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Application of factor analysis for the determination of specific frequency bands in corpus cavernosum EMG power density spectra

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Abstract Corpus cavernosum electromyogram (CC-EMG) recording provides diagnostic information on cavernous autonomic innervation and the intact state of cavernous smooth muscle cells. Evaluation of these signals is time consuming and complex. Therefore, we attempted to facilitate their interpretation and to increase their objectivity by using computer-based digital signal processing. Spectral parameters were used as a starting point for this analysis, which were calculated from the Fourier-transformed time domain CC-EMGs. Factor analysis was applied to determine specific frequency bands in the CC-EMG power density. Two hundred power spectra, taken from normal subjects ($n = 66$) and from patients suffering from erectile dysfunction ($n = 134$), constituted the basic data. As a result of applying factor analysis, four specific frequency bands were depicted: 0.0–0.3, 0.3–3.5, 3.5–6.0 and 6.0–10.0 Hz. The results of this study form the basis for further mathematical evaluation and calculation of the CC-EMG for clinical and diagnostic purposes.

Key words Erectile dysfunction · CC-EMG · FFT · Spectral parameters · Factor analysis

Introduction

Since 1988, recording of the electrical activity of the corpus cavernosum has been performed using the electromyogram (CC-EMG), which is used for diagnostic purposes in patients with erectile dysfunction (ED) [18]. With the assistance of the CC-EMG it has been possible to establish a basic knowledge of the autonomic cavernous innervation as well as of the intact status of the cavernous smooth muscle cells [8, 9, 14–18].

CC-EMG recording is performed on a similar basis to the EMG recording of other smooth muscle cells such as those of the urinary bladder [3, 10, 11]. Interpretation of CC-EMG activity is difficult due to the complexity of the biosignals and the experience required by the examiner. Furthermore, the method is very time consuming: a typical recording session lasts about 60 min. Therefore, interpretation needs to be simplified and shortened with computer-based assistance. Digital signal processing and implementation of adequate signal-processing algorithms result in an increased level of objectivity during the assessment procedure.

Typical CC-EMG activity patterns have already been examined and published [4, 5, 14, 15, 16]. These were used as fundamental data for this work. In the time domain, analogously recorded CC-EMG signals (spontaneous electrical activity during the time period) were transformed to the frequency domain (signal amplitude over frequency) by the use of Fast Fourier transformation (FFT), which was applied after the CC-EMG signals had been digitalized and interactively freed from artifacts. The calculated power density spectra led to typical curves, which are displayed in Fig. 1. Similar results were published by Stief et al. [17]. The diagrams show the logarithmic spectral power density of the FFT-transformed CC-EMG over frequency. Frequency components beyond 10 Hz are not shown here because quantitatively they are negligible.

The application of CC-EMG spectra does not enable essential parameters characterizing the spectra to be determined. The definition of certain spectral parameters, which might represent specific characteristics,

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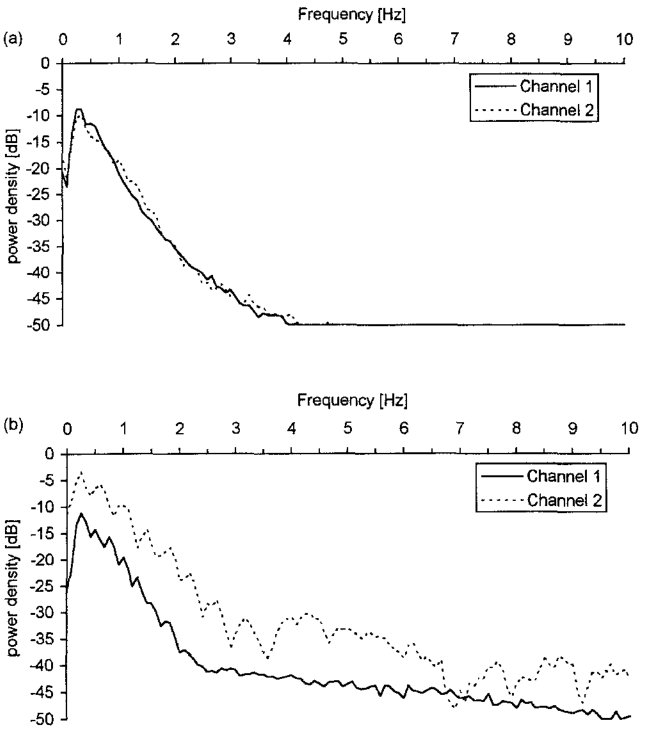

Fig. 1a, b Typical courses of power density spectra taken from a person without erectile dysfunction (**a**) and from a patient with erectile dysfunction (**b**) after pelvic ring fracture

is, in comparison with other application areas, such as electroencephalography (EEG), still insufficiently investigated. The spectral parameters may correlate directly with the patient's state of disease, and, at the same time, lead to a data reduction, thereby simplifying the interpretation of the measurements. The aim of this work was to clarify whether determination of specific frequency bands is possible in analogy to the EEG [7].

Pilot studies [1, 17] have shown that the essential bandwidth of CC-EMG spectra is located mainly between 0 and 10 Hz. These band limits were established by several Fast Fourier transformed CC-EMGs performed on various groups of patients. Parts of the power density are known to lie above 10 Hz. However, based upon their minimal quota of the total power they can be discarded and are of no importance for the evaluation of the spectra here.

The distribution of the power over the frequency of the CC-EMG power density spectra has a characteristic course, which is shown in Fig. 1. This course occurs both in spectra of groups without ED as well as in patients with erectile dysfunction according to the total bandwidth of the spectra. Differentiation into various frequency bands was not carried out. Power density spectra of pathological and normal groups of patients can be clearly distinguished by the power distribution within the range of 0–10 Hz.

Analogous to the subdivision of EEG spectra, mathematically and statistically defined frequency bands in the CC-EMG power spectra were determined. Such a graduation enables further calculation of spectral parameters, e.g., relative bandpower, which can then be used for diagnostic purposes. Furthermore, they may be useful for further computer-based evaluation of CC-EMG.

Materials and methods

One hundred previously recorded CC-EMGs were used as basic data for the determination of specific frequency bands in spectral CC-EMGs. Included were data from 67 patients with erectile dysfunction of different etiologies and 33 measurements from men with no erectile dysfunction. Because all CC-EMGs recordings were performed on two channels (left and right CC-EMG), a total of 200 spectra (66 normal, 134 pathological) constituted the basis for this analysis.

CC-EMG signals were recorded with the Dantec Neuromatic 2000 M neurophysiological unit. The bandwidth utilized was located between 0.5 and 100 Hz. After amplification the signals were low-pass filtered with a hardware-based anti-aliasing low-pass filter with a cutoff frequency of 64 Hz. Using a PC-slot A/D-converter card with a resolution of 12 bits and a sampling frequency of 170.6 Hz, all data were stored in binary format on hard disk. All CC-EMG potentials present were extracted with a software-based algorithm using both gradient and threshold value methods. Following extraction, all known types of artifacts were interactively eliminated. The remaining potentials were weighted with parabolic spectral windows and were then transformed to the frequency domain using the FFT method. The chosen segment length was 2048 samples; frequency resolution was accordingly 0.0833 Hz. Figure 2 shows the method of signal processing in a schematic diagram.

For the determination of specific frequency bands in the CC-EMG power density spectra, factor analysis was used as a statistical method. This method enables variables to be classified into independent groups according to their respective correlative connections

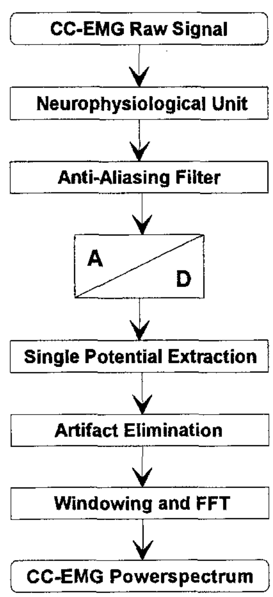

Fig. 2 Signal processing from the analogous signal to the required discrete power spectrum

[1]. The individual groups of variables contain different information. Factor analysis calculation provides information on the allocation of a variable to a certain group or class. The display of factor loads in a diagram clearly indicates these allocations. When applied to CC-EMG power density spectra, the discrete samples of a power density spectrum represent the variables. The number of samples per spectrum in the frequency range between 0 and 10 Hz is exactly $s = 120$. Due to the large number of variables it is obvious that computer-based methods need to be used. Therefore, all calculations regarding the factor analysis were performed using SAS statistic software [12, 13].

At the beginning of an analysis, the number of factors to be calculated needs to be fixed. However, the determination of factor numbers is of importance. Too many factors, as well as too few, may lead to inaccurate results. To overcome this problem and to obtain an impression of the convergence behavior of the method, analyses with different numbers of factors were performed (n = 4–6).

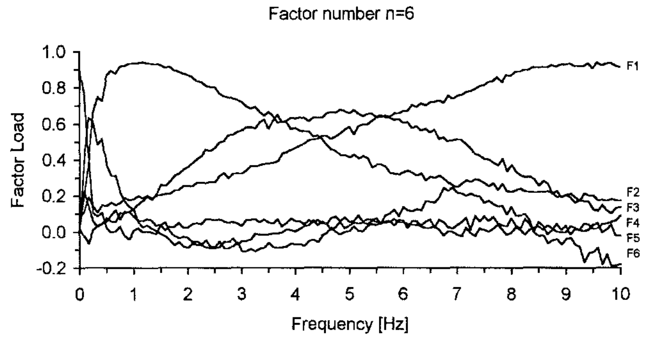

Fig. 5 Distribution of factor loads over frequency for $n = 6$ factors

Results

Figure 3 shows graphically the factor loads over the frequency for $n = 4$ factors. With $n = 4$ factors, 92.13% of the total signal variance is demonstrated. Factor analysis performed with $n = 5$ and 6 factors (see Figs. 4 and 5) led to a fundamentally similar division of frequency bands. Analysis with $n = 5$ factors revealed no new information. The frequency band limits were nearly identical with those of four factors. An additional, very narrow frequency band was maintained when the analysis was performed with $n = 6$ factors. This band is located between 0.2 and 0.3 Hz and has an extremely narrow bandwidth. Because of its location below the lower cutoff frequency of the neurophysiological unit and the narrow bandwidth, it is of no importance within the scope of the hardware used here. All the other band limits of this analysis are the same as mentioned above.

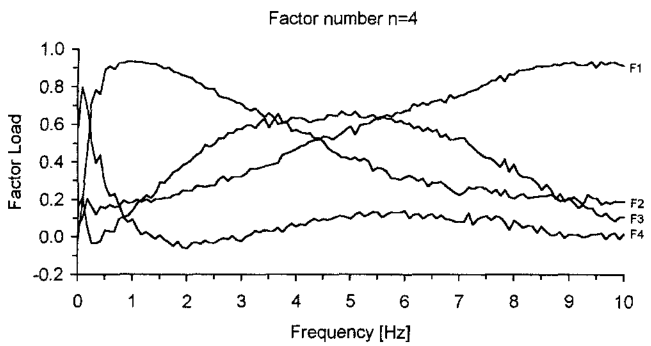

Fig. 3 Distribution of factor loads over frequency for $n = 4$ factors

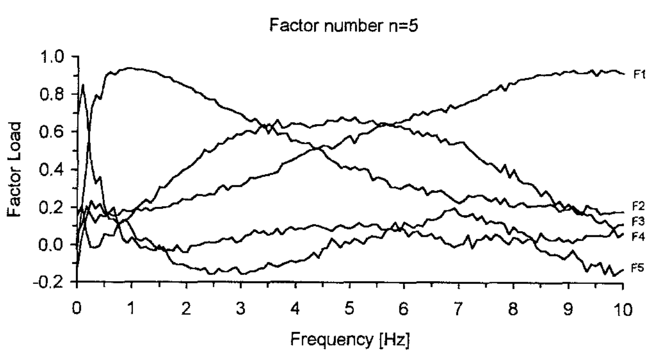

Fig. 4 Distribution of factor loads over frequency for $n = 5$ factors

A number of four factors is, therefore, sufficient to obtain a characteristic division of the 10-Hz-width spectrum of a CC-EMG. The specific frequency ranges are indicated by the intersection points of the factor load distribution curves with the highest amount. The three intersection points led to four resulting frequency bands as follows:

Band I	0.0–0.3 Hz
Band II	0.3–3.5 Hz
Band III	3.5–6.0 Hz
Band IV	6.0–10.0 Hz.

Discussion

Factor analysis was based on 200 spectra. These extensive data were obtained from daily routine diagnostics. We therefore conclude that the results of the examination have a high degree of universal validity. The specific subdivision of CC-EMG power density spectra in the above-mentioned frequency bands can be considered as being universally valid if the conditions of "Guadagnoli" and "Velicer" [1] are based on a generalized interpretation of a factor structure. These terms require that every factor has at least ten variables and the sample size must not be less than $n = 150$ ($n = 200$ in this case). A generalized interpretation is fundamentally possible, providing any of the relevant factors has four variables with loads greater than 0.6 or 10–12 variables with loads greater than 0.4. All these requirements were fulfilled, with no exceptions, for the results of all performed analyses. Therefore, the determined frequency band division of CC-EMG power spectra may be considered as being universally valid.

For the estimation of the stability of a factor structure (FS), the following equation is given in [1]:

$$FS = 1 - (1.1^* \frac{1}{\sqrt{n}} - 0.12^* z + 0.066).$$

The variable n indicates the sample size and z is the minimal factor load value on which the factor interpretation is based. The resulting stability value for the factor analysis with four factors is 0.93 ($n = 200$, $z = 0.6$). This estimation indicates a good correlation of the sample factor structure with the real one, because the index FS is greater than 0.2 [1].

The CC-EMG power density spectra may be evaluated by the use of the statistically determined frequency bands. Specific characteristics may be determined for several groups of patients suffering from ED caused by different etiologies and may be compared with those of normal persons.

For methods which might be used for automatic classification of CC-EMGs, e.g., discriminant analysis, the calculation of parameters for separation is of essential importance. The results of this work establish an additional basis for computer-aided classification and evaluation of CC-EMGs in the frequency domain. In addition, other spectral parameters such as spectral edge frequencies, peak power frequency or similar band power calculations in relative and absolute forms are now available. Even the definition and computation of power-derived parameters may be achieved. Further analysis should clarify the clinical and diagnostic relevance of the lowest frequency range below 0.5 Hz. For this purpose, neurophysiological units for the recording of CC-EMG signals should be used as they are mentioned, e.g., in [2] and [6].

The above-described calculations are part of a project to establish a computer-based interpretation system for routine CC-EMG examinations. This computer-based program will interpret the CC-EMG both in the time and in the frequency domain, thus providing a diagnosis out of both calculations. The determination of the specific frequency bands in the power density spectra enables complex mathematical calculations to be applied to allow classification of CC-EMG in the frequency domain.

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