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# Time-frequency analysis of human motion during rhythmic exercises

S N Omkar, Khushi Vyas and Vikranth H N

*Abstract*— Biomechanical signals due to human movements during exercise are represented in time-frequency domain using Wigner Distribution Function (WDF). Analysis based on WDF reveals instantaneous spectral and power changes during a rhythmic exercise. Investigations were carried out on 11 healthy subjects who performed 5 cycles of sun salutation, with a body-mounted Inertial Measurement Unit (IMU) as a motion sensor. Variance of Instantaneous Frequency (I.F) and Instantaneous Power (I.P) for performance analysis of the subject is estimated using one-way ANOVA model. Results reveal that joint Time-Frequency analysis of biomechanical signals during motion facilitates a better understanding of grace and consistency during rhythmic exercise.

## I. INTRODUCTION

Accurate detection and analysis of human motion is of key interest in sports biomechanics with potential applications to rehabilitation, athlete's training and development of ubiquitous techniques for achieving better performance. Inertial sensors have proved to be very suitable to realize these applications because of their immense portability, compactness and useful, accurate movement information they supply [1],[4]. They offer an alternate way to obtain kinematic data in variety of environments. Commercially available systems combine angular rate gyroscopes, 3D accelerometers and magnetometers into a single assembly known as Inertial Measurement Unit (IMU) [5],[6]. These inertial sensors, when used as wearable devices for motion analysis, enable the measurement of acceleration signals and angular velocity in the IMU co-ordinate frame. IMU's are frequently used to assess human movements because they are small, robust and can be easily attached to human body segments. These specifications render IMU's as a highly viable solution for human motion analysis during training and competition in almost real time without affecting the athletes during motion execution.

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The method suggested in this paper uses an IMU to measure and quantify human movements during exercise. The exercise considered for this study is Sun salutation – a widely practiced yoga technique [7], [8]. Sun Salutation is a rhythmic exercise which can be performed in a limited frame of time and space. Further, it does not need any gadgets or equipments and has proved to have several clinical benefits. Hence, it is chosen for investigation in this work.

It is identified that, while performing sun salutation, the signal recorded using IMU is usually non-stationery i.e., its frequency content varies with time. For such signals, the standard Fourier Transform can evaluate only the average frequency over the entire data or part of it using window methods, but not its instantaneous frequencies (I.F.). As a result, any small jerks or halts in the motion might go unnoticed. On the other hand, Time-Frequency analysis reflects the behaviour of temporarily localised version of the signal thus enabling a deep study and better understanding of time-varying spectra [9]. However, time-Frequency based performance analysis of subjects during a rhythmic exercise using has not been adequately investigated in literature. From the past decade, wavelet transform has become one of the fast-evolving mathematical and signal processing tools. However, the distribution generates undesired small spikes all over the frequency scales and makes the results confusing and difficult to be interpreted. Wigner Distribution Function (WDF) has grown as a widely used tool for I.F. estimation of a signal with fast variations and spectral content [10]. In comparison to other time-frequency distributions like short term Fourier transform (STFT) and spectrogram, WDF facilitates a higher temporal and spectral resolution as well as facilitates faster computations.

In this paper, we demonstrate the application of WDF-powerful tool as a quadratic time-frequency signal representation, to efficiently analyze and quantify human motion during an exercise. In section II, details of the experiment illustrating the proposed method for study of human motion during sun salutation is outlined. Section III provides the mathematical formulation of WDF. By evaluating the moments and marginals of WDF for the IMU data, important features like frequency variance and instantaneous power variations are quantified. In Section IV, performance of the subjects is evaluated using one-way ANOVA model and results are presented.

## II. EXPERIMENT

### A. Participants

Eleven healthy subjects (Four females; mean±SD Age: 30±15 years, Height: 170±15 cm & Weight: 64±15kg) participated. The protocol developed for the experiment was deemed to be safe for all the subjects. The subjects gave their written consent for the active participation in the experiment.

### B. *Exercise (Sun Salutation)*

Sun Salutation consists of 10 subtly powerful postures (asanas) set in a dynamic form performed in a single, conscious, graceful flow. The asanas have been ingeniously combined with forward-bending poses countered with backward-bending ones. The ten asanas of Sun Salutation are shown in Fig. 1. These asanas are ordered so that they alternately stretch the spine backwards and forwards. When performed in the usual way, each asana is moved into with alternate inhalation and exhalation.

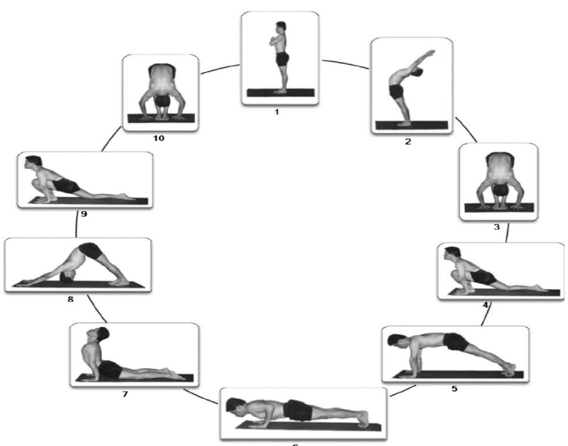


Fig.1. Ten different postures of Sun Salutation

### C. *Measurement Apparatus*

The device used for inertial sensing of motion during sun salutation is an Inertial Measurement Unit (IMU) {Micro-Strain 3DM-GX1} as shown in Fig. 2. 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. The device is calibrated for sensor misalignment and gyro G-sensitivity. IMU records the three angles together with angular rates and linear accelerations along the three axes of the sensor. In this study we consider IMU fixed axis system.

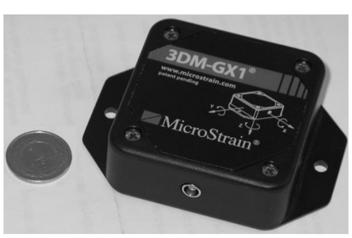


Fig. 2. Inertial Measurement Unit (IMU)

### D. *Procedure*

A total of three trials of five cycles each of sun salutation were conducted. There was a long gap between each of the three trials to ensure that muscle fatigue did not disturb the readings. A practice trial of one cycle was given to the subjects to ensure that the IMU attached to their body did not in any way affect their regular performance. The place of attachment of the device on the human body is an important issue. Since the kinematic and gravitational components of the output are dependent on the measurement location the IMU was placed at the trunk i.e. at the second vertebra [11] of the lumbar pelvic region (center of gravity) as this segment represents the major part of total body mass.

### E. *Data Acquisition*

The readings were taken using the IMU at a sampling rate of 70 Hz and stored into a computer using the software provided along with IMU. The data obtained, consists of measured accelerations and angular changes along the three axes as shown in Fig. 3. The change of angles about these three axes for human body is as follows:

Roll – Rotation about Dextrosinister axis,
Pitch – Rotation about Dorsoventral axis,
Yaw – Rotation about Anteroposterior axis

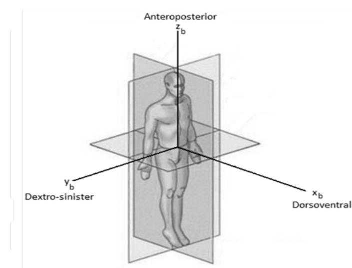


Fig. 3. Three-axes with center of gravity of human body as the origin

The measured accelerations and angles were represented as waveforms that changed continuously throughout each cycle of sun salutation. The Anteroposterior-axis and Dorsoventral-axis (Fig. 3) constitute the sagittal plane. Fig.1 indicates that all the movements during Sun Salutation are planar movements in the sagittal plane. This is evident the plotting the graph of all the measured parameters v/s. time in seconds, for one cycle of sun salutation as shown in Fig. 4.

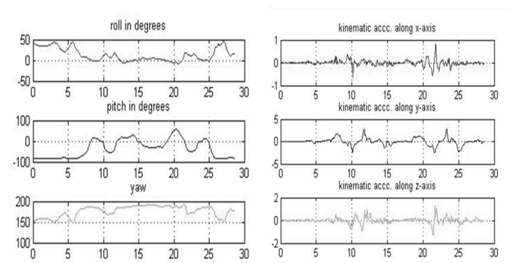


Fig. 4. Angles and kinematic accelerations for one cycle of sun salutation

We have evaluated Kinematic accelerations from measured accelerations (by removing the gravitational component) using the approach discussed in [3] and [6]. The graph presented in Fig. 4 shows changes in the angles of rotation – roll, pitch and yaw along the three orthogonal axes and variation in kinematic accelerations -along $x_b$-axis, $y_b$-axis and $z_b$-axis, respectively. The performance of a subject is regarded graceful if there are minimum jerks/halts in his/her movement in the sagittal plane and minimum movement along the Dextrosinister axis [3]. From Fig. 4, it is evident that kinematic acceleration along the Dextrosinister axis assumes finite values during the course of movement. The protocol of Sun salutation is such that some rolling and yawing action of the body is intended in posture 4 and 9 (Fig. 1). It is desired that, for a graceful performance, the movements in the sagittal plane must be performed at a constant pace with minimum halts and jerks i.e. acceleration in the sagittal plane must be minimized and the frequency variance of pitching angle must be minimal. In addition to this, roll and yaw should be as minimal as possible.

Since the recorded signal is a non-stationary and transient in nature, Fourier analysis does not adequately explain changes in the instantaneous power and spectral variations of the data of interest. For many time signals, a joint time-frequency characterization has proved to be much more useful than a simple frequency representation. With this type of characterization, it is possible to gain insight to the time-varying frequency contents of a signal. The Wigner distribution has matured as a principal representative of distributions with high spectral and temporal resolution, but suffers from limitation of cross-terms due to subcomponent interference. However, the process of reducing the interference between cross terms reduces the precision with which I.F. components are estimated. This is mainly due to the reason that filtering functions do not distinguish between signal components and interference noise. The process of removal of cross-terms also removes signal components. As a result, in this study, a preliminary application of WDF to analyze and quantify human motion during this exercise is presented without any filtering functions.

## III. DATA ANALYSIS

### A. *Wigner Distribution Function (WDF)*

Since Wigner distribution is used for the computations presented in this paper, a brief review of the Wigner distribution function is included in this subsection.

WDF is an important mathematical tool in joint time-frequency analysis [10]. WDF can be considered as local frequency spectrum of the input signal thus forming an intermediate signal description between pure time domain and pure Fourier domain.

WDF for 1-D signal x(t) is represented in time-domain as

$$W_x(t,f)=\int_{-\infty}^{\infty} x(t+\tau/2)x^*(t-\tau/2)e^{-j2\pi\tau f}d\tau \qquad (1)$$

And equivalently in Frequency domain as

$$W_x(t,f)=\int_{-\infty}^{\infty} X(f+\alpha/2)X^*(f-\alpha/2)e^{j2\pi\tau\alpha}d\alpha \qquad (2)$$

Where 't' is time, 'f' is frequency, X(f) is Fourier Transform of x(t) and X* is complex conjugate of X.

WDF possess several interesting properties like realness, finite support, time and frequency shift invariance, time-frequency marginals and Time-Frequency moments. All these properties make WDF, very suitable for our analysis.

For biomechanical signals, Instantaneous Power (I.P.) and energy spectrum are considered as desired densities of interest, over time and frequency, respectively. Likewise to analyze the frequency variance of the recorded signals, Instantaneous Frequency (I.F.) estimation becomes important. As pointed out earlier, evaluation of I.P. of kinematic acceleration in the sagittal plane and I.F. estimation of pitch is important to analyze performance of subjects during an exercise.

The marginal distribution obtained by integrating WDF over frequency variable gives a direct measure of I.P. if the univariate densities fulfill the following relation [9],[10]:

$$I.P.=\int_{-\infty}^{\infty} W(t,f)df=|x(t)|^2 \qquad (3)$$

Further, the I.F. can be recovered from the WDF as its first order moment in frequency expressed as [9],[10]:

$$I.F.=\frac{-1}{2\pi}\left(\frac{d}{dt}arg[x(t)]\right)=\frac{1}{|x(t)|^2}\int_{-\infty}^{\infty} fW(t,f)df \qquad (4)$$

We will be making use of the properties of Time-Frequency marginals and moments of WDF, to quantify the performance of each subject during an exercise.

### B. *WDF based Data Analysis*

In this paper, WDF is applied to the analysis of I.F. of 'pitch' and I.P. of kinematic accelerations in sagittal plane. Mean-amplitude of the I.P. is calculated for accelerations along $x_b$-axis and $z_b$-axis using "(3)". The subject with minimum Mean-Amplitude is considered to have the best performance. Performance analysis based on Smoothness of motion is further evaluated from the I.F. variance of pitch angle of rotation in the plane of motion using "(4)". An example of WDF based estimation of I.F. for experimentally measured pitch angle and I.P. for kinematic accelerations in sagittal plane, v/s. time (in seconds) is shown in Fig. 5.

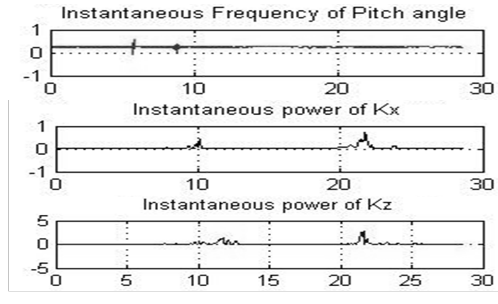


Fig. 5. Estimated I.F. and I.P. for one cycle of sun salutation

From Fig. 5, variations in I.P. of kinematic accelerations in sagittal plane and I.F. changes of pitch angle are evident. These variances of power and frequency are used to quantify performance of the subjects during exercise. The results of the investigations are presented in next section.

## IV. RESULTS AND DISCUSSION

In this study, we have quantified the performance of eleven subjects during exercise by analyzing two different parameters – I.F. variation of pitch angle, and I.P. variation of Kx and Kz (kinematic accelerations in sagittal plane). A one-way ANOVA was used to investigate statistically, the differences in these parameters of each subject. Fig. 6 presents bar plot representation for mean-I.F. changes of pitch and mean-I.P. changes of sagittal plane for eleven subjects performing 5 cycles of sun salutation. An analysis of variance of I.P. and I.F., for all cycles of sun salutation, is presented using 1-way ANOVA testing as shown in Fig. 7. Significance was set a priori at the 0.05 level and all statistical analysis was conducted on Matlab.

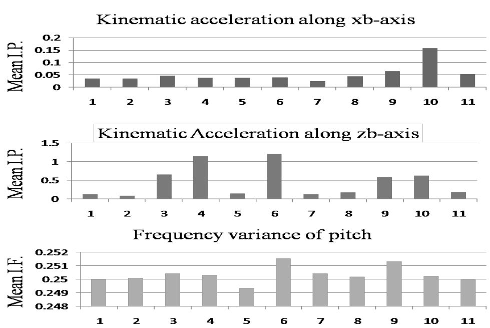


Fig. 6. Bar representation of Mean-amplitude for I.F. and I.P.

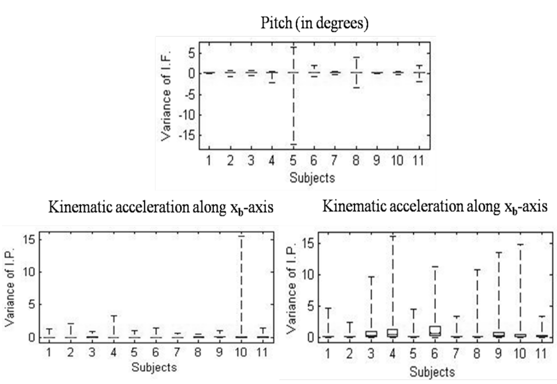


Fig. 7. Variance analysis by one-way ANOVA testing of I.F. and I.P.

From Fig. 6 it is identified that performance of subjects 6 and 10 is less graceful as the mean I.F. and mean I.P. is large. Further, it is identified that mean amplitude of I.P. for subject 7 is minimum; thereby indicating a better performance with least amounts of jerks and halts in the plane of motion. From Fig. 7 it is observed that Subjects 2 and 7 show smooth transitions from one posture to other during the exercise, thus having better performance when compared to other subjects. Experiments were conducted for eleven subjects, three trials each. Results obtained for all three trials were found to be identical.

## V. CONCLUSION

In this paper, human motion during exercise was analyzed to examine and compare performance of different subjects during a repetitive exercise-namely sun salutation. Two parameters of the measured biomechanical signal – Instantaneous Frequency and Instantaneous Power were evaluated based on properties of Wigner Distribution Function and performance was evaluated. The combination of Inertial Measurement Unit as a motion sensor and WDF as a signal analysis tool prove to be a highly viable, cost-effective and robust method for human motion analysis. Since many exercises in routine training for athletes are repetitive in nature, an understanding gained from quantification of grace during the exercise using the suggested method, would help the athlete as well as the trainer to continuously monitor and improve the performance. The investigations can also be of significant importance for rehabilitative and clinical purposes and can be extended to a host of sports and rhythmic exercises.

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