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A Comparitive Study on Performance Analysis of Sun-Salutation Using Fast Fourier Transform, Wavelet Transform and Hilbert-Huang Transform

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Abstract. Most exercises contain repetitive movements that have to be done with perfection to derive maximum benefits. Performance analysis is quantified using the concepts of Grace and Consistency. Grace is the ability of a person to perform exercises smoothly without jerks and to restrict his body only to the plane of action during an exercise. Consistency is the measure of repeatability of an exercise in every cycle of its performance. In this study, an extensive comparison of various signal processing techniques - the Fast Fourier Transform (FFT), the Wavelet Transform (WT) and the Hilbert-Huang Transform (HHT) have been performed in order to find out the best technique for analyzing non linear, non stationary signals. A yogic exercise called Sun Salutation is considered in the study. Sun Salutation or 'Suryanamaskar' is a sequence of 10 postures in a dynamically linked series. Body mounted Inertial Measurement Unit (IMU) at the center of gravity of the body is used for motion analysis. The method finally suggested in this study can be extended to the analysis of any bio-mechanical performance and their corresponding real time signals.

Key Words: Grace, Consistency, Hilbert-Huang Transform, Wavelet Transform, Sun Salutation, Correlation Coefficients

1. Introduction

Biomechanical signal processing helps to analyze body movements and provides us with a greater understanding of the performance of any activity pertaining to human body motion. An effective method of obtaining biomechanical signals for analysis is by using Inertial Measurement Units (IMU), which is a combination of accelerometers and gyroscopes, mounted on various parts of the human body. A majority of the signals obtained through body motion analysis have been shown to be both nonlinear and non stationary [1]. However, many of the methods employed in the field of biomechanical signal processing are still based on rather simplistic assumptions about the linearity and stationarity of the underlying processes, thus using Fourier [2] and Wavelet [3] analysis. Due to this reason, the analysis of biomechanical signals using these methods does not give accurate results. Therefore, the motivation behind this study is to provide an accurate and economical solution in order to analyze the kinematics in a vast range of movements of the human body. This is achieved using the Hilbert Huang Transform [4] (HHT), which is a powerful tool in analyzing nonlinear data, as it relies on adaptive basis functions, and gives frequency information at every instant of time.

The data needed for the analysis is commonly acquired using body mounted Inertial Measurement Units [5,6,7] (IMU's) or optical motion analysis [5]. However, optical methods of analysis have their own disadvantages[5] which make IMU's a better option. The introduction of economical and miniaturized IMU's which comprise of accelerometers, magnetometers and gyroscopes, have been shown to be promising [7-10]. In dynamic situations, magnetometers provide orientation data and using this data, combined with the data provided by the accelerometer, the kinematic and gravitational components of acceleration could be separated with respect to body frame [11]. Due to their low cost and minute size they present a practical system for a wide range of applications such as biomechanical analysis of human motion[7, 9, 12]

[+] Corresponding author. *Email:* badrinarayananjamdarkhana@gmail.com. *Ph* : 001-9198028922 ergonomics and navigation [13].

The data obtained from the IMU consists of accelerations, angles, and rate of change of angles in the three axes and might not suggest any conclusive results to the naked eye, hence they have to be processed to obtain meaningful and relevant information. The processing of the IMU data has traditionally been done using Fourier analysis which uses stationary sines and cosines as basis functions; and Wavelet analysis, which uses window based methods. However, since the IMU data is nonlinear, a more suitable method to process and obtain meaningful information from it is by using HHT.

Many exercises consist of repetitive movements and cycles, and there may be a need to analyze the performance of such exercises. The two parameters used in this analysis are grace and consistency. Grace is defined as smoothness of execution, without any unwanted sudden movement or jerk. Consistency is defined as the ability of a person to repeat his performance of an exercise in exactly the same way in every cycle of the exercise, with minimal variations. In this study, we take as an example, a famous yoga practice known as Sun Salutation (Figure 1), which is a biomechanical procedure that consists of ten subtly powerful postures set in a dynamic form performed in a single, conscious, graceful flow. The reason for choosing Sun Salutation in particular is that the postures are an ingenious amalgamation of a huge diversity of postures, which includes forward bending poses countered with backward bending ones. Also, Sun Salutation does not need any gadgets or equipments and can be done in a limited frame of time and space. The results obtained by analysing sun salutation can be extended to any general biomechanical procedure or activity.

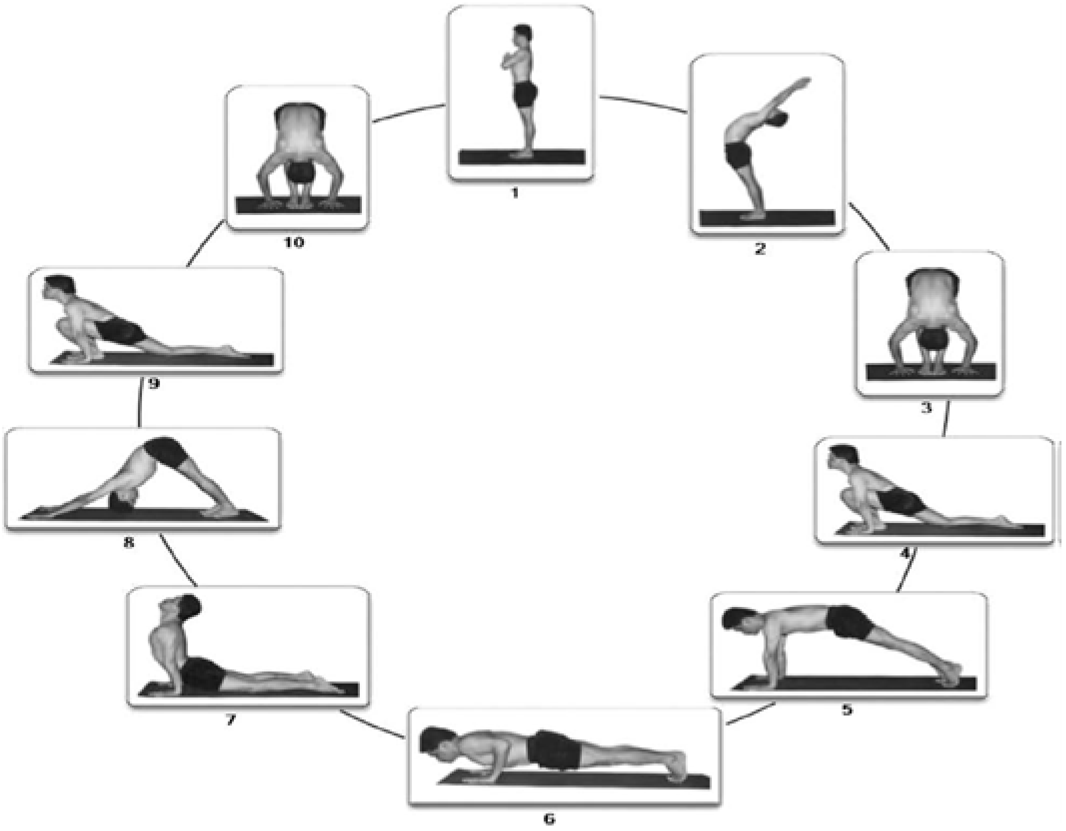

Figure 1: Ten different postures of Sun Salutation

The main objective of this study is to provide a framework to quantify grace and consistency for any exercise with repetitive movements. This is done by applying HHT to the IMU data, which is obtained while performing the exercises. In addition to this, a comparative analysis of the IMU data is done using three signal processing techniques - Fast Fourier Transform [2] (FFT), Continuous Wavelet Transform [3] (CWT) and HHT. The analysis includes the quantification of grace and consistency by using the aforementioned techniques, and thereby showing that HHT is the most suitable method to analyze biomechanical signals. Also included in this study, is the criterion for selecting and distinguishing the relevant IMFs from the IMF's that have been generated due to numerical errors, in the HHT analysis, which is done with the help of correlation coefficients. This increases the accuracy of the results obtained to a great extent. To verify the credibility of information obtained through HHT, the age old yoga technique of Sun Salutation has been used as an example in the analysis. This study, thus, contributes towards formulating a generalized methodology using HHT, to analyze exercises which contain repetitive movements, and hence create a framework to extend these results to other biomechanical signals. The information obtained after processing the data using HHT is very useful and finds its application in various fields of biomechanics such as performance analysis of athletes, finding remedies for body ailments etc.

1.1. Data Analysis

Fast Fourier Transform:

The Fourier Transform [14, 15] is a mathematical operation that gives a signal's constituent frequencies i.e. transforms the signal to its frequency domain representation. Fourier Transform is suitable for linear and stationary signals. The DFT & the IDFT is defined by the respective formula:

$$X_k = \sum_{n=0}^{N-1} x_n . e^{-i2\pi k \frac{n}{N}} \qquad k = 0,...,N-1 \tag{1}$$

$$x_n = \frac{1}{N}\sum_{k=0}^{N-1} X_k . e^{2\pi i k \frac{n}{N}} \qquad n = 0,...,N-1 \tag{2}$$

where

x_n is the sampled original data which is a sequence of N complex numbers.

X_k represent the amplitude and phase of the different sinusoidal components of xn

k/N indicates the frequency in cycles per sample

FFT finds its applications in audio processing including noise cancellation filters using LMS algorithm [16] and data compression [17].

Short Time Fourier Transform:

The Short-Time Fourier Transform (STFT), is a Fourier-related transform used to determine the sinusoidal frequency and phase content of local sections of a signal as it changes over time.

In the continuous-time case, the function to be transformed is multiplied by a window function which is nonzero for only a short period of time. The FT of the resulting signal is taken as the window and slid along the time axis, resulting in a two-dimensional representation of the signal.

It is mathematically represented as,

$$STFT\{x(t)\} = X(\mathrm{T}, w) = \int_{-\infty}^{\infty} x(t) w(t-T) e^{-jwt} dt \tag{3}$$

where,

w(t) - window function, commonly a Hann window or Gaussian "hill" centered around zero

x(t) - signal to be transformed

X(T,ω) - FT of x(t)w(t-T), a complex function representing the phase and magnitude of the signal over time and frequency.

Continuous Wavelet Transform (CWT):

In wavelet analysis, the signal is multiplied with a function, wavelet, similar to the window function in the STFT, and the transform is computed separately for different segments of the time-domain signal. However, there are two main differences between the STFT and the CWT:

1. The Fourier transforms of the windowed signals are not taken, and therefore single peak will be seen corresponding to a sinusoid, i.e., negative frequencies are not computed.

2. The width of the window is changed as the transform is computed for every single spectral component, which is probably the most significant characteristic of the wavelet transform.

CWT [4,18,19] can be defined as below:

$$CWT_x^{\psi}(T,s) = \psi_x^{\psi}(T,s) = \frac{1}{\sqrt{|s|}} \int x(t) \psi^* \left(\frac{t-T}{s} \right) dt \tag{4}$$

where,

s is initialised as ‘1’

x(t) - signal to be analysed

ψ - mother wavelet

t – time taken

T – tau i.e. a specific instant of time when ‘s’ is shifted to the right

Wavelet analysis is suitable for linear, non stationary signals. WT [19, 20] finds its use in applications such as image compression [21] and water marking [22].

Hilbert – Huang Transform (HHT):

Many naturally occurring signals that we come across are nonlinear and non-stationary in nature. These signals have to be analyzed at every instant of time to obtain meaningful information from them. HHT [28] is one such technique which separates the signal into intrinsic mode functions of decreasing order of frequencies. HHT finds its applications in fields such as vibration analysis in machine health monitoring [23], ultrasonic flaws in pipelines [24], texture analysis [25], speech enhancement [26], Chinese font recognition [27] etc.

HHT is done in two steps:

(1) Empirical Mode Decomposition (EMD) method to decompose a signal into smaller intrinsic mode function,

(2) Hilbert Spectral Analysis (HSA) method is used to obtain instantaneous frequency data.

Using EMD a complicated data set is broken down into smaller and finite number of components called IMFs to which HSA is then applied. Choosing the relevant IMFs[31] proves to be extremely essential in the processing of the desired data.

How to choose relevant IMFs:

In HHT, selection of relevant IMFs [31] is done on the basis of correlation coefficients. Since the IMFs are supposed to be more or less the orthogonal components of the original signal, each IMF would have a relatively good correlation with the original signal; hence the irrelevant components would have relatively poor correlation with the original signal. Therefore, a threshold, λ, is introduced, as

$$\lambda = [\max(\mu_i)] / 10, \quad i = 1, 2, \ldots, n, \tag{5}$$

where,

μi - correlation coefficient of the ith IMF with the original signal

n - total number of IMFs

max(μi) - maximum correlation coefficient observed.

Only if $\mu i > \lambda$, we retain that IMF, or else we add that IMF to the residue. This ensures that all the irrelevant IMFs that do not contain any meaningful information are not included in the analysis. A more stringent threshold is given by:

$$\mu_{TH} = \max(\mu_i) / [\, (10 \times \max(\mu_i)) - 3 \,], \qquad i = 1, 2, \ldots, n, \tag{6}$$

where,

μTH - threshold

μi - correlation coefficient of the ithIMF with the original signal

n - total number of IMF’s

max(μi) - maximum correlation coefficient observed.

1.2. Axis System

While studying the motion analysis of the body during Sun Salutation, three axes of movement are identified. The three axes are shown in Figure 2.

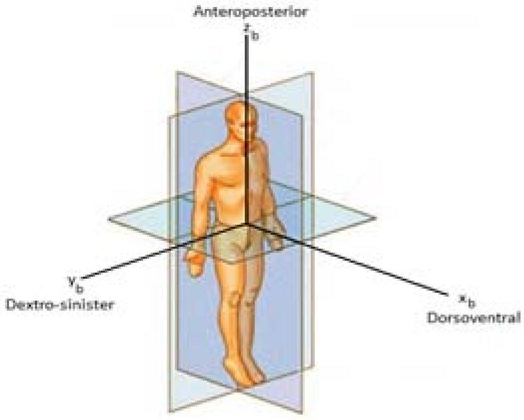

Figure 2: Human Model showing the body axes

Sun Salutation [30] primarily consists of rotation of the body segments about the yb axis. For sun salutation to be graceful the rotation about yb has to be as smooth as possible. This implies that the kinematic accelerations along the x and z axes have to be minimum. These accelerations and change of angles about the axes (roll, pitch and yaw) are used to quantify grace of performance for each subject. Rotation about dextro-sinister axis is measured by pitch, rotation about dorso-ventral axis is measured by roll and that about antero-posterior axis by yaw. A subject might perform gracefully in one cycle and his performance might not be graceful in another. Even if a person has the ability to execute an exercise with grace he might not be able to repeat it in every cycle with the same precision. The consistency of a person is quantified by observing the variance of grace from cycle to cycle.

As the subjects perform the cycles of Sun Salutation (Figure 1), the angles and angular rates about the three axes together with the linear accelerations along the three axes are recorded in real time. From the data obtained, the gravitational and kinematic components of acceleration were separated [11]. The readings thus obtained after removing the gravitational component is referred to as kinematic acceleration i.e., the acceleration due to the body movements.

Analysis of Non Stationary Signal:

Consider a hypothetical exercise whose ideal output is a ‘non stationary’ signal X which is given as:

x1 = sin(2*pi*10*t) for t = 1:100

x2 = sin(2*pi*20*t) for t = 101:200

x3 = sin(2*pi*40*t) for t = 201:300

x4 = sin(2*pi*30*t) for t = 301:400

X = x1+x2+x3+x4;

Assume a subject performs the exercise and his data is analyzed using FFT, HHT and WT independently. Figure 3 shows the frequency domain representation of signal X, after performing the three transforms. It can be noticed that frequency information at any desirable instant of time for the signal X cannot be obtained in FFT; also the frequency resolution is fixed. An improvement over FFT is STFT, but here fixed window size has to be used hence obtaining a fixed resolution. Hence FFT & STFT are not suitable for the analysis of a non-linear or a non-stationary signal.

However, in WT and HHT analysis we get frequency information at every instant of time. Figure 4 depicts the colourmap images of the WT and HHT of signal X. The 4 frequency components present in signal X can be clearly observed in the figure.

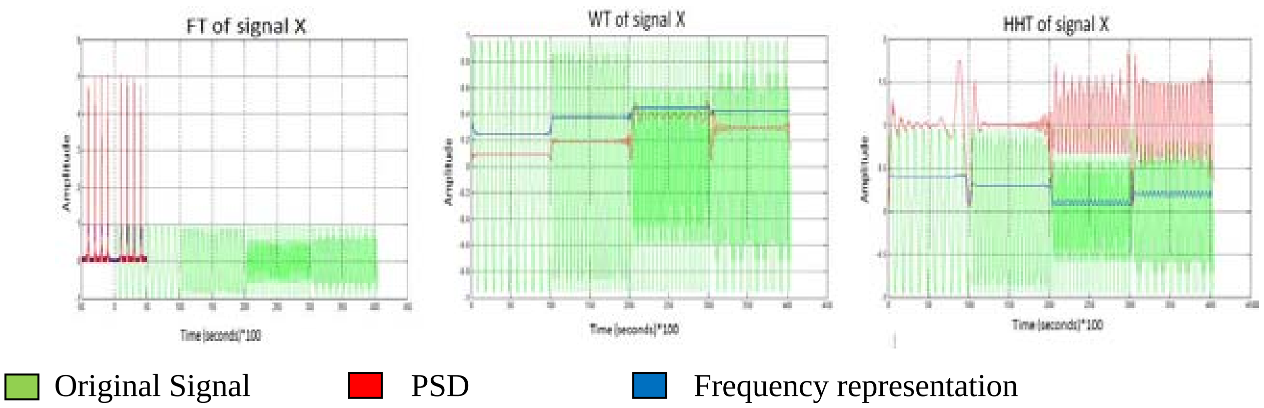

Figure 3 : The frequency domain representation of signal X

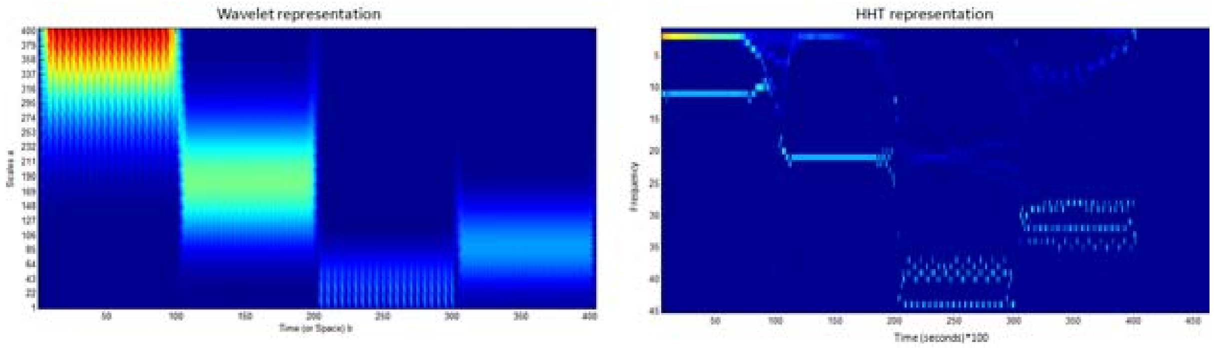

Figure 4: The colourmap of the WT and HHT of signal X

Analysis of Non Linear Signal :

Consider another hypothetical exercise whose ideal output is a ‘nonlinear’ signal Y defined as

$$Y = t + \sin(w.t)$$

which consists of 2 frequency components.

Figure 5 does a comparison between the WT and HHT of this nonlinear signal. The energy distributed at different frequency components is observed, and it is seen that only HHT clearly indicates the presence of different frequency components, whereas the energy spectrum of WT does not.

Also, from Figure 6 it is inferred that the HHT representation has a better correlation with the original signal (which in this case is a random noisy signal) than what is observed with the WT representation. This is mainly due to the reason that HHT is based on differentiation, and therefore will easily follow the sharp changes in the signal in comparison to WT which is convolution based (linear model imposition).

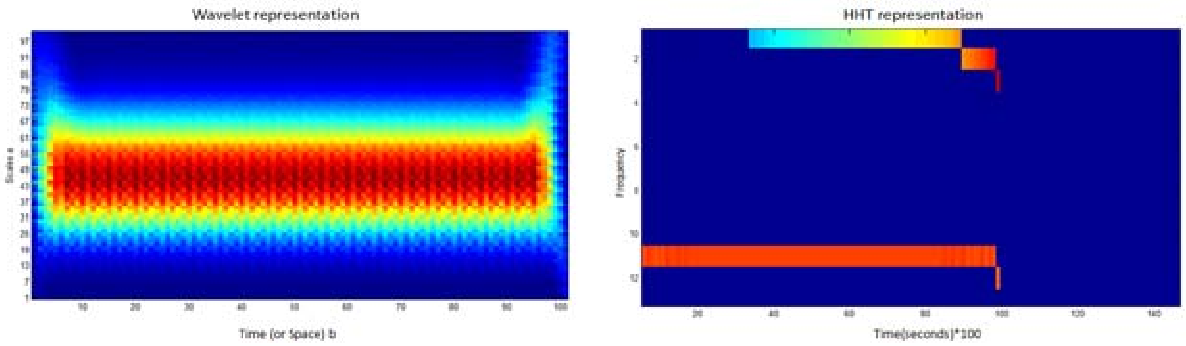

Figure 5: WT and HHT representation for signal Y

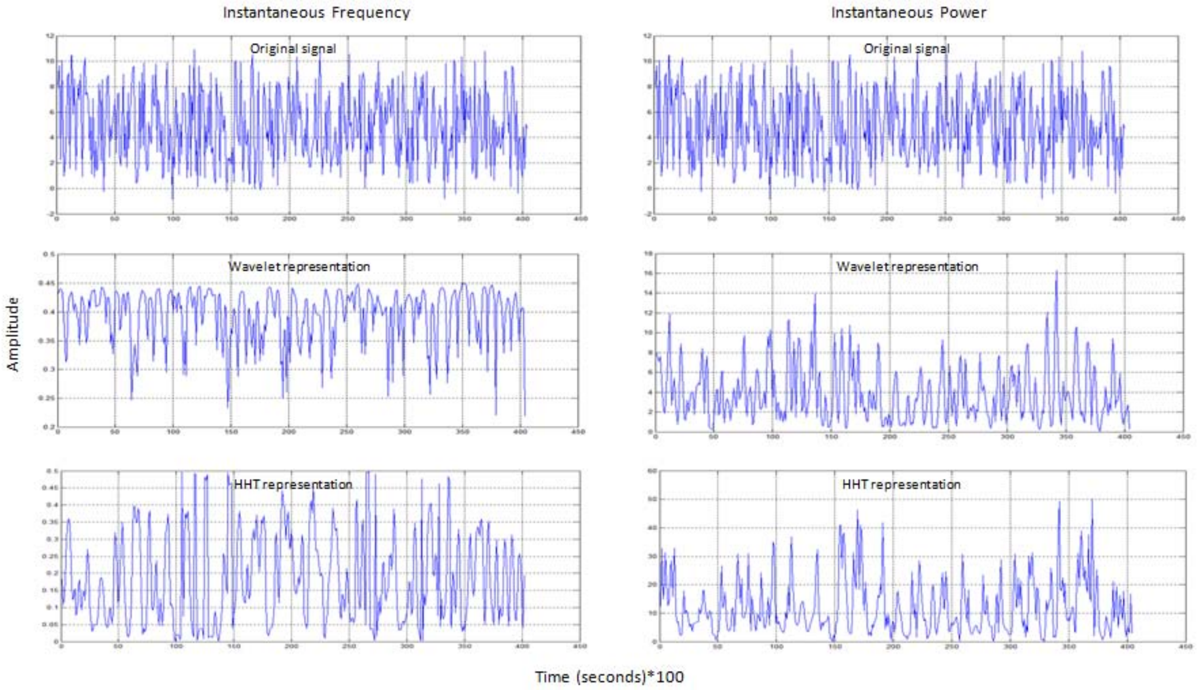

Figure 6: HHT and WT comparison of a random noisy signal

From these comparisons one can note that WT cannot be used to process nonlinear signals, and HHT is a better option. Since most bio-mechanical signals are non-linear in nature, HHT should be used for their analysis.

2. Methods And Procedure

For quantifying grace and consistency during Sun Salutation, an IMU is used to record the human body motion. Subsequent analysis of the data obtained is done using FFT, CWT and HHT.

Equipment: The IMU - MicroStrain 3DM-GX1, is used for analyzing grace and consistency of Sun Salutation. This device combines three angular rate gyros with three orthogonal DC accelerometers, three orthogonal magnetometers, multiplexer, 16 bit A/D converter, and an embedded microcontroller with output orientation in dynamic and static environments, with a sampling frequency of 70 Hz.

Experiment: Nine asymptomatic subjects of both genders (5 males and 4 females), between 25-39 years of age volunteered for this study. The place of attachment of the IMU on the human body is an important issue. Arrangements were made to make sure that the device on the human body didn’t cause any disturbance while performing Sun Salutation. The device was attached at the trunk (second lumbar vertebra) as this segment represents the centre of gravity (CG) of total body mass. The data was recorded directly on the computer with the help of the software provided with the IMU. Detailed instructions of the tests were given to all the subjects and each subject was given a few practice runs. Each subject performed 12 cycles of Sun Salutation with the device attached at the second lumbar vertebra.

3. Results And Discussions

Analysis of Sun Salutation:

Boxplots are used to represent performance analysis in the study for an easy understanding of the readers. Boxplots produce a box and whisker plot for each subject. The box has lines at the lower quartile, median, and upper quartile values. Whiskers extend from each end of the box to the adjacent values in the data, the most extreme values within 1.5 times the interquartile range from the ends of the box. Outliers are data with values beyond the ends of the whiskers. Outliers are displayed with a + sign.

Analysis using FFT:

Figure 7 shows the PSDs of the accelerations along the x, y and z axis respectively. The PSDs show all the frequency components present in the signal, but do not give any information about the time at which each frequency occurs. Hence, we do not obtain any information about the instants at which the jerks occur.

Therefore, we cannot perform a thorough comparison of the performances of the subjects. Also, since FFT analysis is a linear model imposition on nonlinear data, there is loss of information.

For these reasons, FFT analysis is not a good choice for the analysis of the data obtained from the IMU.

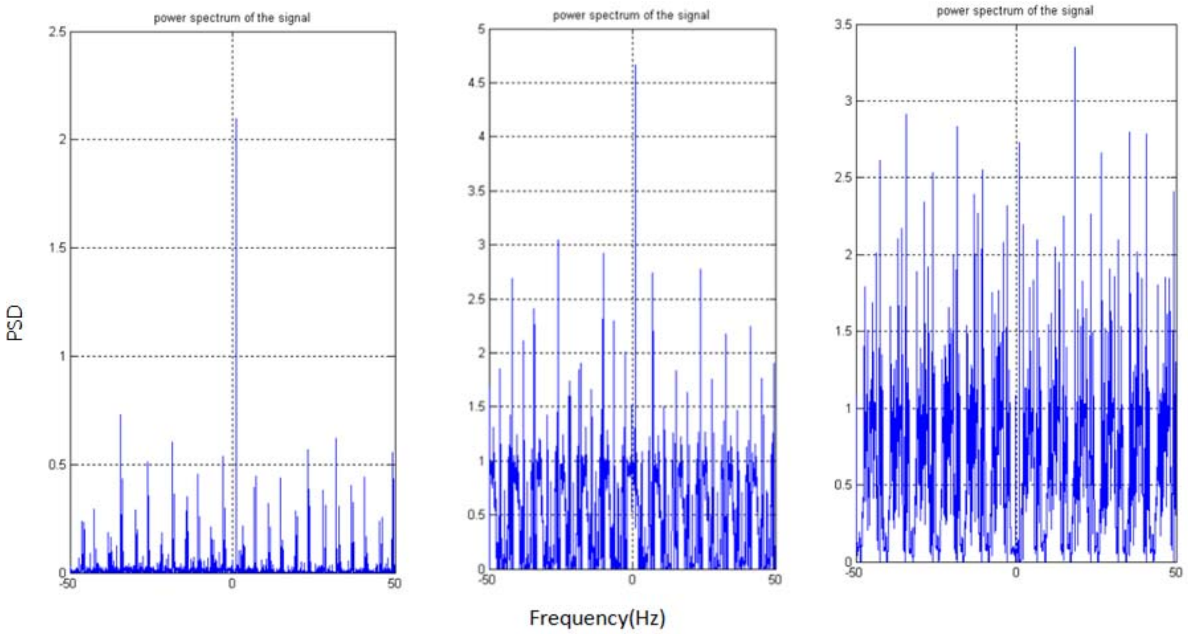

Figure7: PSDs of accelerations along x, y and z axis respectively

Analysis using HHT:

Figure 8 shows Instantaneous frequency and power spectrum of accelerations along x-axis and z-axis after removing acceleration due to gravity, for 3 cycles of sun salutation. The main use of power spectrum is to separate each cycle. It is evident from Figure 8 that the end of every cycle is indicated by zero – crossings. Each posture can be demarcated by looking at plots of both the axes as movement might be in either of the axes or both.

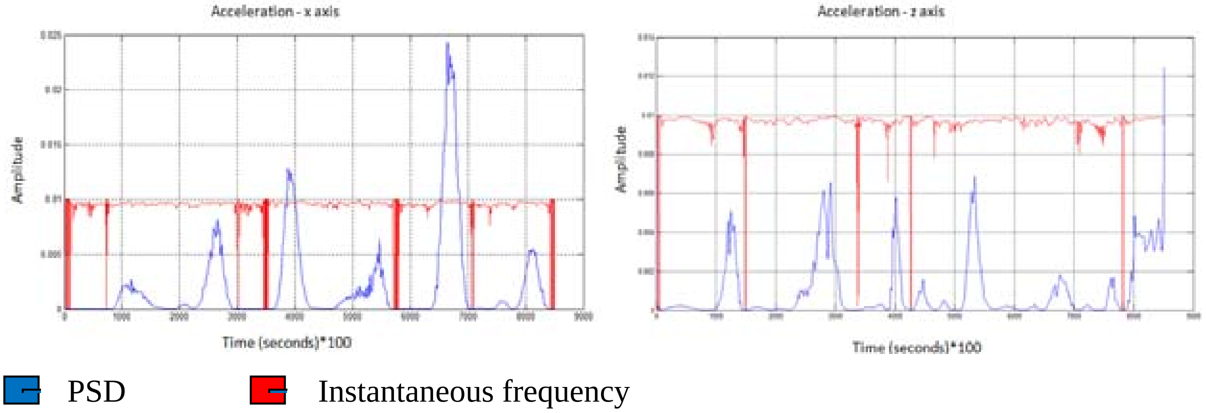

Figure 8: Instantaneous PSDs of acceleration along x and z axis using HHT

After performing the EMD process on the data, and using correlation and thresholding, the relevant IMFs were considered for performance analysis. The following figures present the box plots which compare the performance of 9 subjects after processing their corresponding data using HHT. The figures on the left (Figure 9–Figure 11) represent the boxplots of mean amplitude of acceleration and the figures on the right represent the boxplots of mean of instantaneous energy along the various axes.

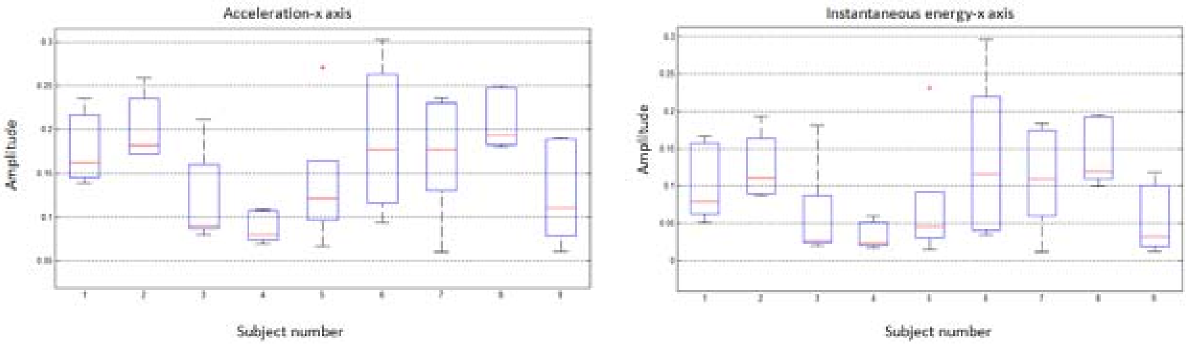

Figure 9: Analysis of acceleration along xb axis

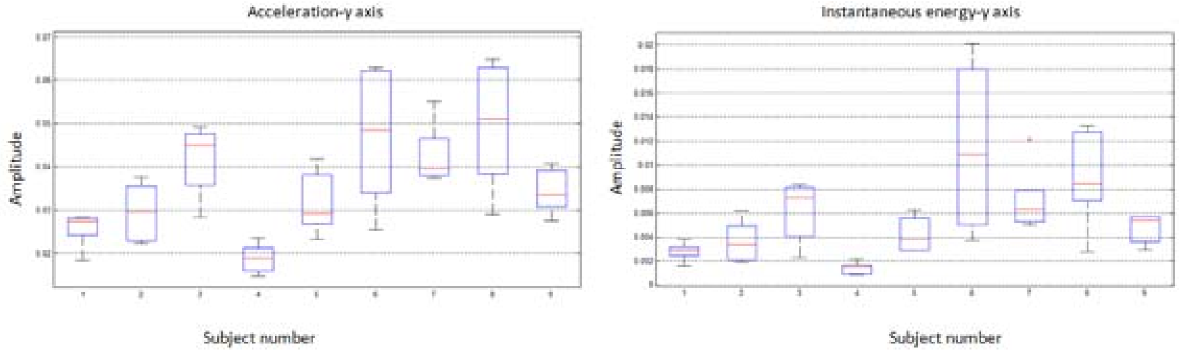

Figure 10: Analysis of acceleration along yb axis.

The subjects with the least mean amplitude and instantaneous energy have the best grace. It can be seen from the figures that a person might be graceful in one axis and might have a jerky performance in another. Variance of the Mean-Amplitude values of acceleration is used to quantify consistency. The sum of length of the box and the whiskers gives the variance.

Since subject 4 has the least mean amplitude in all 3 axes, he has the most graceful performance. Also, since subject 4 has the smallest box size, i.e. least variance, his consistency is the best.

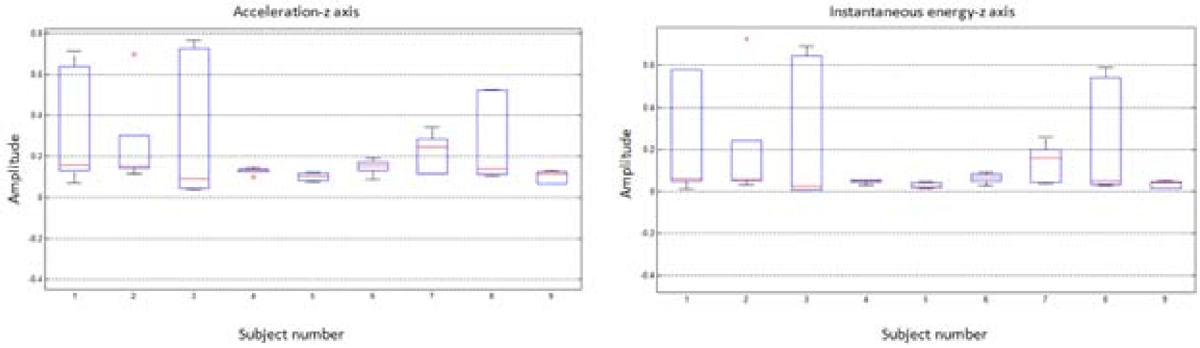

Figure 11: Analysis of acceleration along zb axis.

In all cases subject 6 was found to have very poor grace and consistency of performance and after verification with the subject, it was found that he was a neophyte in Sun Salutation. Similarly, after verification with subject 4 it was found that he had been practicing Sun Salutation for a long time. These enquiries thus verify the authenticity of the results obtained.

Analysis using WT:

Figure 12 shows the boxplots of the mean amplitude of the acceleration along x and y axis respectively, after analyzing the data using wavelet transform. The results obtained contradict with the results obtained using HHT analysis, which were confirmed with the subjects. The reason for this imperfect analysis is because WT cannot be used to analyze nonlinear data. Hence, the Hilbert Huang Transform is the most accurate method to process nonlinear – non stationary data.

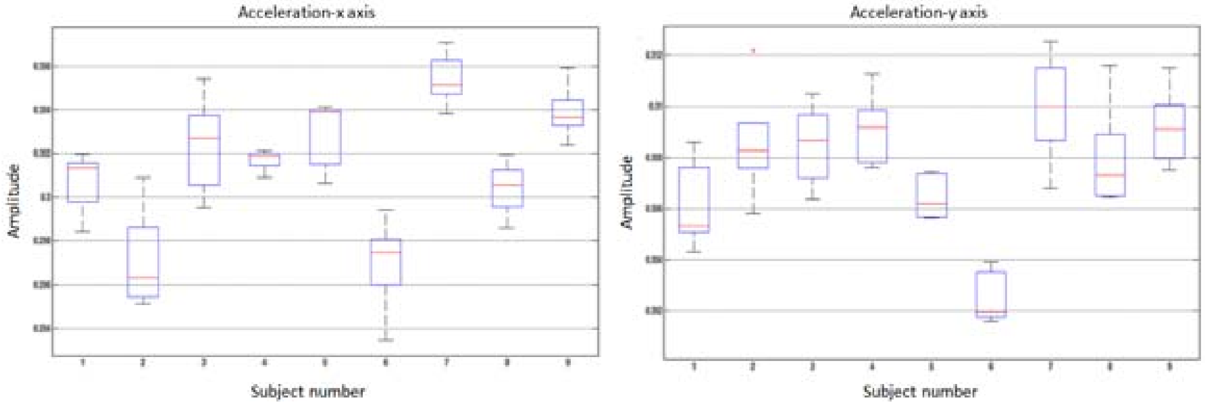

Figure 12: Boxplots of acceleration along xb and zb axis using WT

4. Conclusion

It can be inferred from the study that HHT is the most effective technique compared to FFT and WT in analyzing nonlinear and non stationary signals, such as the data commonly obtained by IMUs in biomechanical experiments. IMU’s are an accurate and efficient way of analyzing body movements and performance related aspects of body mechanics. This method of analysis using HHT can also be used by gymnasts and other sports personnel to analyze their degree of preparation and improve their performance accordingly. It can be extended to a wide range of bio – mechanical processes to identify jerks or phases of incorrect performance, and can also be used by clinicians to suggest apt remedies for their patients.

5. Acknowledgement

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