COMPUTER METHODS AND PROGRAMS IN BIOMEDICINE 130 (2016) 1–12

ELSEVIER

journal homepage: www.intl.elsevierhealth.com/journals/cmpb

Quantification of knee vibroarthrographic signal irregularity associated with patellofemoral joint cartilage pathology based on entropy and envelope amplitude measures

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ARTICLE INFO

Article history:
Received 18 August 2015
Received in revised form
12 March 2016
Accepted 16 March 2016

Keywords:
Approximate entropy
Articular cartilage
Fuzzy entropy
Knee joint
Symbolic entropy
Vibroarthrography

ABSTRACT

Background and objective: Injury of knee joint cartilage may result in pathological vibrations between the articular surfaces during extension and flexion motions. The aim of this paper is to analyze and quantify vibroarthrographic (VAG) signal irregularity associated with articular cartilage degeneration and injury in the patellofemoral joint.

Methods: The symbolic entropy (SyEn), approximate entropy (ApEn), fuzzy entropy (FuzzyEn), and the mean, standard deviation, and root-mean-squared (RMS) values of the envelope amplitude, were utilized to quantify the signal fluctuations associated with articular cartilage pathology of the patellofemoral joint. The quadratic discriminant analysis (QDA), generalized logistic regression analysis (GLRA), and support vector machine (SVM) methods were used to perform signal pattern classifications.

Results: The experimental results showed that the patients with cartilage pathology (CP) possess larger SyEn and ApEn, but smaller FuzzyEn, over the statistical significance level of the Wilcoxon rank-sum test ($p < 0.01$), than the healthy subjects (HS). The mean, standard deviation, and RMS values computed from the amplitude difference between the upper and lower signal envelopes are also consistently and significantly larger ($p < 0.01$) for the group of CP patients than for the HS group. The SVM based on the entropy and envelope amplitude features can provide superior classification performance as compared with QDA and GLRA, with an overall accuracy of 0.8356, sensitivity of 0.9444, specificity of 0.8, Matthews correlation coefficient of 0.6599, and an area of 0.9212 under the receiver operating characteristic curve.

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http://dx.doi.org/10.1016/j.cmpb.2016.03.021

Conclusions: The SyEn, ApEn, and FuzzyEn features can provide useful information about pathological VAG signal irregularity based on different entropy metrics. The statistical parameters of signal envelope amplitude can be used to characterize the temporal fluctuations related to the cartilage pathology.

1. Introduction

The knee joints bear almost the entire weight of the human body in daily activities, and they are vulnerable to different types of arthritis, such as osteoarthritis and rheumatoid arthritis [1]. Osteoarthritis could be the consequence of joint degeneration due to overloading activities with an aging phenomenon or physical injury in strenuous exercises [2]. Articular cartilage pathology is one of the most common degenerative disorders that may lead to the development of osteoarthritis in knees.

In most circumstances, a healthy knee with well-lubricated articular cartilage surfaces and intact menisci can perform smooth flexion and extension motions [3]. However, various pathological conditions of the knee joint, including chondromalacia, ruptured ligaments, and meniscal tears, may cause friction and grinding vibrations when the joint is articulated during daily activities such as walking, squatting, and swinging movement of the leg. The acceleration and vibratory signals of the knee joint, which are also referred to as vibroarthrographic (VAG) signals [4], can be recorded by inertial accelerometers in vibration arthrometry examinations [5]. Shark et al. [6] pointed out that the knee acoustic emission biomarkers are useful for quantitative assessment of joint degeneration, because the pathological VAG signals of knee-joint disorders commonly manifest different types of waveform complexity and frequency variations.

Recently, a number of published research works have advanced digital signal processing and pattern analysis technologies for VAG signal analysis. Rangayyan et al. [7] designed the autoregressive model to parameterize the stochastic process and the nonstationary nature of VAG signal segments. Krishnan et al. [8] and Kim et al. [9] computed optimized time-frequency distributions of VAG signals, and extracted the energy, energy spread, frequency, and frequency spread parameters to characterize the time-frequency variability of pathological signals. Rangayyan and Wu [10–12] proposed several temporal VAG signal features, such as form factor, variance of mean-squared (VMS) values, and signal turns count, along with a number of statistical features such as mean, standard deviation, coefficient of variation, skewness, kurtosis, Shannon information entropy, and Kullback–Leibler distance based on nonparametric Parzen-window probability density functions of VAG signals. Tanaka and Hoshiyama [13,14] compared the VAG signals of patients with high stages of osteoarthritis and those of age-matched healthy control subjects during standing-up and sitting-down movements, and reported that the powers of root-mean-squared (RMS) values are significantly greater in the frequency bands of 50–99 Hz and 100–149 Hz for symptomatic osteoarthritis knee joints. Rangayyan et al. [15] used the 1/*f* fractal model to compute the fractal dimension parameters of power spectral density from different segments of VAG signals. Baczkowicz et al. [16,17] studied age-dependent patellofemoral joint impairment by analyzing the VMS, entropy, difference between mean of four maximum and mean of four minimum values (R4), and the spectral power sums in two frequency bands of 50–250 Hz (P1) and 250–450 Hz (P2). Yang et al. [18] applied the detrended fluctuation analysis algorithm to derive the fractal scaling index parameter for quantification of intrinsic correlated signal fluctuations. The experimental results of Yang et al. [18] also showed that the pathological VAG signals of knee-joint disorders are commonly associated with significantly larger averaged envelope amplitude than the signals of healthy knees.

So far, plenty of previous works on screening of abnormal VAG signals associated with knee-joint disorders have been reported in the literature [19–25], there still calls for more computational methods for better quantification of knee-joint pathology. The aim of our present work only focuses on the analysis and quantification of VAG signal irregularity associated with articular cartilage degeneration and injury in the patellofemoral joint. We computed the symbolic entropy (SyEn), approximate entropy (ApEn), and fuzzy entropy (FuzzyEn) parameters to quantify the intrinsic irregularity in pathological VAG signals, and also measured three distinct envelope amplitude (EA) features to characterize the waveform variations and fluctuations in the time scale. Based on the entropy and envelope features, signal patterns can be effectively distinguished by using nonlinear classifiers.

2. Material and method

2.1. *Experiment*

We recruited 73 subjects to participate in the VAG signal acquisition experiments. The healthy subject (HS) group is composed of 55 control adults (28 males and 27 females) with normal knee-joint conditions, as confirmed by routine physical examinations and medical history records. The patient group consists of 18 subjects (9 males and 9 females) with cartilage pathology (CP) in their patellofemoral joints, the pathological conditions of which were assessed with magnetic resonance imaging examinations. The symptoms of the patients with cartilage disorders mainly contain chondromalacia patellae (CMP), softening of articular cartilage, and patellofemoral arthritis. Eleven CMP patients are with Grade I (3 cases, 2 males and 1 female), Grade II (3 cases, 3 females), Grade III (2 cases, 1 male and 1 female), and Grade IV (3 cases, 2 males and 1 female). There are 2 patients (1 male and 1 female)