WAVELET AND FOURIER BASED ANALYSIS OF ESSENTIAL TREMOR MOTION USING MEMS ACCELEROMETERS AND GYROSCOPES

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ABSTRACT
The use of inertial sensors (accelerometers and gyroscopes) in characterizing essential tremor (ET) motion is quite prevalent. For this reason, it is important to determine the following for accelerometers and gyroscopes: (i) whether frequency localization offered by utilizing wavelets provides significant advantages to a Fourier based approach of analyzing data (ii) whether accelerometers or gyroscopes can better distinguish ET motion from that of a control (iii) whether three axes of inertial sensor measurement are required to assess essential tremor motion.

To examine the above mentioned areas of inquiry, tri-axial inertial sensor signals were captured for patients using their dominant hand to direct a laser at targets on a computer screen whilst sitting in an upright position. Participants were asked to keep their arm extended in front of them with slight bend in their elbow; 7 ET patients (5 males, 2 females) with a mean age of 66 and 9 controls (4 males, 5 females) with a mean age of 64 took part. Analysis of the inertial data showed that both accelerometer and gyroscope sensors mounted along any arbitrary axis provide similar frequency of motion information and that frequency localization using wavelets offers some advantages to a Fourier based approach.

KEY WORDS
Essential tremor, continuous wavelet transform, MEMS

1. Introduction

Essential tremor (ET) is among the most common movement disorders and it is the most prevalent among disorders involving tremor motion [1]. Approximately 0.4-3.9% of people have ET [2]; furthermore, the disorder is degenerative [3] and particularly common among the elderly. One study found that 4.0% of those aged 40 and older had ET [4]. There is a significant degradation in quality of life for those afflicted with ET as they struggle to perform basic tasks such as eating, drinking and shaving; and researchers have found that 73% of people with ET have reported a disability [5]. In severe cases, patients lose the ability to look after themselves which often results incapacitation [6]. ET sufferers tend to exhibit both postural and action tremor, particularly in their limbs [7], with a tremor frequency between 4 and 12 Hz [8]; older patients often exhibit frequencies of motion in the lower end of this range.

Assessment of ET often presents many challenges. There is suspicion among many experts that the condition is often over diagnosed [9]. As well, it is sometimes difficult to distinguish ET motion from motion resulting from other movement disorders [1]. As a result of these difficulties, research in recent years has focused on the use of accelerometers to help diagnose ET. One popular technique is to decompose and analyze the different accelerometer signals to help distinguish between ET motion and the motion of control test subjects [10]. Previous research utilizing a similar approach found that the average error of recognition of ET was less than 3% [11]; this is generally a very good rate of recognition and can help medical specialists a great deal when classifying disorders. Similar work has also been carried out using gyroscopes [12]; using both accelerometers and gyroscopes should produce more reliable results because the former measures lateral motion and the latter measures rotational motion; the combination of both sensors generally provides more information about overall motion. Other researchers have focused on using accelerometers to quantify and assess writing and drawing motion [13, 14]. As well, accelerometers have been used in determining the efficacy of ET treatments [15].

Despite all of the usage of accelerometers and gyroscopes in ET research, there has been relatively little work carried out to understand how utilization of different inertial sensor types and their orientation affects the signal captured and later analyzed when determining if a patient has ET or not. Proponents of the use of gyroscopes claim that accelerometers signals are not as effective in measuring tremor because in addition to lateral displacements they inadvertently measure rotational motion as an accelerometer is being rotated through the gravity field [16]. Gyroscopes, in contrast, only measure rotational motion without any lateral motion components. A further difficulty arises when determining along which axis to mount inertial sensors since tremor motion is...
generally not as prevalent in every direction for which measurements can take place.

The analysis presented in this paper attempts to address some of these difficulties. For the research carried out, one tri-axial microelectromechanical system (MEMS) accelerometer and three perpendicularly positioned MEMS gyroscope were used to gather the data; both sets of three inertial sensors had coincident axes. Analysis of which axes contained the largest tremor components and which of the two inertial sensor types could more adequately assess ET is carried out utilizing Fourier based techniques.

As well, inertial sensor signals are analyzed using wavelet based analysis. The motivations behind using wavelets are as follows:

- Efficient multi-resolution analysis to separate the different components of the ET collected signal, which is contaminated with noise and is spread over several frequencies.
- The de-noising power of wavelets to separate the noise of the different MEMS sensors from the target signal corresponding to ET
- The localization power, which helps in the localization of different singularities and sudden movements expected in the ET data (especially in severe cases)

Wavelets have been used for this application by other researchers, but this paper is one of the first to thoroughly analyze the role of three measurement axes for both accelerometer and gyroscope signals; most research carried out tends to use accelerometers only [10, 17]. One work utilized wavelets to extract features from accelerometer signals; these features were then input into an artificial neural network to determine if a patient was afflicted with essential tremor or another movement disorder [10]. Another paper utilized a similar approach with wavelets as part of a set of tools (among others including bispectrum and empirical mode decomposition based techniques) to diagnose essential tremor from acceleration information [17].

2. Data Collection

2.1 Test Subjects

The subjects utilized for the research carried out had all been previously diagnosed with ET; 7 patients took part (5 males, 2 females) with a mean age of 66 (SD ±17.8). As well, 9 controls (4 males, 5 females) who had not been diagnosed with a movement disorder also participated, they had a mean age of 64 (SD ±15.7). All volunteers provided their signed consent. Approval for the project had been granted by the Conjoint Health Research Ethics Board at the University of Calgary. Exclusion criteria for all participants included presence of significant Parkinson’s like symptoms (such as bradykinesia, postural instability or rigidity), significant cognitive impairment and patients under the age of 21. Two of the ET patients were taking movement disorder related medication. One (female aged 62) was prescribed apomethazolamide but reported that the medication was largely ineffective. Another patient (male aged 84) was taking divalproex to treat myoclonus in his back. Upon evaluation, both patients produced motion characteristics largely consistent with the other ET patients in the study.

2.2 Equipment

The tri-axial accelerometer used to gather the data was a LIS3L06AL MEMS inertial sensor; the manufacturer is ST Microelectronics [18]. Each of the three individual gyroscopes used (to form a tri-axial sensor) were XV-8100CB MEMS inertial sensors; the manufacturer is Epson Toyocom [19]. Both sets of sensors were mounted within a casing and were powered by two 1.2 volt batteries. The data acquisition system, termed inertial measurement unit (IMU), was assembled by the Mobile Multi-Sensor Systems (MMSS) research group in the Department of Geomatics Engineering at the University of Calgary. The acquisition system utilized an analog to digital converter with no on board filtering of data and stored inertial and time series information on a universal serial bus (USB) compatible device for download onto a personal computer after acquisition. The self contained data acquisition device is shown in Figure 1 with x, y and z sensor axes labeled. Both accelerometer and gyroscope sensors were calibrated for bias and scale factor errors. Data were logged at 130 Hz.

2.3 Experimental Procedure

The experimental procedure chosen was chiefly designed to analyze whether a standard computer based test could be implemented as part of the diagnostic criteria for an essential tremor patient. One of the main goals of the test is to have a patient’s hand unconstrained such that tremor motion would be captured by the IMU. A previous test involving the use of a computer mouse for a similar purpose did not provide high quality data because of the ability of patients to rest their arm (i.e. constrain arm motion) on surface over which they were moving the computer mouse; consequently much of the data captured utilizing a computer mouse did not exhibit the degree of tremor motion that was clearly present in the otherwise unconstrained motion of a given test subject.

Before testing, subjects were seated and asked to position their chair at an appropriate distance from the computer screen so that when their arm was fully outstretched and touching the table directly below the screen they would be in an upright seated position, as depicted in the top image of Figure 1. This was done to standardize the distance of test subjects from the computer screen so that their arm would be partially bent at the elbow when data were being gathered. During data
collection, test subjects would be asked to lift the IMU (with a laser mounted on top) out of a holster and move between ten successive rectangular figures randomly positioned on the computer screen (labeled “Click 1” through “Click 10”) by using the laser as a pointing device. Patients would utilize an IMU pushbutton under their thumb to perform a click when targeting an appropriately labeled figure. At the end of the testing procedure, test subjects would seat the IMU back inside the holster. They were also instructed to keep their hand roughly 20 cm from the computer screen whilst moving between successive clicks; rulers protruding from the screen helped them to gauge this distance appropriately as shown in the bottom image of Figure 1. Instructions were given to balance speed and accuracy whilst performing the task defined and to attempt to click when the laser was directed in the middle of each of the rectangular figures displayed on the computer screen. This procedure was repeated ten times for each subject with different random clicking patterns displayed on the computer screen each time.

Figure 1. A test subject before (top) and during (bottom) testing; the axes of orientation for the inertial sensors are shown in the bottom right hand corner of the top image with \( x \) pointing towards the test subject’s right and \( z \) pointing downwards.

3. Data Analysis

3.1 Fourier Based Analysis

The data gathered from test subjects were three accelerometer signals, three gyroscope signals and a corresponding time series. From each of the six signals depicting motion, a corresponding power spectral density estimate is obtained. Before spectrums can be calculated, each signal is band pass filtered between 1 Hz and 30 Hz to eliminate unwanted low frequency data as well as high frequency sensor induced noise. The low end of the passband (1 Hz) was chosen because, given the literature, anything below 3 Hz is very unlikely to be essential tremor data and therefore 1 Hz was a reasonable choice to allow room for unwanted but unavoidable filter distortions [8]. The high end of this passband (30 Hz) was chosen as double to maximum tremor frequency likely to be associated with essential tremor (15 Hz) to avoid signal aliasing [8]. In practice, it is unlikely to see tremor at 15 Hz given the age of the patients that were taking part in this evaluation so this passband criteria was conservative in terms of preserving tremor motion data. The filtering was carried out by employing a 2nd order Butterworth filter.

The analysis methodology used to determine power spectrums is given in detail by Halliday et al. [20]; it was also presented in Aly et al. for analysis of Parkinson’s tremor data [21]. This methodology involved dividing each signal, \( s(t) \), under examination into non-overlapping segments of equal length \( T = 128 \). A total of \( L \) segments were realized after data from each of the ten trials per test subject were segmented in this manner. A discrete Fourier transform, \( d^T_s(\omega, l) \), was applied to each signal segment \( l \) (\( l = 1, \ldots, L \)) at frequency \( \omega \). The power spectral density estimate, \( \hat{f}^s_s(\omega) \), was found by averaging over the \( L \) sections as follows

\[
\hat{f}^s_s(\omega) = \frac{1}{2\pi LT} \sum_{l=1}^{L} |d^T_s(\omega, l)|^2
\]

This averaging methodology was employed so that all data from the ten trials for all test subjects would be represented within the same power spectrum.

3.2 Wavelet Based Analysis

Unlike the Fourier based analysis, which represents the average frequency content of the data analyzed for all patients, wavelet based analysis is applied to signals one at a time and studied in more detail to determine decipherable patterns in the data; this approach is taken because of wavelet time frequency localization properties. For the analysis carried out, the continuous wavelet transform was employed, as opposed to the discrete wavelet transform, to allow for a more information rich display of the signal with full time resolution. For a signal \( q(x) \), the continuous wavelet transform is found utilizing
the inner product of the signal sequence with the mother wavelet analyzing function $\psi(x)$ (whose complex conjugate is $\bar{\psi}(x)$) [23]

$$Q_w(m, x_n) = \frac{1}{m} \int_{-\infty}^{\infty} q(x) \bar{\psi}\left(\frac{x - x_n}{m}\right) dx$$ (2)

The wavelet scaling is controlled by $m$ (to adjust the mother wavelet’s size so the appropriate frequency band can be analyzed). Localization is performed using the shifting parameter $x_n$, which allows the analysis to be applied along different signal portions.

The mother wavelet function is generally chosen to be short and oscillatory so that frequency can be localized appropriately. A coiflets wavelet of order three, as shown in Figure 2, was chosen for the analysis performed because it is matches well with the signal observed since both tend to have a smooth oscillatory nature.

4. Results

The analysis is divided into two parts: “Fourier Based Analysis” and “Wavelet Based Analysis”. The former displays average results of all essential tremor or control test subjects and the latter displays selected representative samples and draws inferences from the results. By applying both methodological approaches, a lot of insight into essential tremor and control motion can be gained.

4.1 Fourier Based Analysis

Figure 3 shows the average population spectra for the accelerometer data and the gyroscope data (averaged overall all test subjects). ET patient data are shown with dashed lines and control data are shown with solid lines. From Figure 3, it can be seen that the peaks in the ET spectra tend to be consistently between 4 and 6 Hz. Note also that the magnitude between ET and control spectral frequencies is somewhat similar for all plots in the region where spectral divergence is greatest (4-6 Hz). These observations tend to suggest that frequencies of motion characteristics are consistent for all axes of motion and for both lateral displacement and rotational motion. This is quite significant for ET researchers because it tends to imply that either sensor type mounted along any axis can generate relevant spectral information.

As well, note that the largest ET spectral magnitude for accelerometers was in the x-direction and the largest ET spectral magnitude for gyroscopes was in the y-direction. This suggests that even though spectral frequency characteristics are similar for different axes, their absolute magnitude can vary significantly. It is important to point out that absolute spectral magnitudes, when comparing processed accelerometer data to processed gyroscope data, differ significantly due to the different units in which the two data sets were logged (m/s^2 versus deg/s respectively).

4.2 Wavelet Based Analysis

The wavelet analysis displayed is only shown here for a few representative samples for sake of brevity. In Figure 4, the wavelet analyses of the x accelerometer signal for a control and essential tremor patient are shown for one trial. The frequencies displayed in the figure are based on pseudo frequencies converted from wavelet scales and for this reason the frequencies axes are non-linearly displayed in the plots with non-whole number terms (i.e. 70.6 and 7.8 instead of 71 and 8).

It is important to point out that the raw signals shown in Figure 4 were not filtered and so large signal spikes can be seen at the beginning and end of trials when test subjects inadvertently hit the IMU on the holster during data collection. As well, accelerometers are sensitive to gravity and this accounts for much of the drifting low frequency signal components, which occur as the IMU is rotated with respect to gravity (this is particularly evident in the raw signal captured from the control).

Looking at the (pseudo) frequencies of interest (4-12 Hz, especially the lower end of this range given what is depicted in Figure 3) it is clear that the essential tremor patient produces a lot more frequency content at frequencies of interest based on the scalogram which displays signal energy content (more energy content is displayed in the scalogram as a more white and less black display). This is exactly what should be expected given the literature and the results from the Fourier based analysis. What is not expected is the pulsating nature of the frequency content. It is quite clear that as time passes the amount of signal energy at any given frequency seems to increase and decrease in a somewhat oscillatory manner. These oscillations of signal energy seem to occur at all frequencies displayed, albeit with different periods of oscillation. This is quite relevant because it suggests the both controls and essential tremor patients have a non-constant frequency spectrum.

Another important point is that other than the frequencies of interest (4-12 Hz) both control and essential tremor patient seem to have very similar frequency content. This seems to suggest tremor motion is
Figure 3. Population spectra (averaged over all test subjects) for accelerometer and gyroscope signals (the dashed line represents spectra for ET patients and the solid line for controls).

As was the case for accelerometer wavelet plots, both the gyroscope plots seem to depict similar patterns of motion for the control and essential tremor patient; albeit the control does not depict the same frequency content at the frequencies of interest (4-12 Hz).

superimposed on what is otherwise quite normal lower frequency of motion components.

The wavelet analysis carried out for two representative gyroscope signals is shown in Figure 5. The results mirror much of what was found in Figure 4.

The pattern for the frequency content information is very similar when comparing the gyroscope data with the accelerometer data. This further seems to verify what was found in Figure 3; that any sensor aligned along any axis of motion seems to pick up similar frequency of motion information.
5. Conclusion

The results presented could open doors for future ET research. Accelerometers and gyroscopes seem to depict similar frequency information regardless of which axes of motion they were monitoring. As well, the pattern of motion depicted from signals for each of the two sensor types seemed to be quite similar based on the analysis of wavelet scalograms. This tends to suggest only one inertial sensor may be necessary for evaluating ET in some circumstances, such as when monitoring the efficacy of treatments. Previous research has highlighted the use of accelerometers as part of a larger set of tools used when diagnosing ET. Given what is presented here, single sensor systems (either an accelerometer or gyroscope) could be used substantially for this type of work. By avoiding multi-sensor systems and associated data acquisition equipment, researchers avoid costs and complications arising from capturing and analyzing multiple signals.

Another interesting result was that the pattern of motion found when comparing wavelet scalograms seemed to suggest that the motion of an ET patient was the same as the motion of a control except for tremor frequency components. This tends to suggest that underlying neurological motor function is not impacted by essential tremor outside of motion related to the frequency of tremor. In future work, correlations of the scalograms from essential tremor patients and controls will be compared at different frequency bands to determine the similarity between the two motion profiles.

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