mean and variance of postural sway during quiet stance changed over time, especially during the initial 20 seconds of their 60 second trials. The authors conclude that the interpretation of postural sway data analyzed via conventional stationary approaches (e.g., Fourier analysis) must be done with care, and more importantly, a method of analysis appropriate for such nonstationary data should be sought and applied.

Similar results and conclusions have been reported by Harris *et al.* [8]. In their study of postural stability in children, Harris *et al.* [8] reported a time-varying mean in up to 60% of the data for both healthy children and those with cerebral palsy. Given the observed nonstationary nature of postural stability, the authors advise caution in analyzing such data via conventional approaches that assume stationarity. Furthermore, they propose the investigation of "techniques used to define the spectral characteristics of nonstationary data such as...the frequency-time methods" [8].

3 Methods and Results

We have applied time-frequency analysis to postural sway data obtained from healthy and vestibularly impaired individuals. To assess the feasibility of time-frequency analysis of postural sway, a pilot study was initially performed on healthy subjects who were instructed to sway about their ankles in time with a metronome as its oscillations gradually decreased from 2 Hz to 1 Hz over thirty seconds [23]. COP data were recorded from a force platform at a sampling rate of 20 Hz, and then processed via time-frequency analysis [23]. A typical result is shown in figure 1. Note the (expected) change in frequency of postural sway from 2 Hz down to 1 Hz. The spectrum, also shown in figure 1, shows a strong peak at 1 Hz, and frequencies ranging between approximately 1 and 2 Hz, as expected. The spectrum reveals the total spectral content of the signal, but it clearly can not indicate how the frequencies evolved over time, as the time-frequency plot does. The goal of this experiment was simply to demonstrate that the frequencies of postural sway can indeed change over time, and this change is clearly observable via time-frequency analysis of COP data.

In a second experiment [23], COP data were obtained from five healthy and five vestibularly impaired individuals during quiet stance. Subjects were instructed to stand with eyes closed, feet shoulder-width apart and arms comfortably at their sides. COP data were digitized at 20 Hz and recorded for 100 seconds. Time-frequency analysis revealed qualitative differences between the groups, and nonstationary behavior in the postural sway of both groups [23]. An example comparison is shown in figure 2. Note the changing spectral content for both healthy and impaired individuals, and the significantly higher power fluctuations in the patient's postural sway.

In a third experiment, COP data were recorded from patients and healthy subjects in response to visual perturbations. Subjects stood on a force platform as before, except with eyes open, looking straight ahead at a painted scene on a movable wall about 1 meter directly in front of them. For the first thirty seconds of a ninety second trial, the wall remained motionless while COP data were recorded. At thirty seconds, the wall began to move first away from and then toward the subject in a sinusoidal fashion at a frequency of 0.25 Hz. Postural sway increased at the onset of wall motion for both patients and healthy subjects. However, there are differences that are clearly observed in both the time waveform and the time-frequency plot between patients and healthy subjects. For example, healthy subjects tend to adapt to the stimulus, with the energy at 0.25 Hz in their postural sway response decreasing over time (see figure 3). Patients, on the other hand, take longer to adapt; indeed, some don't adapt during the sixty seconds that the wall is in motion. Other interesting features are also observed from time-frequency analysis of postural sway in response to visual perturbations. For example, frequencies other than the stimulus frequency appear at some times in the postural response (see figure 3).

4 Discussion and Conclusion

Our application of time-frequency analysis to postural sway supports the recent conclusions of Carroll and Freedman [4] and Harris *et al.* [8] that postural sway is not a stationary process.

In addition, we have found time-dependent spectral differences in the postural sway of patients versus that of healthy subjects. For example, the rate of adaptation to a sinusoidally moving scene appears to be faster in healthy

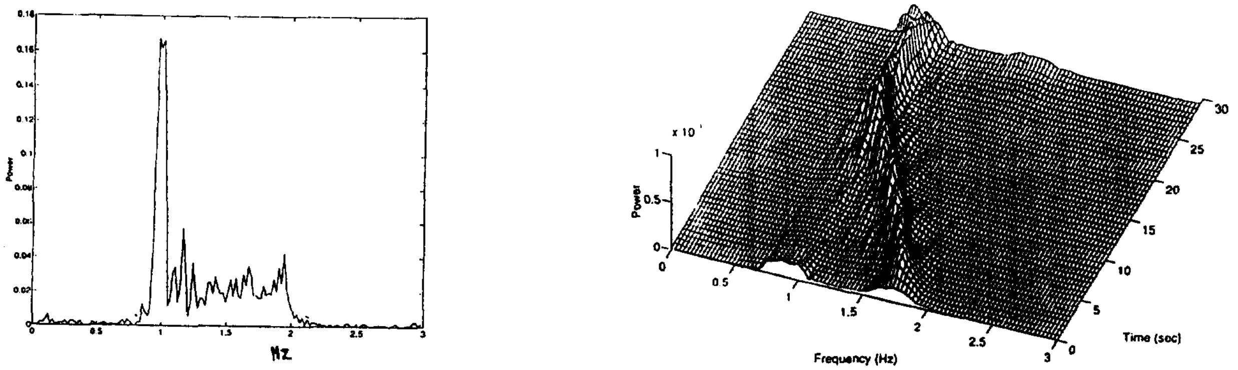

Figure 1: The spectral density (left) and the time-frequency density (right) of the postural sway of a subject instructed to sway about the ankles in time to a metronome as its frequency decreased from 2 Hz to 1 Hz. The time-frequency density clearly reveals the evolution of the frequencies in the signal. The spectral density reveals only what frequencies were present, not when. Summing the time-frequency density over time yields the spectral density.

subjects than in patients, as clearly observed in the time-frequency plot (figure 3).

The appearance of frequencies other than the stimulus frequency in the postural response at certain times indicates that postural sway is not only a time-varying process, but a nonlinear one as well. From figure 3 (and similar results not shown here), the generation of non-stimulus frequencies appears to coincide with increased power in the postural sway response. For example, the healthy subject exhibits frequencies other than the stimulus frequency only during the initial twenty seconds following the onset of wall motion (30-50 sec), which is where the postural sway has the largest amplitude. The patient's postural sway, however, has large amplitude (relative to 0-30 sec) throughout wall motion (30-90 sec), coincident with the appearance of multiple frequencies in the time-frequency plot.

It may be that postural control is nonlinear following abrupt external disturbances, and becomes less so as (healthy) subjects adapt to the stimulus. Patients that have a harder time adjusting to the disturbance may remain in a more nonlinear mode of control for a longer period of time. If and how these nonlinearities differ between patients and healthy subjects is an area of ongoing investigation, as are the development of techniques for quantifying the differences between the time-varying responses of patients and healthy subjects. Discovering and quantifying these differences may provide additional information for diagnosis of vestibular disorders, as well as general knowledge of the mechanisms of postural control.

5 Acknowledgment

Funding was provided in part by NIH grant AG10009.

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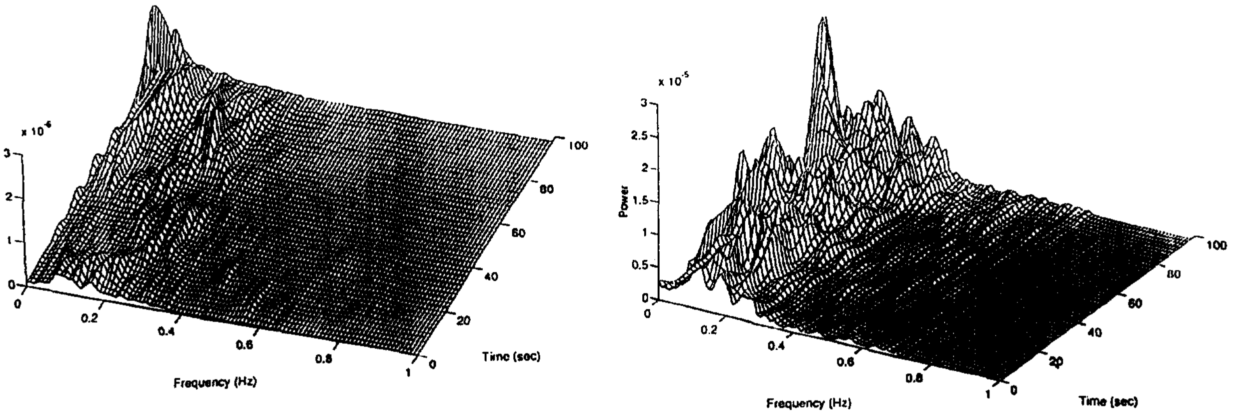

Figure 2: Time-frequency densities of postural sway during quiet stance with eyes closed for a healthy individual (left) and a patient with a vestibular impairment (right). Note the higher power fluctuations and higher frequency content for the patient, and the time-varying spectral changes for both.

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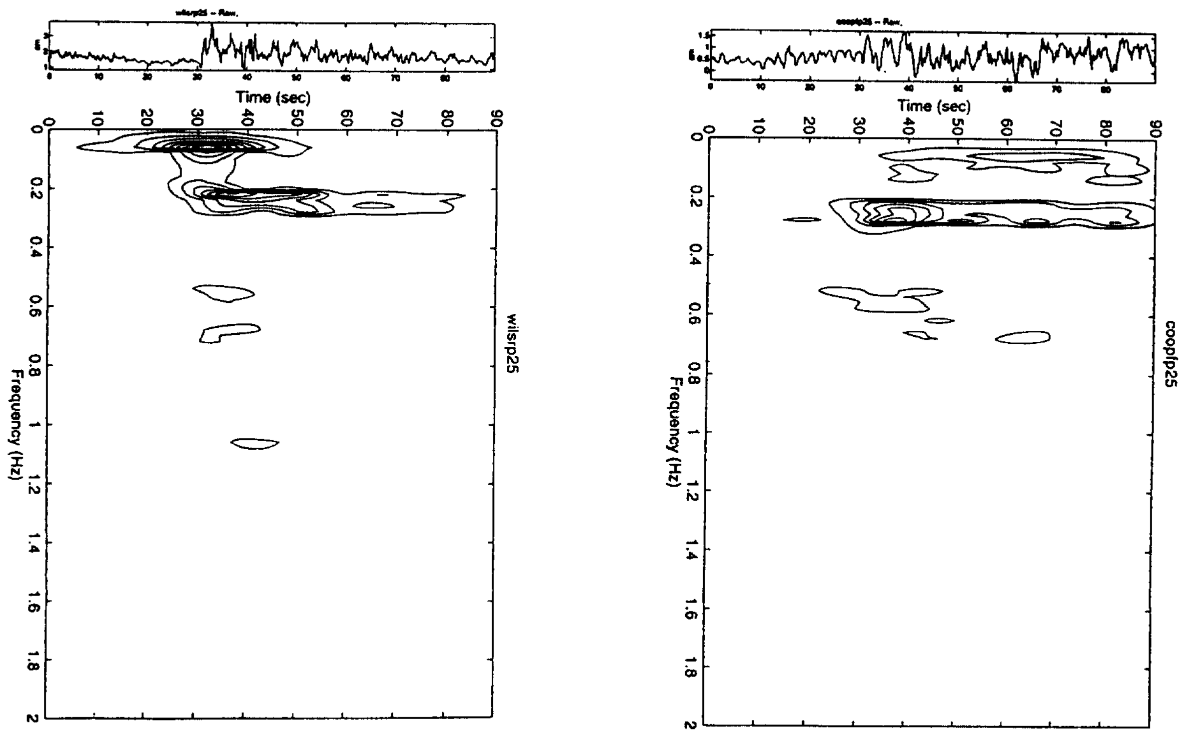

Figure 3: Time-frequency densities of postural sway in response to a 60 second 0.25 Hz sinusoidal visual perturbation initiated at 30 seconds for a healthy individual (left) and a vestibularly impaired patient (right). The postural sway recordings (COP) are shown along the top of each plot. Note the quicker rate of amplitude decay of the healthy subject. Both subjects generate frequencies other than at the stimulus frequency, indicating that postural control is nonlinear. The healthy individual generates these other frequencies only during the initial 20 seconds following the onset of the 60 second stimulus. The patient generates other frequencies throughout the 60 seconds of stimulation.