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To cite this article: A C D Faria *et al* 2018 *J. Phys.: Conf. Ser.* **1044** 012038

View the article online for updates and enhancements.

Instrumentation for the analysis of changes in the knee joint of patients with rheumatoid arthritis: focus on low-frequency vibrations

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Abstract. One of the most common occurrences in patients with rheumatoid arthritis (RA) is the presence of problems in the knee joint. The methods used in the diagnosis of this damage, however, are expensive and/or invasive. This work describes the design and application of a system able to non-invasively evaluate changes in knee joint using accelerometry. Three accelerometers mounted perpendicularly were used, providing signals to a portable instrument. In vivo tests investigating the knee joint vibration power between 2 and 10 Hz showed increased values in RA patients ($p<0.006$). The developed system could be a useful tool for the evaluation of changes in the knee joint introduced by RA.

1. Introduction

The rheumatoid arthritis (RA) is an autoimmune disease of unknown etiology, characterized by peripheral polyarthritis, symmetrical, which leads to deformity and a destruction of the joints [1]. In the United States there are two million adults with RA [1]. It is estimated that RA reaches approximately 0.5% of the Brazilian population [2]. In this disease, the main changes are related with articular problems [1]. The presence of knee joint abnormalities in these patients is one of the most common occurrences, being its detection often based on the simple report of pain and stiffness in the articulation [3]. Among the techniques used to assess the knee joint, the most popular methods of evaluation of joint cartilage damage are arthroscopy and arthrography. These methods, however, are of high price, invasive and may result in infection or further damage to the cartilage [3]. The evaluation of the degree of passive and active movement, ultrasonography, scintigraphy, radiography and magnetic resonance imaging are non-invasive techniques able to evaluate knee joint abnormalities. However, these techniques have disadvantages including inability to radiograph the joint at all degrees of flexion, presence of radiation, high cost, extensive time of examination, and limited ability to delimit the extent of joint cartilage destruction. The auscultation of the knee has been suggested as a diagnostic method, but the ambient noise and the lack of sensitivity of the microphone to the low

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frequencies emitted by the joint limit the effectiveness of this method [4]. Therefore it was observed the need for the development of new non-invasive methods for evaluating knee disorders [3].

The measurement of the vibration produced during knee movement using accelerometry was proposed by Reddy and contributors [4] as a non-invasive method for the analysis of pathologies of the knee. This movement in normal individuals results in an acceleration pattern that is changed in the presence of RA [4]. The technique is minimally intrusive, requiring only the positioning of the transducers on the surface of the knee on analysis, contributing to the diagnosis and follow-up of patients. In addition, this method provides new parameters for analysis that may contribute to deepen the knowledge about the pathophysiology of joint diseases. Previous studies used high frequencies in the evaluation of the oscillations produced as a result of knee disorders [3, 5], typically above 10 Hz. However, there are evidences indicating that this signal is predominantly low-frequency in nature and that most of the signal power fall below 10 Hz [6]. Previous works also point out the importance of subsonic range present in the signal [7, 8]. In this context, the objectives of this study were: (1) to describe the development of a portable system suitable for performing knee accelerometry exams and (2) Investigate the potential of using this methodology in patients with RA, with emphasis on low frequency analysis.

2. Materials and Methods

2.1. System development

2.1.1. Hardware design. Figure 1 presents a simplified block diagram of the instrument. It basically consists of a set of transducers, an analogic signal processing system, including amplifiers and filters, an analogue-to-digital conversion stage and a personal computer running a program responsible for the acquisition of the signals, analysis, presentation and storage of results. The transducers consist of three piezoelectric accelerometers mounted perpendicularly (low power, 3-axis model ADXL335; Analog Devices Inc. EUA). This transducer measures static and dynamic acceleration in a band comprised between ±3.0 g and has a maximum operating frequency of 550 Hz [9]. The transducers are powered by means of a reference voltage of 3.3 V obtained from the integrated LM 2671 (National Semiconductor Inc.) [10]. The signals from the three accelerometers are initially amplified and then processed by analogic low-pass filters (Butterworth, 4th order, 500 Hz) to reduce interference and avoid spectral leakage [3]. This initial stage is powered by two batteries (9 V). Low energy consumption operational amplifiers (LMC 6484, National semiconductor) [11] were used to increase the system autonomy. The acceleration signals were connected to a data acquisition module (NI 6008, National Instruments, Austin, Texas) with a resolution of 12 bits, four channels and maximum sampling frequency (fs) of 10 kHz. In the present project the fs used was 3.0 kHz [3]. To simplify clinical evaluations, the hardware platform used was a small netbook (LG X120, LG Electronics). An important additional advantage resulting from the use of this subsystem is to allow the complete isolation of the patient in relation to the electrical network.
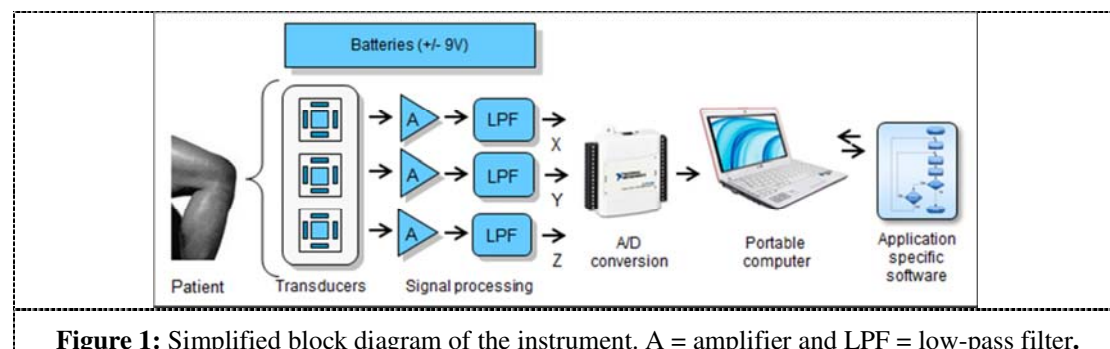

Figure 1: Simplified block diagram of the instrument. A = amplifier and LPF = low-pass filter**.**

2.1.2. Software design. The program was developed in a LabVIEW$^{®}$ environment, containing two main modules. The first, whose front panel is shown in figure 2, contains the acquisition subroutines via the USB port and allows the presentation of the vector sum of the acceleration signal. The acquisition is carried out over 10 s, during movement of the patient's leg, whose frequency must be between 0.4 Hz and 0.5 Hz for the test to be accepted [3, 4]. The program also has routines that allow the user to store patient data, including biometric features, data for contact, and disease history. At the end of the test, the system offers the possibility to save an ASCII file with the acceleration signals over time. The values of the periods and frequencies associated with each cycle of knee movement are also saved.
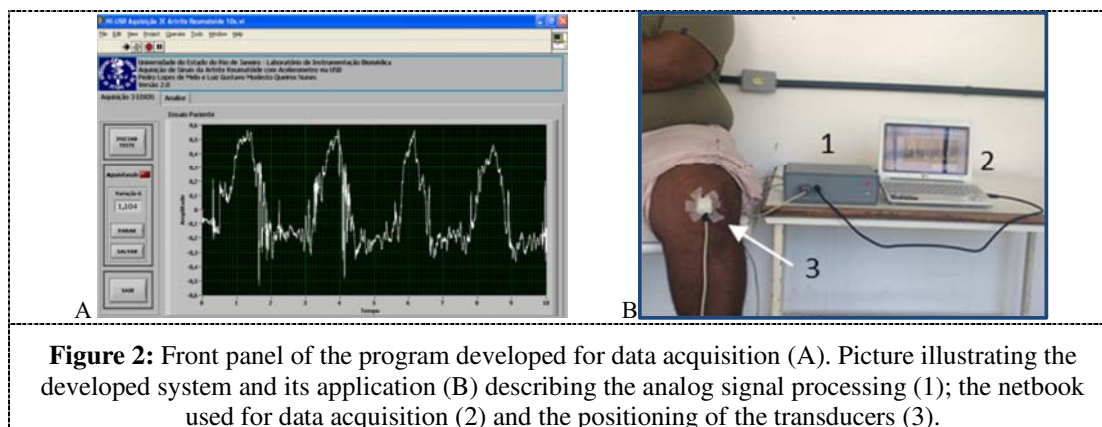

Figure 2: Front panel of the program developed for data acquisition (A). Picture illustrating the developed system and its application (B) describing the analog signal processing (1); the netbook used for data acquisition (2) and the positioning of the transducers (3).

The second module provides a quantitative analysis of the measured accelerations. Initially, the signal is normalized dividing the acceleration values by the maximum value of the basic knee movement signal [3], which was obtained by means of a low pass filter (Butterworth, 4th order, 2 Hz). Subsequently, the length of the signal to be analysed is chosen to include complete cycles of movement. This segmentation is done manually using cursors to identify the start and end points of the segment to be analysed. The signal is processed by a high-pass filter (Butterworth, 4th order, 2 Hz) and, using the routines available in LabVIEW, the program estimates the RMS power spectrum of the signal. Based on this spectrum, it estimates the average power between 2 and 10 Hz (Pm). The software also allows the evaluation of the short-time spectra. This is very useful for characterization of the frequency distribution of knee vibration signal segments in the transient time spans. The spectrograms were obtained by computing the short-time Fourier transform and the Hanning window in the length of 3000 samples, with the overlapping segment length of 2700 samples.

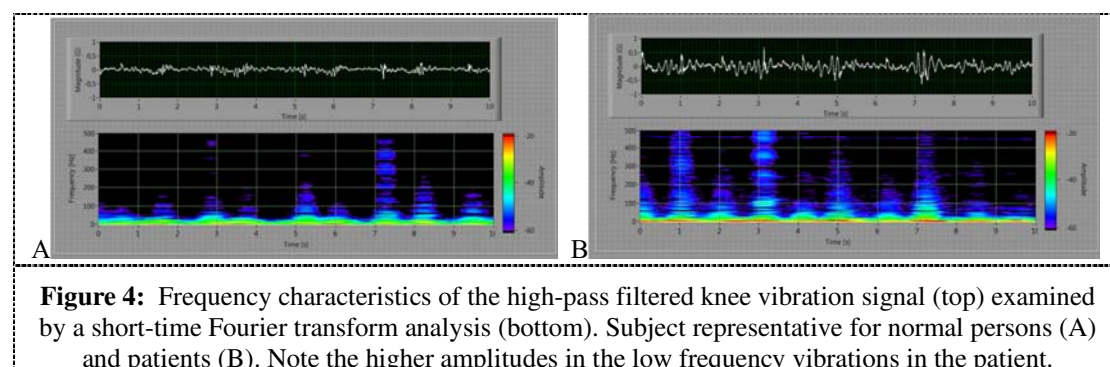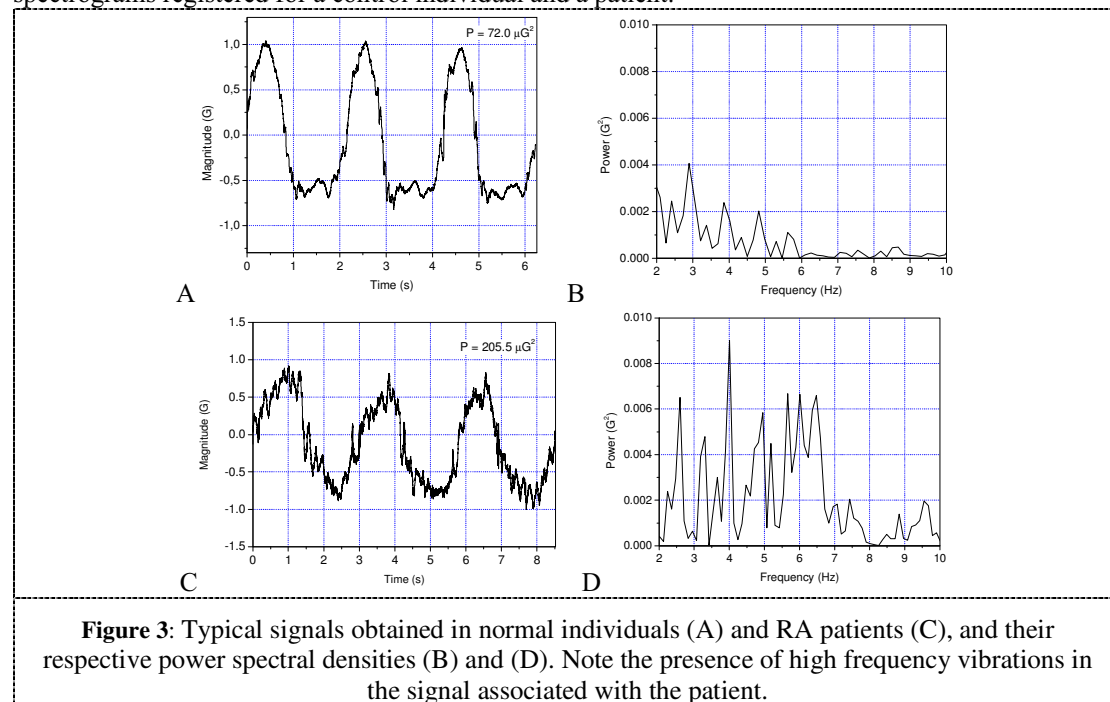*2.2. In vivo tests in healthy individuals and patients with rheumatoid arthritis*

The present study was approved by the Ethics Committee of the Pedro Ernesto University Hospital (HUPE). The protocol obeys the guidelines of Declaration of Helsinki and the post-informed consent of all volunteers was obtained. A comparative analysis was carried out among the results obtained in seven healthy individuals (23.7±3.8 years, 72.6±12.9 kg, 177.3±7.5 cm) and six patients with RA (52.7±9.8 years, 78.6±15.2 kg, 168.0±4.5 cm). The transducers were adapted to the patella of the volunteers with a tape of medical use. Measurements were obtained with the volunteers by cyclically moving the 90° flexion leg to full extension. The flexion-extension procedure was repeated at a uniform rate of approximately 0.5 Hz [3], with the aid of a physiotherapist who guided the volunteer in relation to periods of extension and flexion. The volunteers were analysed wearing loose clothing or shorts and were invited to sit so that they could perform full flexion and extension without feet touching the floor (figure 2B). The RA is a disease that results in bilateral attack [12]. Thus, the

analyses were performed on both knees of all volunteers. Three measurements were performed on each knee, completing a total of 42 normal exams and 36 exams in patients with RA. Results are presented as mean ± standard deviation. The comparison between the results was performed using the STATISTICA version 5.0 program by means of the Mann-Whitney test.

3. Results

3.1. System development

Figure 2B illustrates the developed system and its use. The current consumed by the circuit is 7.9 mA, which results in an autonomy of 45.7 hours. In this project, the limitation of autonomy refers to the autonomy presented by the netbook (3 hours). Considering the average time of an evaluation (10 min), observed during the examinations carried out in the present study, this autonomy allows the accomplishment of approximately 18 exams. Figure 3 shows typical signals obtained in patients and normal volunteers. Figure 4 describes representative high pass-filtered signal courses and associated spectrograms registered for a control individual and a patient.

Figure 3: Typical signals obtained in normal individuals (A) and RA patients (C), and their respective power spectral densities (B) and (D). Note the presence of high frequency vibrations in the signal associated with the patient.

Figure 4: Frequency characteristics of the high-pass filtered knee vibration signal (top) examined by a short-time Fourier transform analysis (bottom). Subject representative for normal persons (A) and patients (B). Note the higher amplitudes in the low frequency vibrations in the patient.

On average, were observed significantly higher values of Pm (p<0.006) in patients with RA (figure 5A). Considering the mean values obtained, including the two knees in each individual studied (figure 5B), it was observed that 4 of the 6 patients studied were above the values observed in normal individuals.
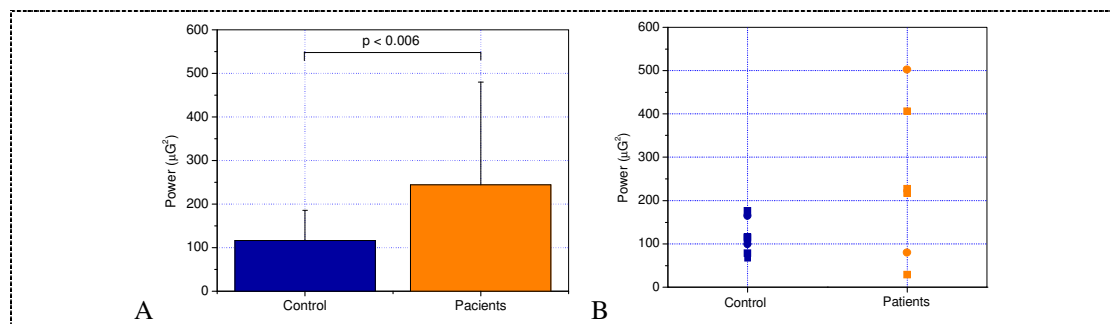

Figure 5: Power obtained in the two groups studied in average terms by group (A) and considering the average values obtained in each individual including the two knees (B).

4. Discussion

The system proposed in the present work is suitable for outpatient use, being small (figure 2B). It was observed that the control program is easy to use by biomedical professionals (Figures 2A). The instrument allows the accomplishment of 18 exams with complete isolation of the patient in relation to the electrical network, which makes the system intrinsically safe. An important advantage refers to allowing a quantitative characterization of the process. The Pm calculated by the instrument presents a high potential to contribute as a useful objective clinical parameter, both for the diagnosis and for the monitoring of knee injuries.

The signals in the time domain show an approximately sinusoidal, low-frequency component associated with the leg movement of the volunteers (Figure 3A,C). It may also be noted that higher frequencies components overlapping on these signals. These components present higher amplitude values in the patients with RA, which allows differentiating the groups (Figure 5). The amplitude of vibrations in normal individuals (figure 3A) is reduced because the surfaces of the knee joints are smooth and integral. In RA patients (figure 3C), on the other hand, there is an increase in friction between the joint surfaces due to the extensive erosion typical of this disease [4]. These principles are clearly described in the results presented in figures 3 and 4. These results are also consistent with those described previously by Reddy et al. [3, 4], which, however, estimate the mean power in a frequency range between 100 and 500 Hz. On the other hand, in the present study, no differences were observed between normal individuals and RA patients in this frequency range. The visual analysis of the results (figure 3) indicates that differences between normal individuals and RA patients can be observed at lower frequencies, which was confirmed by the spectral analysis of the signals (Figure 3B,D). Based on these practical results, it was studied the Pm in the range where the spectral analyses were more selective (2 and 10 Hz). The high-pass filtered signals described in figure 4 eliminate the low-frequency component associated with leg movement (approximately 0.5 Hz). These signals were consistent with the recent work of Yang et al. [13] and clearly showed increased spectral amplitudes in the 2-10 Hz frequency in the presence of frictional events (figure 4). Considering the studied groups, this increased amplitudes resulted in significantly higher values of power in the patients (figure 5A).

It is important to point out that the present study investigated patients in the early stages of RA. In this case there is only inflammation in the synovial tissue; the joint surfaces have not yet been eroded, still encountering the smoothing close to normal. This results in small friction between the surfaces [4]. This may explain the low Pm values observed in two patients described in Figure 5B. One of these patients was in the initial phase of treatment because it was a case of a recent diagnosis of RA. The

other case was a patient with no joint pain. Thus, these results are consistent with the clinical evaluations and the pathophysiology of RA and indicate that the proposed system may be useful in discriminating between the early and late phases of the disease. Studies in a larger number of patients are needed to confirm this hypothesis.

5. Conclusion & future work

A new system was developed for non-invasive analysis of knee disorders using accelerometry. The main characteristic of this system is the low frequency analysis. The application of the system in normal individuals and patients with RA showed results in close agreement with the literature, as well as with the physiological principles involved. The system has a high potential to contribute to the improvement of the analysis of alterations resulting from RA or associated to rehabilitation procedures. The next phases of this project include its use in the evaluation of patients with different degrees of joint impairment and the evaluation of the performance of medications in patients attended at our University Hospital.

Acknowledgments

References

[1] Brown K K 2007 Rheumatoid lung disease *Proc Am Thorac Soc* **443-448**

[2] Senna E R, De Barros, A.L., Silva, E.O., Costa, I.F., Pereira, L.V., Ciconelli, R.M., Ferraz, M.B. 2004 Prevalence of rheumatic diseases in Brazil: a study using the COPCORD approach. *J Rheumatol* **31(3)** 594-7

[3] Reddy N P, Rothschild B M, E. V and A. J 2001 Noninvasive Measurement of Acceleration at the Knee Joint in Patients with Rheumatoid Arthritis and Spondyloarthropathy of the Knee *Ann Biomed Eng* **29** 1106-11

[4] Reddy N P, Rothschild B M, Mandal M and Gupta V 1995 Noninvasive acceleration measurements to characterize knee arthritis and chondromalacia *Ann Biomed Eng* **23** 78-84

[5] Baczkowicz D, Majorczyk E and Krecisz K 2015 Age-related impairment of quality of joint motion in vibroarthrographic signal analysis *BioMed research international* **2015** 591707

[6] Tavathia S, Rangayyan R M, Frank C B, Bell G D, Ladly K O and Zhang Y T 1992 Analysis of knee vibration signals using linear prediction *IEEE transactions on bio-medical engineering* **39** 959-70

[7] Mollan R A, McCullagh G C and Wilson R I 1982 A critical appraisal of auscultation of human joints *Clinical orthopaedics and related research* 231-7

[8] Kernohan W G, Beverland D E, McCoy G F, Shaw S N, Wallace R G, McCullagh G C and Mollan R A 1986 The diagnostic potential of vibration arthrography *Clinical orthopaedics and related research* 106-12

[9] ADXL335 2009 Data sheet In: *Analog Devices, Inc. ,* (http://www.analog.com/en/sensors/inertial-sensors/adxl335/products/product.html.

[10] LM2671 2007 Data sheet In: National Semiconductor http://www.national.com/pf/LM/LM2671.html.)

[11] LM6484 2000 Data sheet. In: National Semiconductor (http://www.national.com/mpf/LM/LMC6484.html.

[12] Bértolo M B, Brenol C V, Schainberg C G, Neubarth F, Lima F A C and Laurindo I M e a 2007 Atualização do consenso brasileiro no diagnóstico e tratamento da artrite reumatóide *Rev Bras Reumatol* **47** 151-9

[13] Yang S, Cai S, Zheng F, Wu Y, Liu K, Wu M, Zou Q and Chen J 2014 Representation of fluctuation features in pathological knee joint vibroarthrographic signals using kernel density modeling method *Medical engineering & physics* **36** 1305-11