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Best estimation of spectrum profiles for diagnosing femoral prostheses loosening

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ABSTRACT

For the past few years, some authors have proposed several vibration analysis techniques to detect the prosthetic femoral stem loosening, having found some differences in the frequency response between secure and loose stems. Classical methods like *periodogram* have been used in most studies for the spectral estimation, and their conclusions have been reached only by visual inspection. A new metric called Non-linear Logarithmic Weighted Distance (NLWD), based on log-spectral distance is presented. As its name suggests, the spectral power is weighted in order to highlight discriminatory patterns of the spectral profiles. A Generalized Discriminant Ratio (GDR) based on NLWD metric has been also defined. In this study, experiments on a cadaveric dried bone with two kinds of fixation, Loose Stem class (LS) and Secure Stem class (SS), have been analyzed. To select the most discriminating approach to spectral estimation, five well known algorithms (Welch's, Burg's Auto-Regressive (AR), Auto-Regressive Moving Average (ARMA), Multiple Signal Classification (MUSIC) and Thomson's Multi-taper (MTM)) have been compared by using GDR. Finally, the use of the MTM method is proposed for the analysis of bone–stem interface vibratory signals, since it yields the most discriminatory profiles.

1. Introduction

Aseptic loosening of one or more components is nowadays the main cause of hip arthroplasty failure [1]. The most common non-invasive and inexpensive method of diagnosing prosthesis loosening is the detection of radiolucent lines by means of plain radiography. Unfortunately, this method is only able to detect late loosening stages [2]. Conventional arthrography, namely X-ray, tomography or magnetic resonance visualization of the joint after injecting a contrast agent, seems to offer slight advantages to detect radiolucent lines, but the membranes around the prosthesis are difficult to detect due to the similar radiographic densities between the contrast medium and the prosthesis. The improved technique of digital subtraction arthrography allows distinguishing between implant and contrast medium, and seems to offer much better results in cemented implants than conventional arthrography [3]. Joint inspection by means of gamma camera (scintigraphy) or by using fluorodeoxyglucose positron emission tomography (FDG-PET) after injection of a radionuclide into the circulatory system, are modern and expensive techniques. FDG-PET seems to be the most specific technique to diagnose loosening [4]. Some of the new diagnostic techniques are related to the use of vibrational techniques, currently under investigation [5–14]. All these vibrational researches try to develop a technique able to determine the continuous damage on the bone-implant structure, so they can be considered structural health monitoring methods.

There are several main studies with respect to femoral loosening detection. The research of Qi et al. [6] using the finite elements method showed that the free vibration technique is a simple and inexpensive method for diagnosing femoral component loosening. He delimits four characteristic frequency bands in the spectral profiles, identified as blind band (frequencies lower than 500 Hz), low sensitive band (500–1500 Hz), sensitive band (1500–2500 Hz), and high sensitivity band (above 2500 Hz). According to the distribution and intensity of the detected harmonic spikes, the status of femoral loosening could be estimated. Evidence of differences in the spectral profiles between secure and loose stems has been found in experiments with forced vibrations.

Rowlands et al. [7] proposed an approach with low frequency excitation, lower than 1000 Hz. Sinusoidal vibration was applied to the femoral condyles and the transmitted signal was measured at the femur's greater trochanter. When the prosthesis was securely fixed, the output signal matched the input whereas the output was distorted and showed harmonics with a loose prosthesis.

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Another way of extracting information from spectrum profiles is through rules. Georgiou et al. [8] have created rules for diagnosing loose prosthesis that include parameters such as the ratio of harmonics, fundamental frequency, number of harmonics, number of resonant frequencies and the ratio between these frequencies. Other studies have proved the feasibility of detecting several stages of femoral stem loosening by using techniques based on harmonic distortion and frequency spectrum patterns [9].

The problem of prosthesis loosening quantification remains uncovered because conclusions are mainly based on visual inspection of spectrograms. Moreover, most of the spectrograms are displayed in linear scale [6,7,9] but this is not suitable for analyzing the spectrum because it can hide low intensity patterns. In addition, there is less accuracy. Besides this, these studies employ a traditional algorithm (similar to the periodogram approach) for estimating the frequency spectrum. Although power spectral estimation using periodogram approaches are enough to demonstrate loosening evidence, the method shows high variance and does not eliminate distortions caused by the noise inherent to living systems and to data acquisition systems. So, for developing reliable methods of diagnosis, it is necessary to improve the accuracy of the spectral profiles in order to have better resolution and less variance.

In this work, free vibration experiments in a cadaveric dried femur with an implanted stem have been performed and strain gauges have been used to record the vibratory signal as a simple way to perform a repeatable experience. The experiments have been divided into Loose Stem (LS) and Secure Stem (SS) classes and the recordings have been processed in order to evaluate and select the best spectral estimation methods. By searching for a non-manual technique to diagnose prosthesis loosening, a new metric called Nonlinear Logarithmic Weighted Distance (NLWD) has been developed for the comparison of spectral profiles. NLWD has been used to compute Generalized Discriminant Ratio (GDR) measurement, with the aim of determining the best discrimination method capable of distinguishing between loose and secure stem classes.

2. Methods

The most common method for spectral estimation is based on Discrete Fourier Transform (DFT). For a finite-duration and for a discrete-time signal $x(m)$, which has a length of M samples, the Power Spectral Density (PSD) function defined in Eq. (1) is the basis of non-parametric methods for spectral estimation, usually called *periodogram* method.

$$\hat{P}_{XX}(f) = \frac{1}{M}\left|\sum_{m=0}^{M-1} x(m)\, e^{-j2\pi f m}\right|^2 \tag{1}$$

The spectrum obtained by using Eq. (1) shows high variance and the values vary randomly around an average spectrum. Modern methods of spectral estimation can offer better frequency resolution and less variance.

In this study, five spectral estimation methods have been evaluated: Welch's, Burg's Auto-Regressive, Auto-Regressive Moving Average, Multiple Signal Classification and Thomson's Multi-taper. In Welch's method, the spectrum estimation is the average of K *periodograms* obtained from overlapped and windowed signal segments, and it reduces the noise of the spectral estimation in order to cut down the frequency resolution [15]. In Burg's Auto-Regressive method (AR), the signal is modeled by an auto-regressive procedure and the parameters of the model are employed to compute the PSD estimation [16,17]. The Auto-Regressive Moving Average method (ARMA) models the data as the output of a causal, pole-zero, discrete filter whose input is white noise. In the absence of noise, it can be shown that the AR and ARMA methods interpret the spectral estimation peaks as the true frequencies. It has been found that ARMA methods give frequency estimations which are unbiased for low signal-noise ratio (SNR) [18–20].

The Multiple Signal Classification (MUSIC) algorithm is an Eigen-based subspace decomposition method for the frequency estimation of the complex sinusoids that appear in additive white noise [21–23]. This technique is recommended if spectral estimation is employed for the extraction of uncorrelated sinusoids from noisy spectrum, since it can resolve frequencies that are closely spaced. Even when the SNR is low, the MUSIC method gives high resolution frequency spectra. Thomson's Multi-taper method (MTM) is another nonparametric modern technique that tries to reduce the spectral estimation variance by using a small taper set rather than a unique data taper or spectral window [24,25].

2.1. Non-linear weighted logarithmic distance

In classification tasks and cluster analysis, it is important not only to use the proper spectral estimation algorithm. The accuracy of any classification method depends significantly on the metrics used to compute the distances among the different profiles, so that the distance measuring method is a key issue in many learning machine algorithms. For example, it becomes necessary to supply a suitable metrics to K-means and K-Nearest Neighbor (KNN) through which neighboring data points can be identified [26].

When there is not an *a priori* knowledge of the patterns to be compared, it is usual to use the Euclidean norm, but a quality metrics should identify the important features and discriminate between the relevant and the irrelevant ones [27]. Consequently, the suitable metrics can significantly benefit from the classification accuracy when compared to the standard Euclidean distance [28–30].

The Euclidean norm or linear distance assumes that each data point feature is equally important and independent from the others. This assumption is not valid in our studies, because we hope to obtain spectral profiles similar to those found in previous works with forced vibrations experiments [6,7,9]. Therefore, we consider that there are bands which are more important than others in detecting stem loosening. However, we have no information neither to quantify the significance of the spectral power of each frequency nor to delineate the most important frequency bands. Other proposed metrics such as the Mahalanobis distance have not been considered because they require a significant number of experiments [31].

It is usually difficult to have the necessary amount and variability of samples because the access to biological materials, such as cadaveric bones, is very restricted. For this reason, it is needed to generalize and draw conclusions with a reduced number of experiments. Consequently, we propose the metrics called Non-linear Logarithmic Weighted Distance (NLWD), which is a generalization of log-spectral distance [29], with non-linear weighted contribution of each frequency.

Taking two discrete spectral profiles P_A and P_B, linearly distributed with N values in the normalized frequencies range of 0–1, the NLWD distance is defined as

$$d_{\mathrm{NLWD}}(P_A, P_B) = \left[\frac{1}{N}\sum_{i=1}^{N}\left(10\ \log_{10}\left[(1+\omega(f_i))\frac{\left\|P_A(f_i)\right\|}{\left\|P_B(f_i)\right\|}\right]\right)^2\right]^{\gamma} \tag{2}$$

The effectiveness of this metric resides in the weight distribution $\omega(f_i)$ along the frequency bandwidth and the setup value of γ.