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The Use of Electromyography for the Identification of Fatigue in Lower Back Pain

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Abstract - A surface EMG technique is described which was developed to provide an objective measure of paraspinal muscle function in patients with LBP. The device, referred to as a Back Analysis System (BAS) records changes in spectral and amplitude parameters from 6 EMG electrodes during a series of fatiguing isometric tasks that rely on visual force-feedback. Changes in the EMG median frequency, a fatigue index, are first compared in this report for different electrode locations and different constant force levels in healthy control subjects. The results demonstrate that there is a characteristic "normal" pattern of fatigue among the various paraspinal muscle sites that is symmetric with respect to contra lateral paravertebral locations, but significantly different when comparing upper and lower lumbar levels. Changes in EMG median frequency during a sustained contraction are significantly increased with increases in force level of the contraction. In patients with chronic LBP in remission, the degree of median frequency change is significantly higher than in control subjects matched for strength. These findings are likely related to muscle deconditioning resulting from chronic disuse. Other findings are reported from BAS protocols among sub-acute LBP patients with moderate to severe disability. These patients have a distinctive asymmetrical pattern of muscle fatigue as measured by the median frequency and amplitude parameters. This pattern is interpreted as a way of measuring muscle imbalances resulting from to pain-related inhibition or avoidance behavior. Implications of these characteristic EMG findings are discussed in terms of differential treatment strategies for LBP.

Key Words - Low Back Pain, electromyography, EMG, muscle function.

O uso da eletromiografia para identificação de fadiga na dor lombar baixa

Resumo- É descrita uma técnica de eletromiografia (EMG) de superfície, desenvolvida para fornecer uma medida objetiva da função muscular para-espinhal em pacientes com dor lombar baixa (LBP). O equipamento, denominado de Back Analyses System (BAS) registra alterações nos parâmetros de amplitude e espectro, a partir de seis eletrodos de EMG, durante uma série de tarefas isométricas fatigantes com retro-alimentação visual da força. Mudanças na freqüência média da EMG – um índice de fadiga, foram previamente comparadas, neste relato, em diferentes localizações dos eletrodos e em diferentes níveis de força constante, em sujeitos-controle saudáveis. Os resultados demonstram que há um padrão característico "normal" de fadiga entre as várias regiões musculares para-espinhais, que é simétrico em relação às regiões para-vertebrais contra-laterais, contudo significativamente diferente ao se comparar níveis lombares alto e baixo. Alterações na freqüência média da EMG, durante uma contração sustentada, são significativamente aumentadas com aumentos do nível de força da contração. Em pacientes com LBP crônica, o grau de mudança da freqüência média é significativamente maior que em sujeitos-controle num mesmo nível de força. Estes achados são provavelmente relacionados com o descondicionamento muscular resultante do desuso crônico. Outros achados são relatados através de protocolos do BAS entre pacientes com LBP sub-aguda com incapacidade de moderada a severa. Estes pacientes apresentam um padrão assimétrico distinto de fadiga muscular medido através de parâmetros de amplitude e freqüência média. Este padrão é interpretado como uma maneira de medir desequilíbrios (desbalanços) musculares resultantes comportamento de escape (evitar) ou de inibição associada à dor. As implicações destas descobertas com EMG peculiar são discutidas em termos de estratégias de tratamentos diferenciais para a LBP.

Palavras-chave: Dor lombar baixa, eletromiografia , EMG, função muscular.

Introduction and Background

Within the past two decades there has been a renewed interest in developing better instruments to objectively quantify back muscle impairment and functional limitations associated with lower back pain (LBP). Two key factors have influenced this development: 1) a growing demand on the part of health care providers and third-party providers for evidence-based practice and accountability of diagnostic and treatment procedures, and 2) a change in the philosophy of back care providers from one of assessing and treating pain to that of assessing and treating functional limitations. A variety of back dynamometers were developed in response to this need (7,17). These "Back Machines" differed in their methods of restraining the body and isolating the back.

They assessed the paraspinal muscles during different kinds of muscle contractions and measured different mechanical parameters. Most of these systems were first introduced into the market without rigorous studies of their efficacy for LBP or how the results are should be applied to guide treatment prescription. Since then, a number of research studies have been published to validate their use (1,3,7) but there is little compelling evidence that the use of Back Machines resulted in more favorable outcomes than standard assessment procedures (17). These back machines share a common flaw in that the measured kinematics and force variables are cognitively perceived by the subject and thus can be voluntarily regulated to influence the outcome (8). In contrast, the surface electromyographic (EMG) approach to back muscle assessment is based on relative changes in spectral parameters of the EMG signal associated with localized fatigue (e.g., the *median or mean frequency*) or relative changes in the amplitude of the signal (e.g., the Root Mean Square)(8, 14, 15). Secondary gain or motivation may have less of an effect on these parameters compared to force measures, so long as the subject complies with the assessment protocol (8).

Lower back pain specialists are in need of more effective methods to objectively quantify paraspinal muscle impairments. Measurements of trunk strength, endurance, and motor control are considered important for optimizing the delivery of lower back pain (LBP) rehabilitation (1). Surface EMG techniques have played an important role in helping researchers understand normal functioning of concurrently active trunk muscles when specific static postures or movements against gravity take place. These procedures have been successfully applied to document the alteration to normal paraspinal muscle functioning associated with chronic or acute LBP. By monitoring concurrent changes in surface EMG spectral or amplitude parameters from multiple muscle sites, it is possible to evaluate the relative contribution of individual paraspinal muscle groups during sustained extension of the trunk, or during repetitive work tasks. This paper summarizes and compares two generalized methods of monitoring fatigue from the SEMG signal in paraspinal muscles during 1) a sustained, constant-force, isometric task performed in a device referred to as the Back Analysis System (BAS), and 2) during a standardized repetitive lifting task used for work capacity assessment.

Back Analysis System (BAS)

The Device:

The BAS is a computerized surface EMG system coupled to a postural restraint apparatus that isolates and stabilizes the musculature of the trunk (Figure 1). The BAS analyzes the EMG signals acquired during isometric fatiguing contractions of the back. It uses spectral estimates of the signal to monitor localized fatigue, and amplitude estimates of the signal to monitor muscle imbalances from contra lateral paraspinal muscles (Figure 2). The BAS was developed to provide a more objective means of assessing muscle performance of the lower back in people with LBP. It measures maximal isometric trunk extension strength, a classification index of paraspinal impairment based on EMG median frequency parameters, and estimate of muscle imbalance based on the ratio of contra lateral EMG signal amplitude measurements. The system has been tested among healthy control subjects and been validated among chronic and acute patients with LBP (14, 15, 16). The BAS test protocol requires about 30 minutes to complete and has been used extensively in patients with LBP, including the elderly. Subjects are tested while standing in the postural restraint apparatus, which secures them with the use of padded straps and plastic molds. Surface EMG sensors (DelSys Inc., Boston, USA) are taped to the skin overlying superficial lumbar paraspinal muscle sites. The subject is then instructed to produce a maximal trunk extension force by pulling back against a padded strap that is positioned across their shoulders and fastened to non-compliant load cells housed in the device. A monitor provides visual force feedback to assist them in performing the task. The maximum force from the load cell is used to establish trunk extensor strength and to normalize the target force levels for the next series of contractions. In these tests, the subject must sustain a contraction at a specified percentage of their maximal value (%MVC) for a specified duration (e.g., typically less than 1 minute). Rest periods are provided between the sustained contractions to minimize overexertion on the part of the subject and control for cumulative fatigue effects. In some instances, particularly when acute or sub-acute patients with LBP are tested, percentage of Ideal Body Weight (%IBW) is used instead of % MVC to define the target force level (10). This was done to overcome the difficulty in establishing an accurate MVC in persons complaining of relatively high levels of back pain.

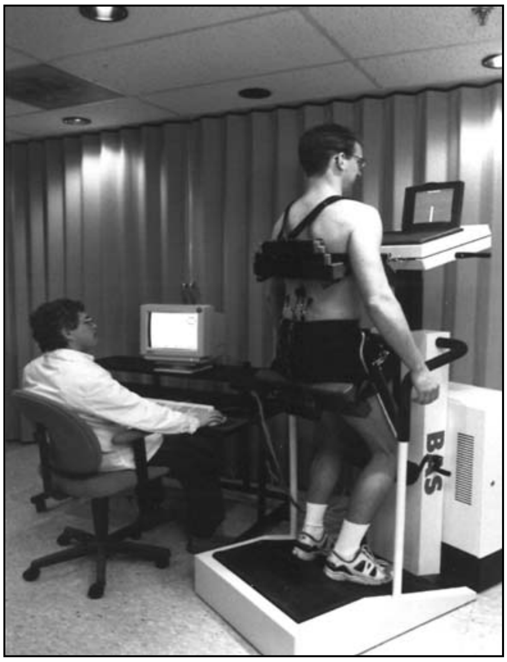

Figure 1. A subject is shown being tested in the Back Analysis System (BAS). The subject's task is to try and extend their trunk against the Data from SEMG electrodes and load cells are acquired and processed from the desktop PC.

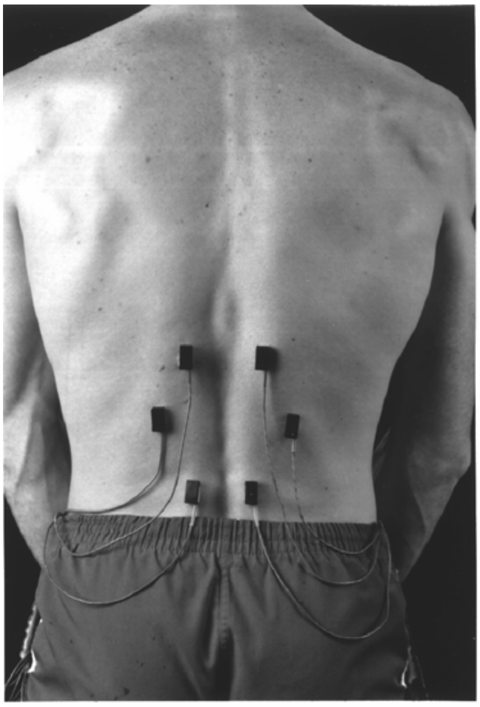

Figure 2.The location of surface EMG electrodes are shown for monitoring changes in EMG spectral parameters during the Back Analysis System test protocol. The muscle sites correspond to Longissimus thoracis, Iliocostalis lumborum, and Multifidus at L1, L2 and L5 spinous process levels, respectively.

Study Findings:

Our preliminary studies were conducted primarily to characterize the response of paraspinal muscles to sustained loads (14). More specifically, we were interested in the effects of incremental loads on the degree of spectral shift, as well as how this indicator of localized fatigue was distributed with respect to muscle location. Findings in n=12 male subjects without a history of LBP (mean (SD): age 27.3 (7.2) yr, height 169.8 (17.0) cm, weight 71.1 (5.9) kg) were reported for contractions sustained at 40%, 60%, and 80% MVC for 60s in the BAS. Their results were compared to equal number of males with chronic LBP of similar age, height, and weight. These patients had chronic LBP for an average of 5.2 years but were in remission at the time of testing (i.e., they scored less than 1 on a 10-point visual analog pain scale). The relative change in median frequency (MF Slope) was significantly greater among LBP subjects compared to the control subjects, particularly at the higher target force levels and lower (L5) lumbar muscle sites. No significant contra lateral differences were observed, however. The difference in MF slope between LBP and Control could not be explained on the basis of different relative loads between the two groups, because their MVC values were not significantly different for the two groups. Instead, the findings were interpreted as an indication of differences in paraspinal muscle fatigability between the two groups; possibly due to muscle deconditioning in the LBP group. The technique was therefore considered as being of possible value in evaluating and monitoring LBP impairments in patients undergoing rehabilitation. A multi-variate discriminate analysis technique was used to further analyze this data set to come up with an EMG-based classification for LBP impairment. The procedure used a step-wise linear regression approach and an F-test for entering and removing median frequency parameters from the different muscle sites to maximize between-group variance and minimize within-group variance. The results demonstrated the test's ability to identify the subjects with LBP with an accuracy of 92 percent and the control subjects with an accuracy of 83 percent based upon just 4 median frequency parameters.

Similar studies were done among acute and sub-acute patients with relatively high self-reports of pain (i.e.; greater than a score of 3 out of a 10-point visual analog pain scale) (15). Data were acquired and analyzed for LBP (n=28) and Control subject (n=46) populations similar procedures as described above for the BAS. Discriminate functions classified subjects into LBP and Control groups with 86 percent and 89 percent correct classification, respectively based on the EMG median frequency parameters. The "fatigue patterns" are distinctly different when comparing the data for these groups of subjects as evidenced by considerable contra lateral muscle imbalances in the LBP group, but not the Control group. These imbalances were attributed to muscle favoring. Such pain-related behaviors have been associated with fear or avoidance responses to pain, which some clinicians believe, can be reversed as a part of a comprehensive back rehabilitation program (11).

Standardized Repetitive Lifting Protoco

The Method:

The relatively recent development of spectral analysis procedures for non-stationary EMG signals enabled us to expand our research on paraspinal fatigue and impairment to include a repetitive lifting task (4,5,12). A primary limitation to EMG signal processing techniques at the time was the assumption that signals are *wide sense stationary*; i.e. the first and second statistical moments of the stochastic process do not change in time. This pre-condition can only be satisfied by recording surface EMG signals during highly constrained conditions in which there are negligible changes in muscle length and force during the fatigue-inducing activity. During a dynamic contraction, changes in muscle force, muscle length, and the location of the electrode with respect to the active muscle fibers result in signal non-stationarity which appear as variations of the frequency content of the EMG signal. It is for this reason that spectral EMG techniques have been traditionally limited to isometric, constant-force contractions. Although this contraction mode is useful in characterizing the ability of paraspinal muscles to perform static anti-gravity functions, it is not likely to be generalized to the numerous other functional activities of the back which incorporate non-isometric contractions. The limitation of the procedure to constant-force isometric contractions seriously compromised its clinical usefulness because many dynamic activities, such as lifting, are commonly associated with LBP injury. In an attempt to overcome this limitation, some researchers have attempted to monitor localized fatigue during dynamic activities by introducing periodic constant force, isometric test contractions (9). This approach can be criticized because it may introduce additional fatigue to the task being monitored and muscle fibers recruited during the static test contraction may differ from those recruited during the dynamic activity. Another approach was to segment the signal sequence into sub-sequences during which stationarity may be assumed or statistically tested. The short-time Fast Fourier transform algorithm is the most commonly used method of implementing this strategy (2). A limiting factor with this approach is that since the frequency resolution is proportional to the length of the observation window, relatively short observation windows result in poor frequency resolution of the distribution. Hence, the short-time Fast Fourier transform may only be successfully applied when non-stationary components are slow enough to allow for the choice of a relatively long observation window, yielding acceptable frequency resolution. Although this pre-condition may be reasonably well met for most constant-force isometric contractions in which the surface EMG signal is typically assumed to be stationary for epochs of 0.5 to 2.0 s (2), the non-stationarity of the surface EMG signals recorded during dynamic contractions cannot be disregarded. It follows, therefore, that the short-time Fast Fourier transform algorithm is not adequate to estimate the changes in the frequency components of the surface EMG signal during dynamic contractions.

Recent developments in the field of signal processing have provided a possible mechanism to overcoming this limitation by the use of the Cohen Class of time-frequency transforms (4,5). This family of transforms was specifically designed to handle non-stationary signals. In addition, Cohen transforms are particularly suitable for the analysis of surface EMG signals recorded during dynamic contractions because they constitute the class of bilinear time-frequency transforms which are invariant to time and frequency shifts. This property is important to correctly represent the time evolution of the frequency content of the surface EMG signal because any time delay or frequency shift applied to the signal results in an equivalent delay or shift in the time-frequency representation. We have demonstrated in previous work that the Choi-Williams transform (6), which belongs to the Cohen class of time-frequency transforms, is particularly suitable for representing the time-course of the frequency content of the surface EMG signal. A method for calculating the *instantaneous* median frequency (IMDF) from the Choi-Williams transform was utilized (Figure 3)(4,5,12). Because this technique is based on the assumption that the biomechanics of the task for the chosen portion of the cycle is the same across cycles, it was desirable to utilize a portion marked by high repeatability of the biomechanics. Previous results have shown that these portions are also marked by low variability of the IMDF (4,5). This is because there are two possible sources of changes in the IMDF parameter during the task, i.e., muscle fatigue and the variability of the biomechanics of motion. It follows that the portion of the lifting cycle associated with minimum variability (across cycles) of the IMDF parameter is the one minimally affected by factors that relate to the biomechanics of motion and thus the IMDF time-course derived using such portion reflects muscle fatigue during the lifting task. Therefore, the following procedure was implemented: 1) compute the IMDF for all the lifting cycles; 2) resample the IMDF time-series in order to have the same number of estimates within each cycle; 3) divide the IMDF time-series into time-intervals (i.e., portions) lasting 1% of the lifting cycle and compute the standard deviation of the IMDF associated with each portion of the cycle; and 4) choose the portion of the cycle associated with minimum variability for deriving the time-course of the parameter during the task.

Preliminary findings are presented in which this analysis procedure is utilized to measure changes in spectral measurements during a repetitive lifting task.

Results:

Results from healthy control subjects with no history of LBP (n=9; mean age 26.3 ± 6.7) were reported from surface EMG data recorded from 6 electrodes on the thoraco-lumbar region (4,5). Data were recorded during a standardized repetitive free-lifting task (load =15% body mass; 12 lifts/min; 5-min duration). An example of the results of the EMG analysis is illustrated in Figure 4. The average and standard deviation values derived from 6 cycles at the beginning (baseline) and the end (at 5-minutes) of the exercise are shown for each of the electrode sites. The results show a significant decrease in IMDF between the baseline and completion of the 5-minute task (Wilcoxon test, $p<0.05$), particularly for muscles located at L5 region. Also, the decrease in IMDF was symmetric for contra lateral muscle sites.

In many of the individual plots of IMDF, there were noticeable periods of IMDF decay and recovery during the repetitive work task (Figure 5). We have speculated that this behavior may represent a highly developed ability of paraspinal muscles to limit fatigue in any one muscle by allowing for recovery during the exercise. This could be achieved if the relative force contributions between concurrently active muscle groups were periodically redistributed to allow for these periods of reduced activity. It suggests that this behavior might be orchestrated with other thoraco-lumbar muscle groups as a possible strategy to preserve localized muscle endurance. Further tests and analyses are needed to support this interpretation of the findings. In addition, we are interested in determining whether such a strategy, if present, is compromised as a result of LBP. Preliminary results shown in Figure 5 indicate that pain may limit the ability of paraspinal muscles to utilize the "fatigue-sparing" strategy. The figure compares two data sets from patients with and without pain-related disability, as measured by an Oswestry LBP Disability scale. The patient without pain-related disability shows more periods of IMDF decay and recovery during the 5-minute cyclic lifting task the Pain-disabled subject. The implication of this finding, if validated among a greater numbers of subjects, is that impairments in the ability of paraspinal muscles to counteract the effects of fatigue may predispose these individuals to recurrent back injury. Whether such impairments can be reversed through therapeutic interventions, remains to be seen.

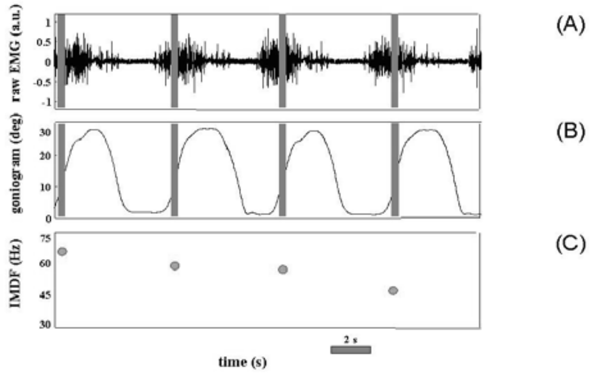

Figure 3 Schematic describing the method used to extract instantaneous median frequencies (IMDFs) from emg "bursts" produced by a single lifting and lowering of a weighted box. The upper plot shows the emg "bursts" for repetitive lifts. The vertical line identifies a specific phase of each lift cycle. This phase corresponds to the most repeatable portion of the lift, as indicated in the middle plot of the box trajectory. The lower plot is the corresponding time history of IMDF decay, which is used to monitor localized fatigue.

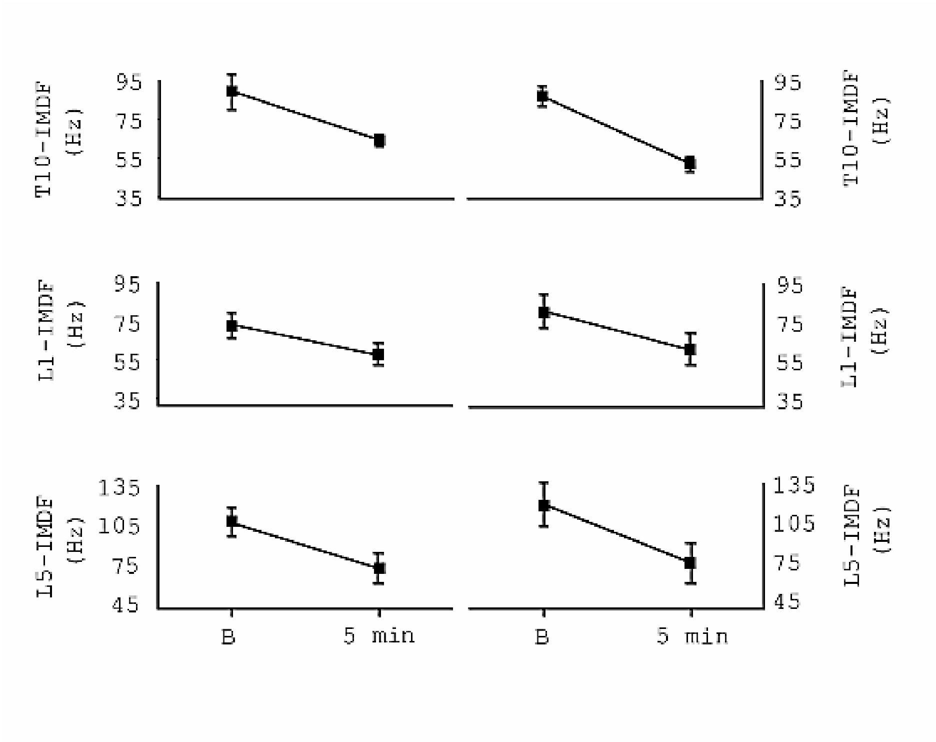

Figure 4. Mean changes (SD bars) of Instantaneous Median Frequency (IMDF) for six muscle sites corresponding to T10, L1, and L5 vertebral levels. Changes are shown for baseline and completion of the 5-minute exercise of lifting and lowering a load from mid-shank to waist height. (a) Changes in Instantaneous Median Frequency for two patients; one with pain related disability and the other without. The higher cyclic activity of fatigue and recovery can be observed in the patient without pain. (b) The cycle frequency of the IMDF data is plotted for the data depicted in (a).

Figure 5 (a)

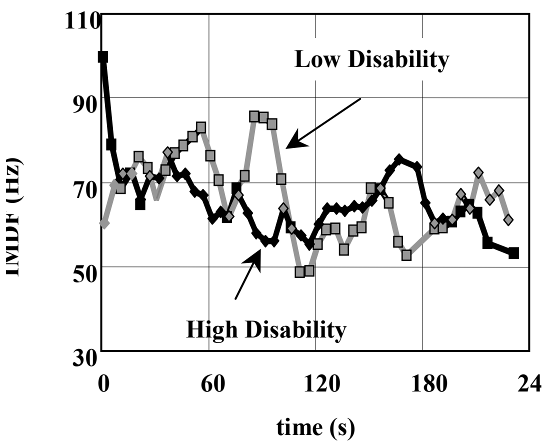

Figure 5 (b)

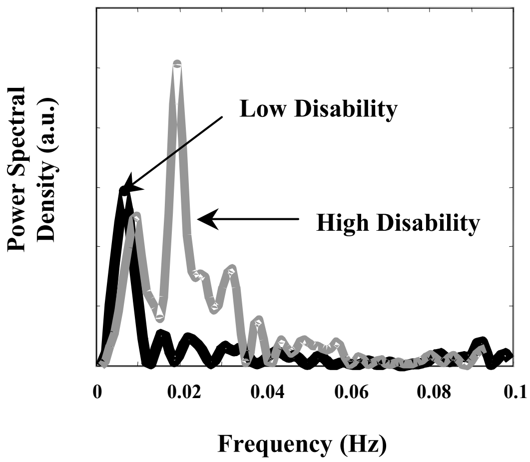

Figure 5. (a) Changes in Instantaneous Median Frequency for two patients; one with pain related disability and the other without. The higher cyclic activity of fatigue and recovery can be observed in the patient without pain. (b) The cycle frequency of the IMDF data is plotted for the data depicted in (a).

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