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Murali et al.(10) **Pub. No.: US 2018/0085069 A1**(43) **Pub. Date: Mar. 29, 2018**(54) **METHOD AND DEVICE FOR PROCESSING
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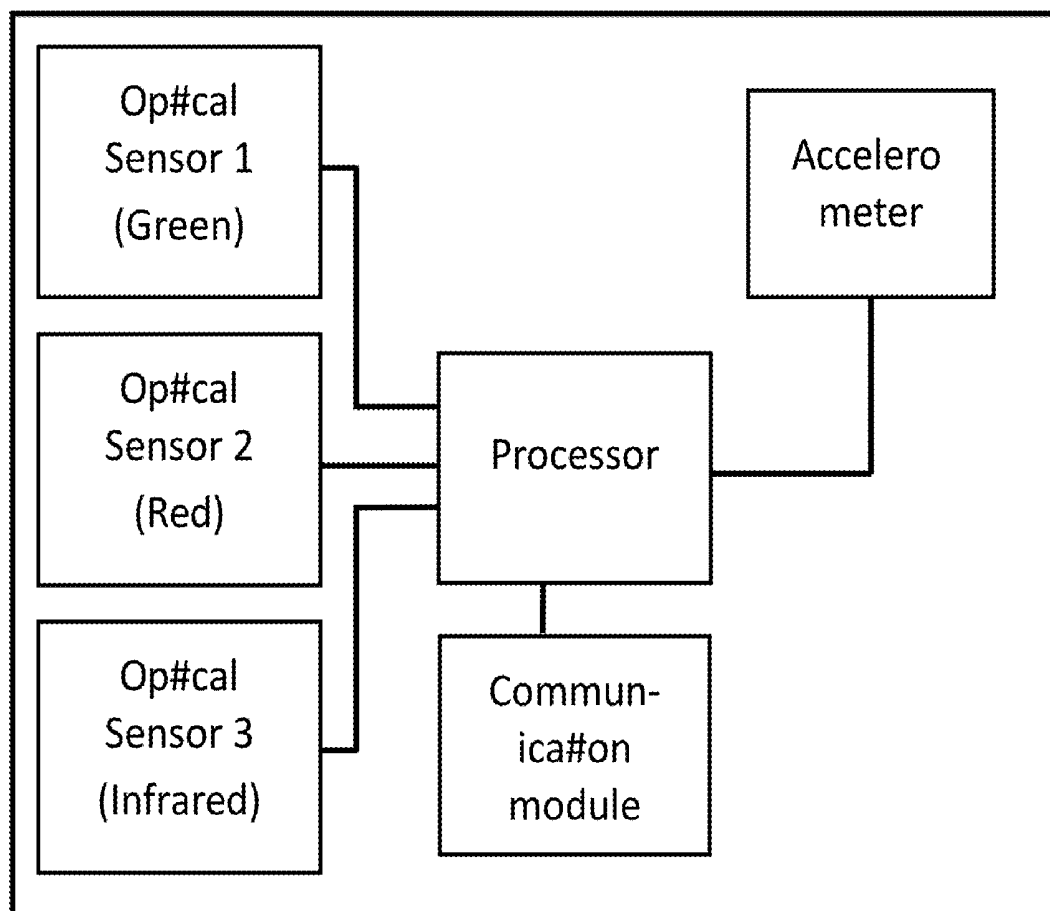
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(57)

ABSTRACT

A method for computing the heart rate value of a user, including detecting a time-dependent optical waveform including a pulse induced by the heartbeat with an optical pulse sensor attached to the user, detecting of a time-dependent accelerometer waveform by an inertial sensor arranged in proximity of the optical pulse sensor, computing of frequency components of the time-dependent optical waveform by a mathematical transform, computing of frequency components of the time-dependent accelerometer waveform by the mathematical transform, first removing of computed frequency components of the time-dependent accelerometer waveform that are below a pre-defined threshold, second removing the computed frequency components of the time-dependent optical waveform that are matching the computed frequency components, third removing the computed frequency components after the second removing that are below a pre-defined threshold, and choosing one of the computed frequency components from the third removing as the heart rate.



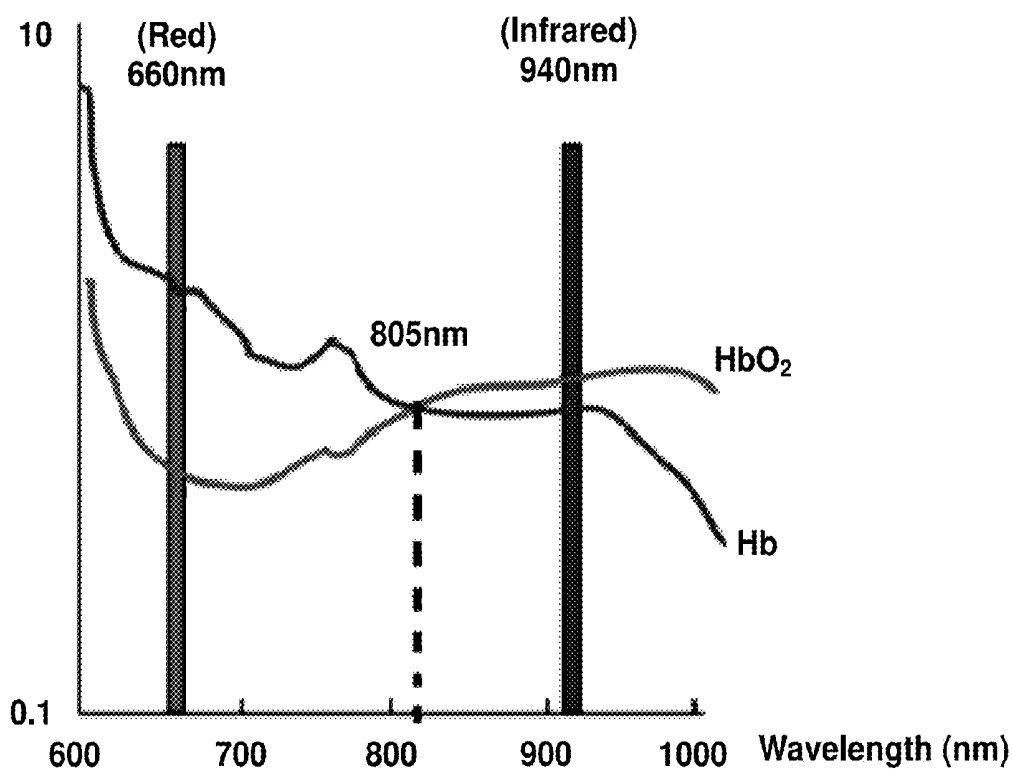


FIG.1

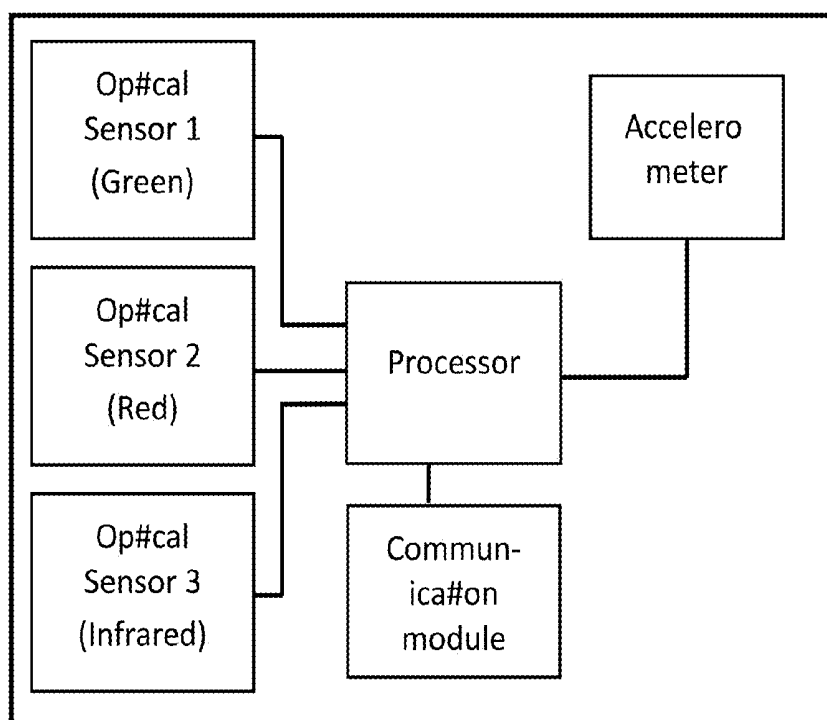


FIG.2

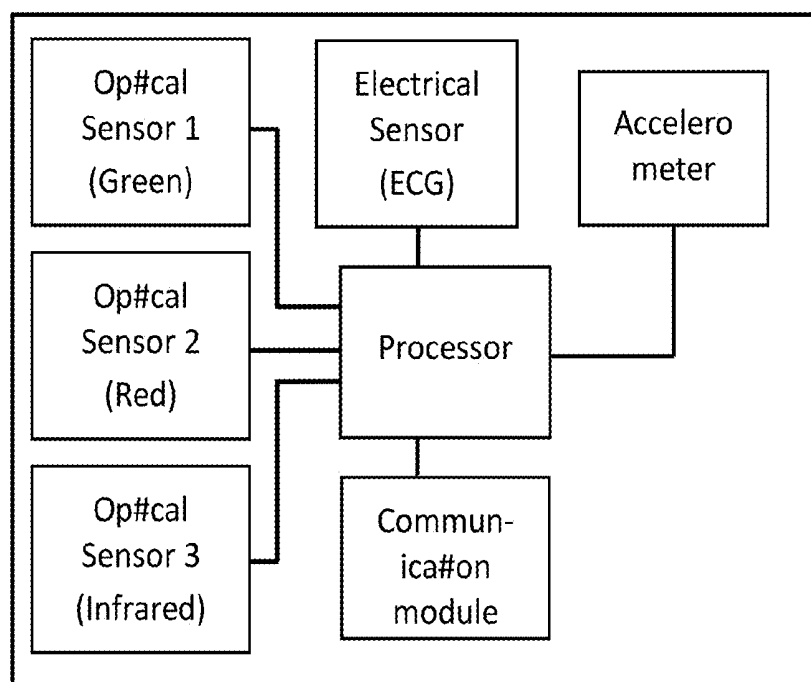


FIG.3

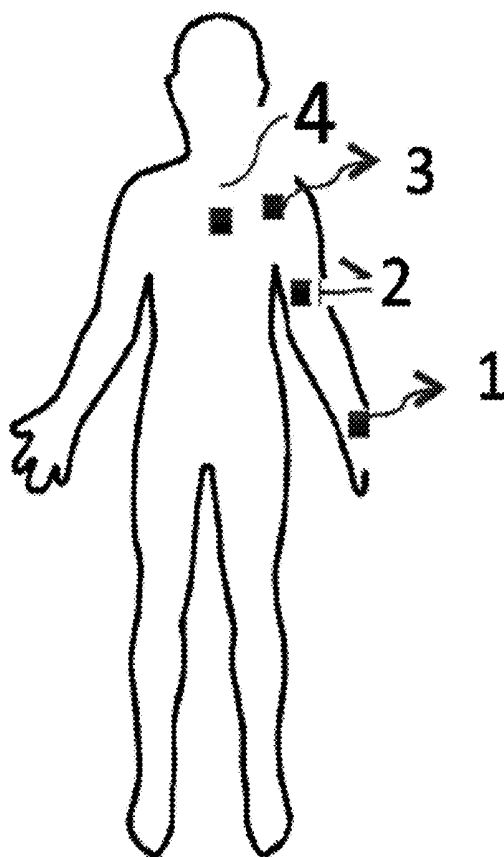


FIG.4

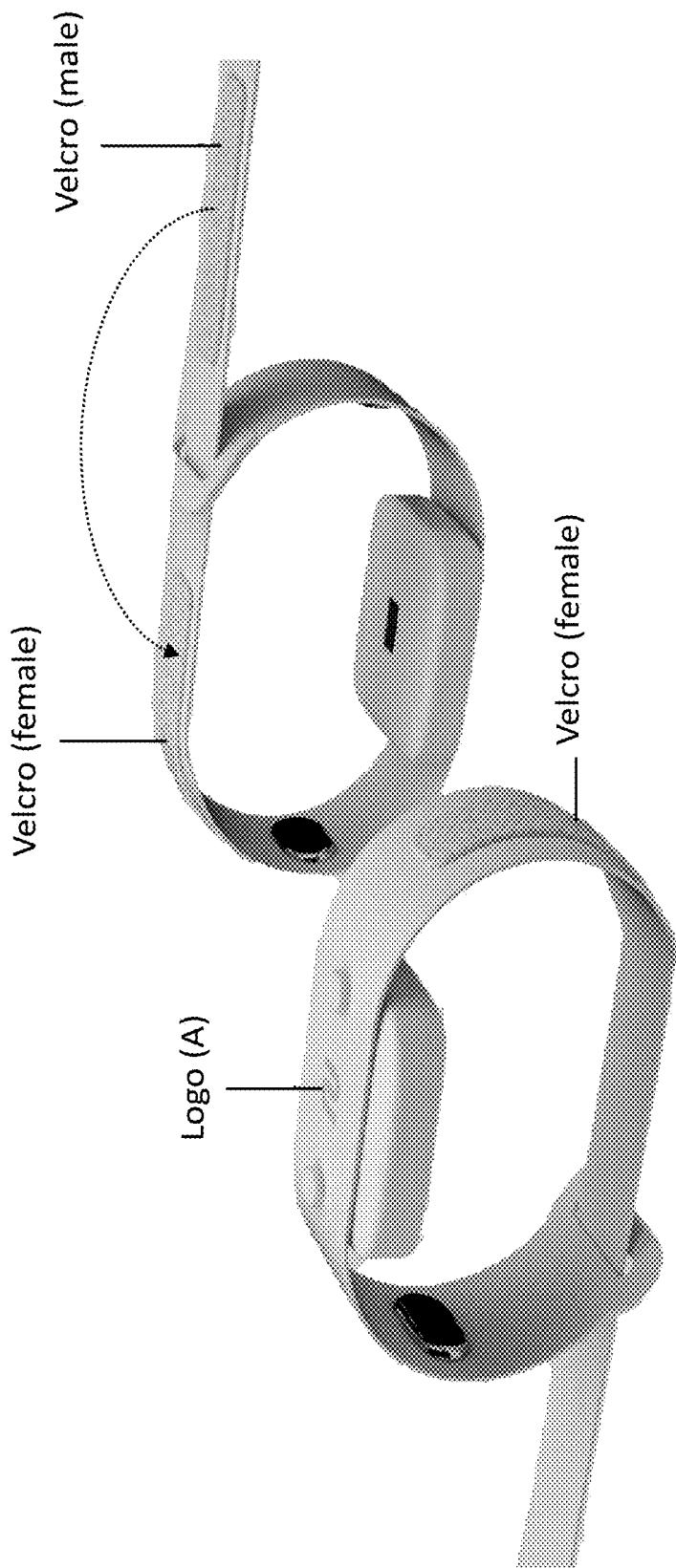


FIG.5A

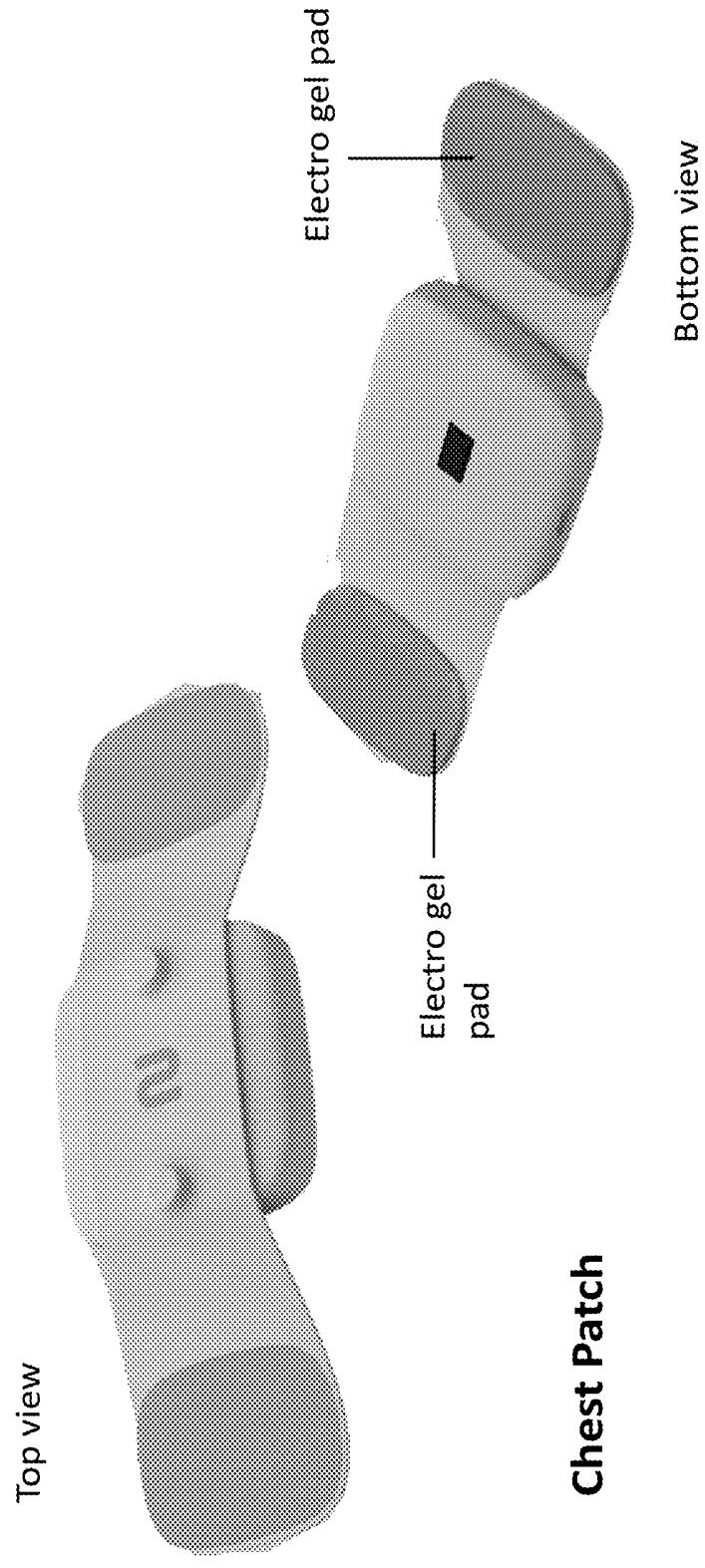


FIG. 5B

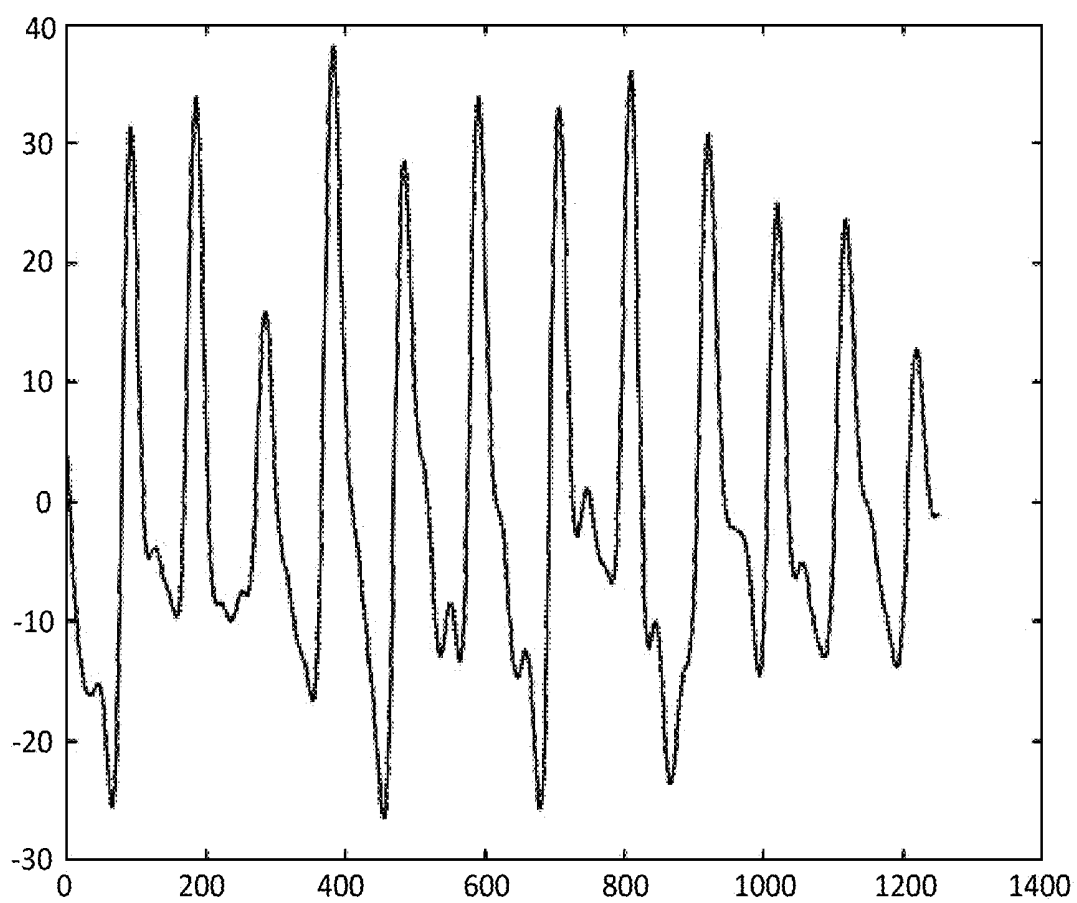


FIG.6

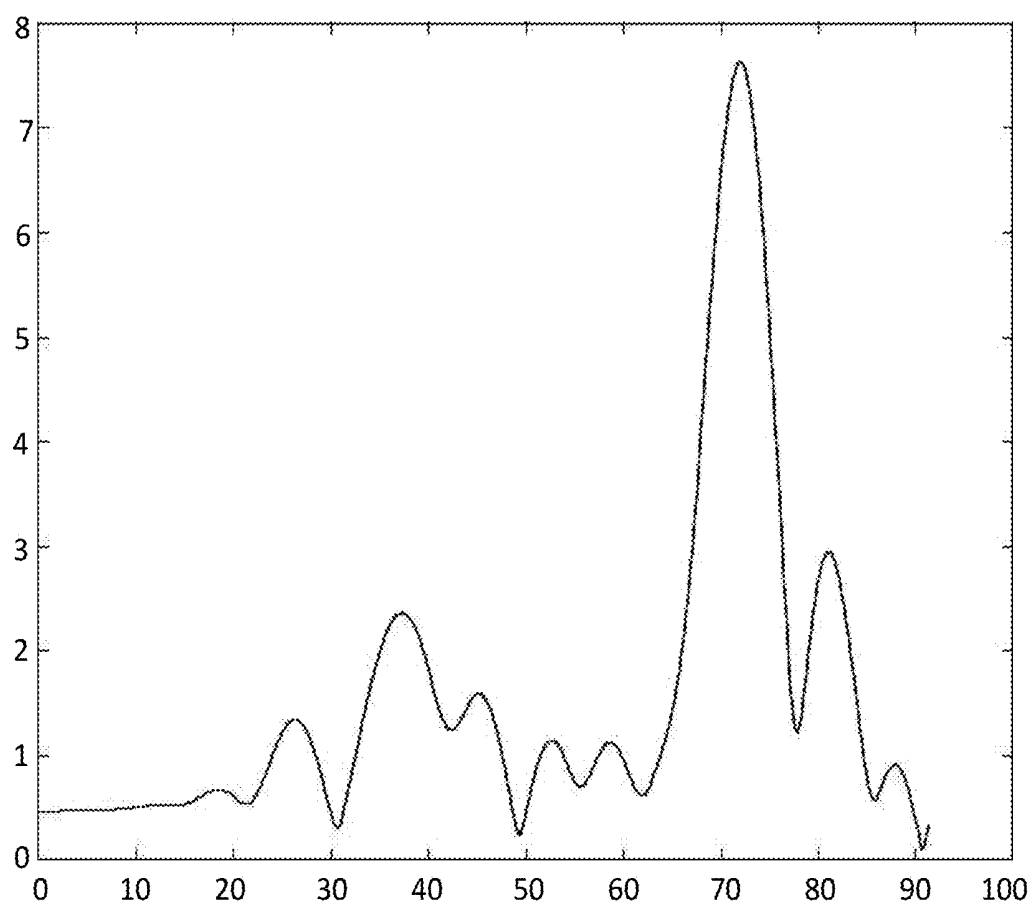


FIG.7

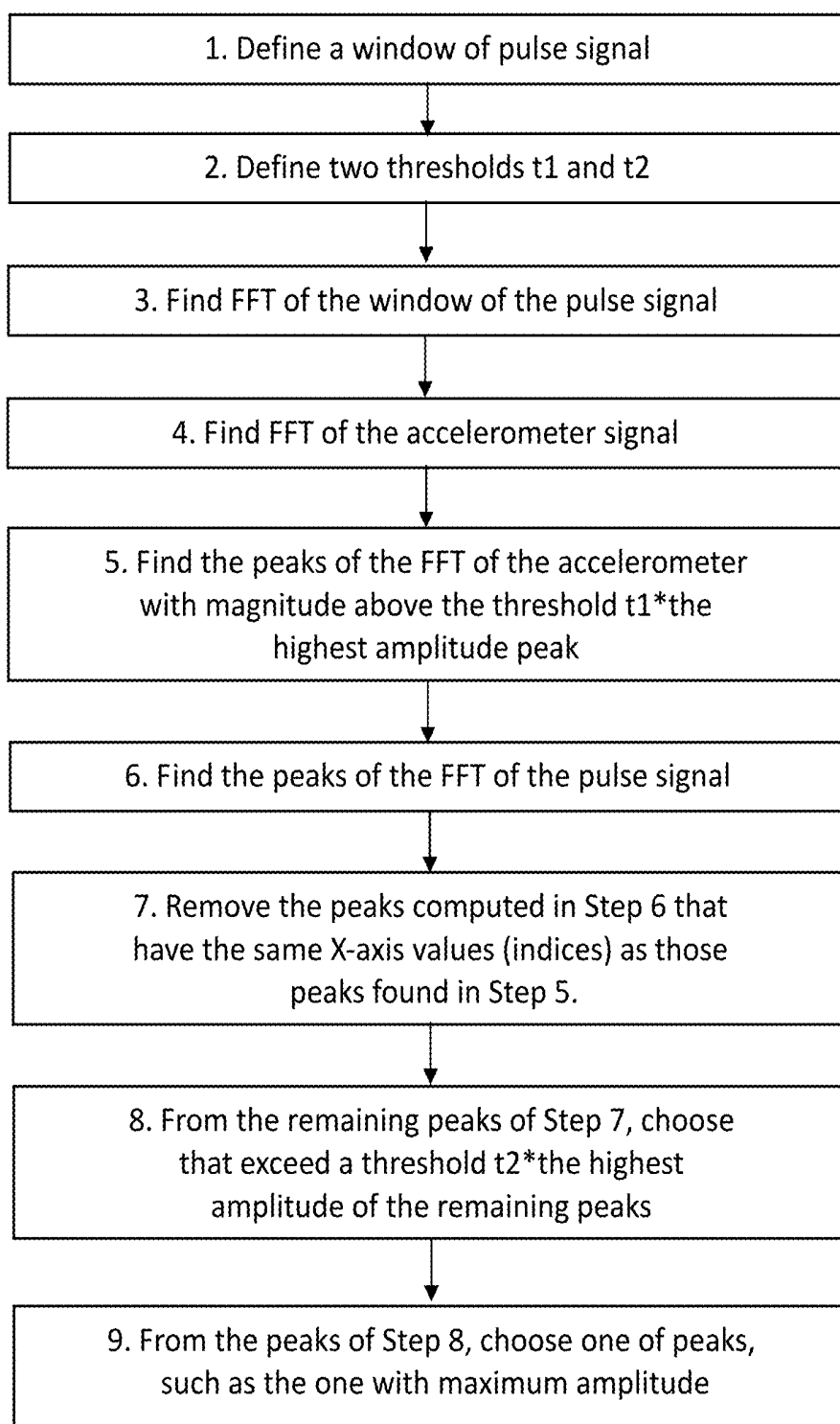


FIG.8

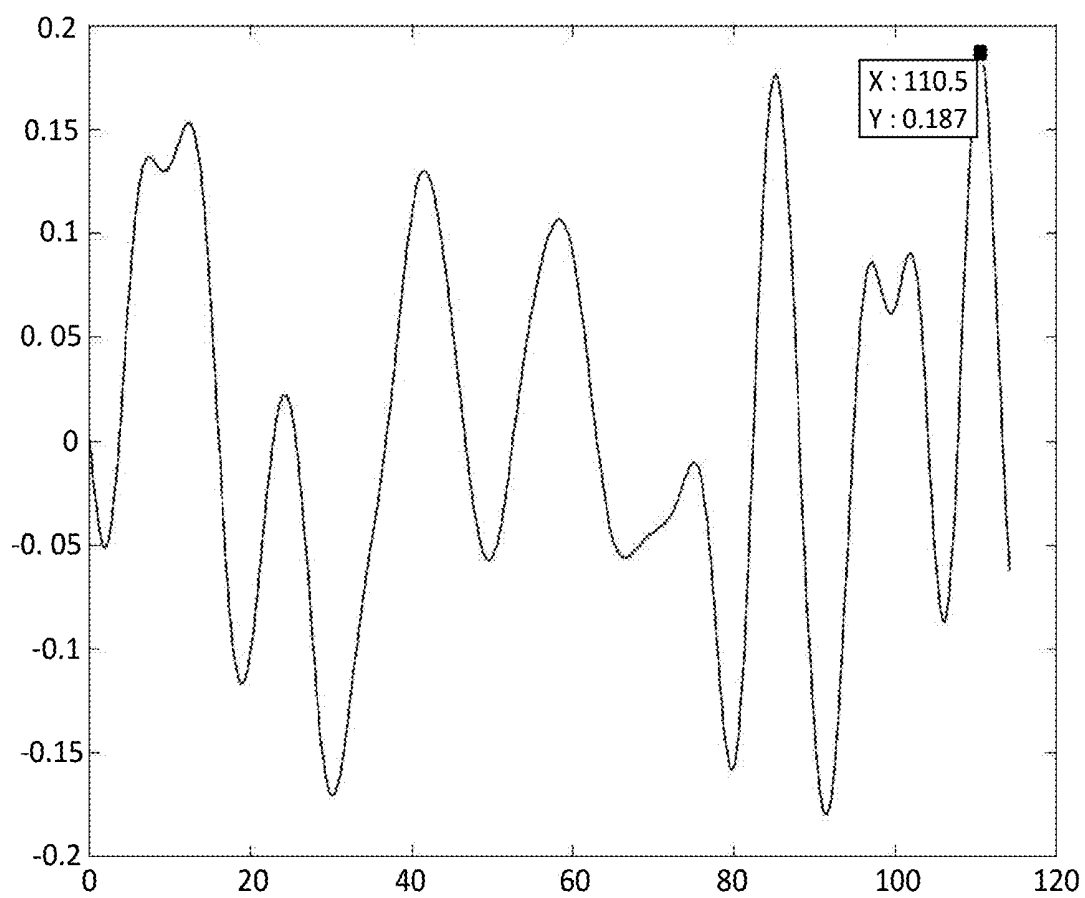


FIG.9

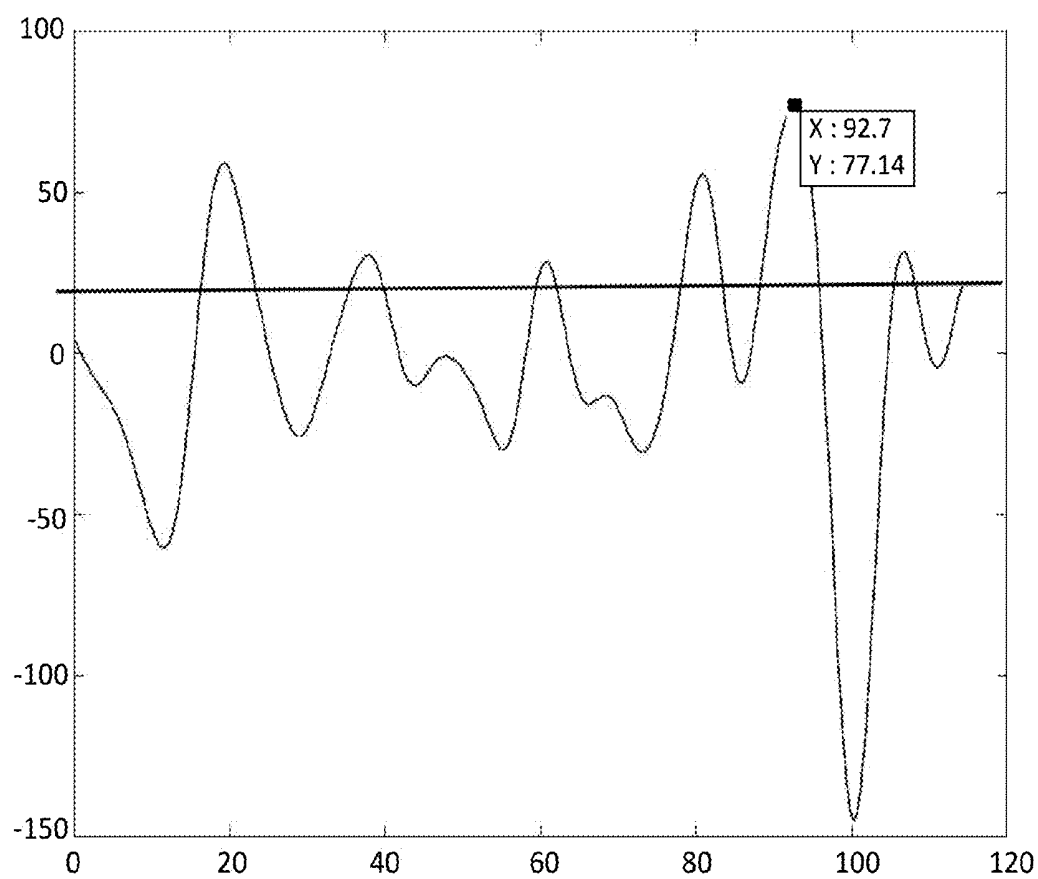


FIG.10

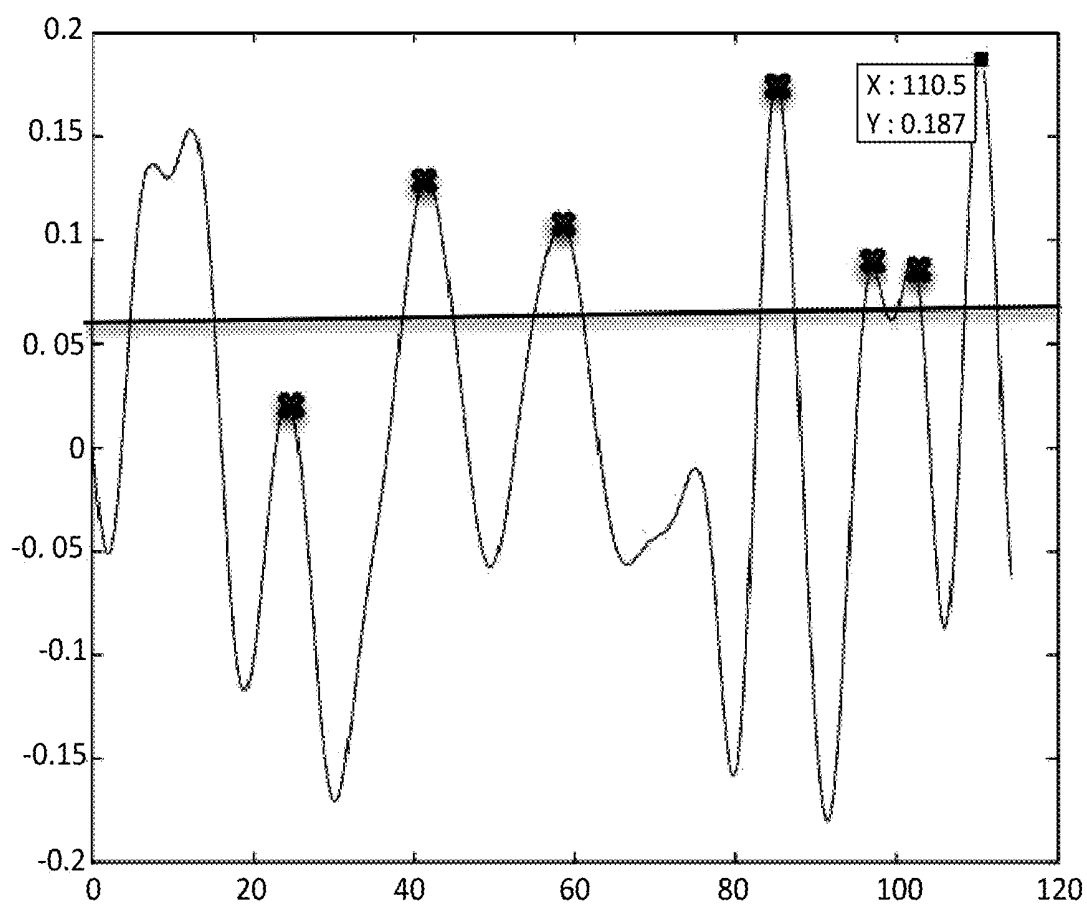


FIG.11

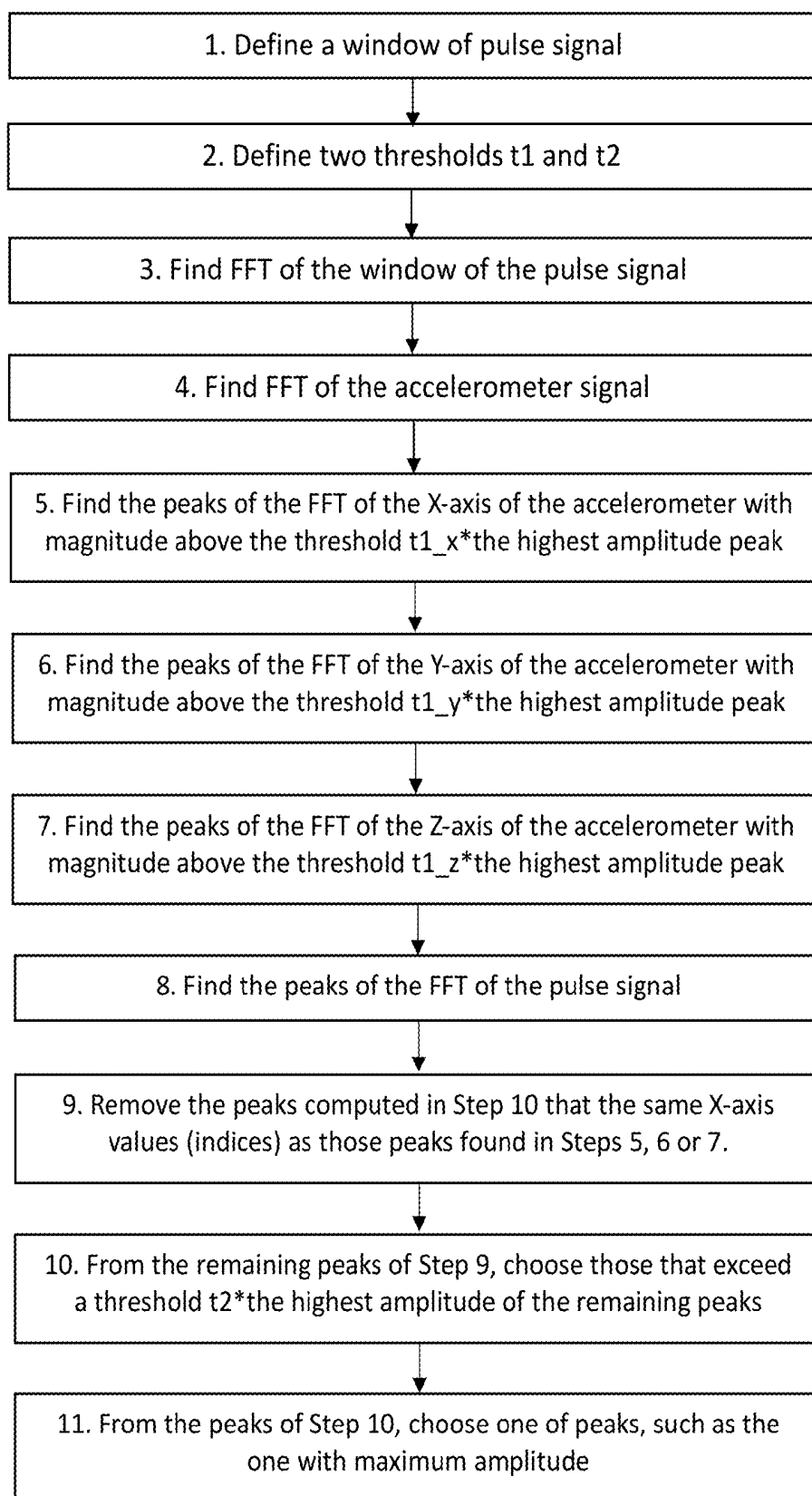


FIG.12

METHOD AND DEVICE FOR PROCESSING BIO-SIGNALS

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] The present application claims foreign priority to International Patent Application PCT/IB2016/055158 filed on Aug. 29, 2016, the entire contents thereof herewith incorporated by reference.

TECHNICAL FIELD

[0002] The present invention relates to a method and a device for processing bio-signals to obtain heart rate and oxygen saturation under activity.

BACKGROUND

[0003] Accurate tracking of vital signs plays an important role in determining the health status of individuals. Typical hospital grade monitors measure one or more vital signs, such as the ElectroCardioGram (ECG or EKG), pulse signal, oxygen saturation and arterial blood pressure. To derive clinical insights from the different bio-signals, the important features need to be extracted. One of the major challenges in wearable and ambulatory bio-signal monitoring is to obtain accurate features under different noise sources, such as motion artefact due to activity, electromagnetic interference and power supply noise.

[0004] Photoplethysmography (PPG) based wrist worn or body worn sensors are widely used for heart rate monitoring. PPG sensing involves transmitting light waves at one or more wavelengths, and detecting the pulsatile variations due to blood flow in the reflectance of the signals.

[0005] Arterial oxygen saturation (SaO₂) level signifies the amount of oxygen-saturated hemoglobin relative to total hemoglobin in the blood. While SaO₂ levels are typically obtained from testing the blood samples, the peripheral oxygen saturation values (SpO₂) are a good approximation of SaO₂ values. A SpO₂ sensor, typically used at the fingertip, transmits light at two different wavelengths (Red and Infrared range) and measures the absorption patterns at the two wavelengths. In FIG. 1, the absorption of the light waves at different wavelengths due to oxygenated and non-oxygenated hemoglobin is shown in International Patent Publication WO 2013/038296.

[0006] The SpO₂ value is calculated in a ratio-metric manner, by measuring the dissimilar absorption coefficients to oxygenated and deoxygenated hemoglobin. The R/IR values of SpO₂ sensor is calculated using the following equation:

$$\frac{R}{IR} = \left(\frac{\frac{AC_R}{DC_R}}{\frac{AC_{IR}}{DC_{IR}}} \right) \quad (\text{Equation 1})$$

where AC_R and DC_R are the AC (pulsatile) and DC components of the sensed Red waveform, and AC_{IR} and DC_{IR} are the AC (pulsatile) and DC components of the sensed Infra-red waveforms. The R/IR values are, in some instances, calculated on a logarithmic scale (by taking a logarithm of numerator and denominator of the AC/DC

values of Red and Infrared in the right hand side of the above equation and dividing the logarithm values to get the ratios).

[0007] By measuring the R/IR values of different subjects at different oxygen saturation levels, such as using an altitude chamber to change the oxygen saturation levels, a calibration model can be built to equate the R/IR to measured SaO₂ values or to pre-calibrated SpO₂ sensor.

[0008] Several works have shown the use of a linear model to relate the two, such as the following:

$$SpO_2 = a - b * R/IR, \quad (\text{Equation 2})$$

where a and b are constants that are obtained from the calibration model.

[0009] While the calculation of SpO₂ has been performed for decades, the main challenge is to obtain accurate SpO₂ values under physical activity, where there is a lot of noise generated from the movement of the user, and to obtain under low perfusion levels, when the sensing is performed at the wrist, arm, chest or other points in the body. Accordingly, novel and substantially improved methods and devices are desired for the calculating the peripheral oxygen saturation values SpO₂, and other types of bio-signals that are related to blood oxygen levels.

SUMMARY

[0010] In a first aspect, the invention provides a method for computing the heart rate value of an user, including (a) a first detecting of a time-dependent optical waveform including a pulse induced by the user's heartbeat, with an optical pulse sensor attached to the user, (b) a second detecting of a time-dependent accelerometer waveform by means of an inertial sensor arranged in proximity with the optical pulse sensor, (c) a first computing of frequency components of the time-dependent optical waveform by means of a mathematical transform, (d) a second computing of frequency components of the time-dependent accelerometer waveform by means of the mathematical transform, (e) a first removing of the computed frequency components of the time-dependent accelerometer waveform that are below a first pre-defined threshold of the maximum amplitude across the frequency components of the accelerometer, (f) a second removing of the computed frequency components of the time-dependent optical waveform that are matching to the computed frequency components of the time-dependent accelerometer waveform that remain after the first removing, (g) a third removing of the computed frequency components after the second removing that are below a second pre-defined threshold of the maximum amplitude across the remaining frequency components after the second removing, and (h) choosing one of the computed frequency components from the third removing as the heart rate.

[0011] In a preferred embodiment, the inertial sensor has more than one axis, and the computing of the heart rate further includes (a) measuring activity across more than one dimension, (b) a third computing of the frequency components of the different axes of the accelerometer signal of the second detecting by means of the same mathematical transform as in the first detecting, (c) a fourth removing of the computed frequency components from the third computing that are below pre-defined thresholds of the maximum amplitude across the frequency components of each axis of the accelerometer, (d) a fifth removing of the computed frequency components of the pulse signal computed in the first computing that are matching to those frequency com-

ponents of each axis of the accelerometer signal that remain after the fourth removing, (e) a sixth removing of the frequency components of the fifth removing that are below another pre-defined threshold of the maximum amplitude across the remaining frequency components of the pulse signal of the fifth removing, and (f) choosing one of the frequency components from the sixth removing as the heart rate.

[0012] In a further preferred embodiment, the step of choosing one the computed frequency components from the third removing as the heart rate, the frequency component with the highest amplitude is chosen as the heart rate.

[0013] In a further preferred embodiment, the pulse signal and accelerometer signal are divided into multiple time windows, with the steps of claim 1 executed for each window, and for a particular window, in the step of choosing one of the computed frequency components from the third removing as the heart rate, the frequency component that is closest to the one chosen as the heart rate in the previous time window is selected as the heart rate for the window.

[0014] In a further preferred embodiment, the pulse signal and accelerometer signals are divided into multiple time windows, with the steps of the computing of the heart rate further including (a) measuring activity across more than one dimension, (b) a third computing of the frequency components of the different axes of the accelerometer signal of the second detecting by means of the same mathematical transform as in the first detecting, (c) a fourth removing of the computed frequency components from the third computing that are below pre-defined thresholds of the maximum amplitude across the frequency components of each axis of the accelerometer, (d) a fifth removing of the computed frequency components of the pulse signal computed in the first computing that are matching to those frequency components of each axis of the accelerometer signal that remain after the fourth removing, (e) a sixth removing of the frequency components of the fifth removing that are below another pre-defined threshold of the maximum amplitude across the remaining frequency components of the pulse signal of the fifth removing, and (f) choosing one of the frequency components from the sixth removing as the heart rate executed for each window, and for a particular window, in the step of choosing one of the frequency components from the third removing as the heart rate, the frequency component that is closest to the one chosen as the heart rate in the previous time window is selected as the heart rate for the window.

[0015] In a second aspect, the invention provides a method for computing the Spo2 value of a user, including (a) a first detecting of a time-dependent optical waveform including a pulse induced by a heartbeat of the user, with an optical pulse sensor attached to the user that transmits light at a first wavelength, (b) a second detecting of a time-dependent optical waveform including a pulse induced by the user's heartbeat, with an optical pulse sensor attached to the user that transmits light at a second wavelength, (c) a first computing of the DC value of the signal of the first detected waveform (d) a second computing of the DC value of the signal of the second detected waveform, (e) a third computing the heart rate using Steps 1(a)-1(h) using the first detected waveform, (f) a fourth computing of the frequency components of the first detected waveform and choosing the amplitude of the frequency component that matches the heart rate computed in step (e) as the AC value of the first

detected waveform, (g) a fifth computing of the frequency components of the second detected waveform and choosing the amplitude of the frequency component that matches the heart rate computed in the step of the third computing as the AC value of the second detected waveform, and (h) a sixth computing of the ratio of the ratio of the AC value of the fourth computing to the DC value of the first computing to ratio of the AC value of the fifth computing to the DC value of the second computing, which is then transformed by a polynomial to obtain Spo2 value.

[0016] In a preferred embodiment of the method of Spo2 computation, (a) apart from the pulse signals at two different wavelengths computed in the steps of the first detecting and the second detecting, the method further includes detecting a time-dependent optical waveform including a pulse induced by the user's heartbeat with an optical sensor configured to attach to the user that transmits light at a third wavelength, and (b) the heart rate computation of the step of the third computing is performed using the pulse signal at the third wavelength.

[0017] In a further preferred embodiment of the method of Spo2 computation, the SpO2 computation is performed in windows, with the heart rate computation of the step of the third computing performed using at least the following steps: (a) measuring activity across more than one dimension, (b) third computing of the frequency components of the different axes of the accelerometer signal of the second detecting by means of the same mathematical transform as in the first detecting, (c) a fourth removing of the computed frequency components from the third computing that are below pre-defined thresholds of the maximum amplitude across the frequency components of each axis of the accelerometer, (d) a fifth removing of the computed frequency components of the pulse signal computed in the first computing that are matching to those frequency components of each axis of the accelerometer signal that remain after the fourth removing, and (e) a sixth removing of the frequency components of the fifth removing that are below another pre-defined threshold of the maximum amplitude across the remaining frequency components of the pulse signal of the fifth removing.

[0018] In a third aspect, the invention provides a device for estimating the heart rate of a user under activity including: (a) means of recording a time-dependent optical waveform pulse induced by the user's heartbeat with an optical pulse sensor configured to attach to the user, (b) means of recording a time-dependent accelerometer waveform including using an inertial sensor configured to be in proximity with the optical pulse sensor, (c) a processor that acquires the optical waveform and accelerometer waveform, with (i) first means for computing the frequency components of the optical signal using a mathematical transform; (ii) second means for computing the frequency components of the accelerometer signal using the same mathematical transform as the first means for computing, (iii) first means for removing all frequency components computed by the second means for computing that are below a pre-defined threshold of the maximum amplitude across the frequency components of the accelerometer, (iv) second means for removing all the frequency components of the pulse signal computed by the first means for computing that are matching to those frequency components of the accelerometer signal that remain after removal by the first means for removing, (v) third means for removing all frequency components result-

ing from the second means for removing that are below another pre-defined threshold of the maximum amplitude across the remaining frequency components of the pulse signal resulting from the second means for removing, (vi) means for choosing one of the frequency components from the third means for removing as the heart rate.

[0019] In a preferred embodiment of the device, (a) the accelerometer has more than one axis, measuring activity across more than one dimension, (b) means for computing the frequency components of the different axes of the accelerometer signal from the second means for computing use the same mathematical transform as the first means for computing; and the device further includes (c) fourth means for removing all frequency components of each axis of the accelerometer in the means for computing that are below pre-defined thresholds of the maximum amplitude across the frequency components of each axis of the accelerometer, (d) fifth means for removing all the frequency components of the pulse signal computed in the first means for computing that are matching to those frequency components of each axis of the accelerometer signal that remain after removal by the fourth means for removing, and (e) sixth means for removing all the frequency components from the second means for removing that are below another predefined threshold of the maximum amplitude across the remaining frequency components of the pulse signal in the fifth means for removing.

[0020] In a further preferred embodiment of the device, in the second means for removing, the frequency component with the highest amplitude is chosen as the heart rate.

[0021] In a further preferred embodiment of the device, the processor segments the pulse signal and accelerometer signal into multiple time windows, with the first and second means for computing and the first, second and third means for removing executed for each window, and for a particular window, in the means for choosing one of the frequency components, the frequency component that is closest to the one chosen as the heart rate in the previous time window is selected as the heart rate for the window.

[0022] In a fourth aspect the invention provide a device for computing the SpO₂ value of an user, including (a) means for detecting a time-dependent optical waveform including a pulse induced by the user's heartbeat with an optical sensor configured to attach to the user that transmits light at a first wavelength, (b) means for detecting a time-dependent optical waveform including a pulse induced by the user's heartbeat with an optical sensor configured to attach to the user that transmits light at a second wavelength, (c) means for computing the DC value of the signal of the first wavelength, (d) means for computing the DC value of the signal of the second wavelength, (e) means for computing the heart rate using a processor that acquires the optical waveform and accelerometer waveform, with (i) first means for computing the frequency components of the optical signal using a mathematical transform, (ii) second means for computing the frequency components of the accelerometer signal using the same mathematical transform as the first means for computing, (iii) first means for removing all frequency components computed by the second means for computing that are below a pre-defined threshold of the maximum amplitude across the frequency components of the accelerometer, (iv) second means for removing all the frequency components of the pulse signal computed by the first means for computing that are matching to those fre-

quency components of the accelerometer signal that remain after removal by the first means for removing, (v) third means for removing all frequency components resulting from the second means for removing that are below another pre-defined threshold of the maximum amplitude across the remaining frequency components of the pulse signal resulting from the second means for removing, (vi) means for choosing one of the frequency components from the third means for removing as the heart rate. using one of the pulse signal at the first wavelength, (f) means for computing the frequency components of the signal at the first wavelength and choosing the amplitude of the frequency component that matches the heart rate computed with the means for computing the heart rate as the AC value at the first wavelength, (g) means for computing the frequency components of the signal at the second wavelength and choosing the amplitude of the frequency component that matches the heart rate computed with the means for computing the heart rate as the AC value at the second wavelength, (h) means for computing the ratio of AC/DC at first wavelength to AC/DC at second wavelength, which is then used for calibration to obtain the SpO₂ values.

[0023] In a preferred embodiment of the device for computing the SpO₂ value (a) apart from the pulse signals at two different wavelengths computed in the means for detecting a time-dependent optical waveform and the means for detecting a time-dependent optical waveform, the device further comprises means of detecting a time-dependent optical waveform including a pulse induced by the user's heartbeat with an optical sensor configured to attach to the user that transmits light at a third wavelength, and (b) means for computing the heart rate enabled to perform using the pulse signal at the third wavelength.

[0024] In a further preferred embodiment of method of SpO₂ computation, the signals are divided into time segments of activity and inactivity, based on the accelerometer values, and the SpO₂ computations are performed individually in the different segments.

[0025] The above and other objects, features and advantages of the present invention and the manner of realizing them will become more apparent, and the invention itself will best be understood from a study of the following description and appended claims with reference to the attached drawings showing some preferred embodiments of the invention.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWINGS

[0026] The accompanying drawings, which are incorporated herein and constitute part of this specification, illustrate the presently preferred embodiments of the invention, and together with the general description given above and the detailed description given below, serve to explain features of the invention.

[0027] FIG. 1 shows oxygenated versus de-oxygenated blood light absorption of IR and Red from source as shown in reference [5];

[0028] FIG. 2 schematically illustrates a wearable sensor with 3 optical sensors, accelerometer, an on-board processor and a communication module;

[0029] FIG. 3 schematically illustrates a wearable sensor with 3 optical sensors, electrical sensor (ECG), accelerometer, an on-board processor and a communication module;

[0030] FIG. 4 shows different example locations for wearing the device according to the invention on the body;

[0031] FIGS. 5A and 5B show different perspective views of the wearable device according to an example embodiment of the invention, that can obtain multiple wavelength pulse signals and/or ECG with inbuilt accelerometer, and configured to be attached using an arm band/wrist band or a chest patch, the armband having metal sensors on the band to acquire the ECG signal;

[0032] FIG. 6 depicts an example of a window of pulse signal under no or very low movement of the user;

[0033] FIG. 7 depicts an example of an FFT of the window, wherein a maximum amplitude peak signifies the pulse rate of around 72 bpm;

[0034] FIG. 8 depicts an exemplary flowchart illustrating an algorithm for determining heart rate using a window of pulse and accelerometer signal, according to an example embodiment of the invention;

[0035] FIG. 9 depicts an example of the FFT of the pulse signal under noise;

[0036] FIG. 10 depicts an example of the FFT of the accelerometer signal under noise, wherein t_1 is a pre-defined threshold, the value of $t_1 \times \text{maximum peak}$ being shown by the horizontal line in the plot—the value of t_1 is set experimentally, based on user data collection, in this example, 6 peaks are above the threshold;

[0037] FIG. 11 depicts an example of the FFT of the pulse signal, after removing the peaks from FIG. 9 (the crossed ones are peaks removed), with the threshold $t_2 \times \text{maximum amplitude of remaining peaks}$ marked by the horizontal line; and

[0038] FIG. 12 depicts an exemplary flowchart illustrating an algorithm for determining heart rate using a window of pulse and accelerometer signal from a three-axis accelerometer.

[0039] Herein, identical reference numerals are used, where possible, to designate identical elements that are common to the figures. Also, the images in the drawings are simplified for illustration purposes and may not be depicted to scale.

DETAILED DESCRIPTION OF THE EMBODIMENTS

[0040] First and overview of the different aspects of the invention is provided. According to one aspect of the present invention, a method and a device is provided to accurately determine heart rate under activity and SpO₂ under activity under noisy ambulatory conditions and/or under low perfusion levels and/or with ambient noise sources (such as different light conditions, electrical interference and power supply noise).

[0041] Several methods have been proposed to measure heart rate under activity. In Z. Zhang, Z. Pi, S. Member, and B. Liu, "TROIKA: A General Framework for Heart Rate Monitoring Using Wrist-Type Photoplethysmographic (PPG) Signals During Intensive Physical Exercise," IEEE Transactions on Biomedical Engineering, Vol. 62, No. 2, pp. 522-531, 2015, hereinafter reference [1], a framework was presented for obtaining heart rate from wrist based PPG sensors under activity. They use a periodogram based transformation, followed by signal decomposition and sparse signal reconstruction. The method has high complexity to be implemented using a low power microcontroller. Another method is based on periodic moving average filter as shown

in H.-W. Lee, J.-W. Lee, W.-G. Jung, and G.-K. Lee, "The Periodic Moving Average Filter for Removing Motion Artifacts from PPG Signals," International Journal Of Control Automation And Systems, Vol. 5, No. 6, pp. 701-706, 2007, hereinafter in reference [2]. The filter segments the PPG signal into periods and performs resampling in each period. One key issue with the method is that it is difficult to remove in-band noise, when the heart rate and activity have similar periodicity. Adaptive filters for motion compensation have been proposed in T. Tamura, Y. Maeda, M. Sekine, and M. Yoshida, "Wearable Photoplethysmographic Sensors Past and Present," Electronics, Vol. 3, No. 2, pp. 282-302, 2014, hereinafter reference [3]. Such methods typically require a reference signal to minimize the error between the filter output and reference. In patent application U.S. Pat. Pub. No. 2015/0131879, herein cited as reference [4], Independent Component Analysis (ICA) is used to detect the heart rate under activity.

[0042] In International Publication WO 2014/163583, herein cited as reference [6], a method and apparatus to determine SpO₂ is presented. In this document, the authors describe a method to bin R-values into different predetermined frequency bins. It does not provide any methods for accurately estimating the R-value under activity. In U.S. Pat. No. 8,954,135, herein cited as reference [7], devices for measuring SpO₂ using Green and Infrared pulse sensors are presented.

[0043] In International Publication WO2013/038296, herein cited as reference [5], a threshold-based method is presented for heart rate detection under activity. In the patent, a predefined threshold is used and when the bio-signal quality is above the threshold, the heart rate is calculated. This is different from the method according to some aspects of the present invention, where we present a method and device with thresholds that are used in the frequency domain for selecting the frequency domain peaks of accelerometer and pulse signal. In U.S. Pat. No. 8,998, 815, a wearable heart rate monitor is presented in which the frequency components of the accelerometer and pulse sensor are used to detect the heart rate. The method does not have predefined thresholds to remove noise.

[0044] According to one aspect of the present invention, a low complexity method for heart rate estimation under activity is provided. In one embodiment of the invention, one or more optical sensors and inertial sensor, for example single or multiple axis accelerometer, are located in close proximity. The unit may be worn at different body parts, such as the upper arm, wrist and chest. The optical sensor is used to detect a time-dependent optical waveform including a pulse induced by the user's heartbeat attached to the user. The accelerometer is used to detect a time-dependent activity waveform. During physical activity, such as walking, running or movement, the pulse signal measured by the optical sensor is corrupted by the movement artefact. The movement artefact also has a combination of different noise sources, such as the muscle noise and movement of the sensor under activity. By cancelling the movement, measured using the accelerometer from the pulse signal, the heart rate (or pulse rate) due to the user's heart beat can be obtained.

[0045] In a further embodiment of the invention, the optical sensor may emit a green light and the reflecting pulsatile variations are measured. In another embodiment of the invention, two optical sensors that emit red and infrared

light are used. In yet another embodiment of the invention, three optical sensors that emit green, red and infrared lights are used. The three optical sensors are sampled alternatively, so that three time-dependent optical waveforms are measured simultaneously.

[0046] In another embodiment, an electrical sensor is used along with the optical sensors and the accelerometer. The electrical sensor uses two or more sensing pads and measures the ElectroCardioGram (ECG or EKG) of the user, at either the arm, wrist or chest. The wearable device architecture with the three optical sensors and accelerometer is shown in FIG. 2. The device also has an onboard processor to compute the heart rate, oxygen saturation values, and a communication module. The process can include but is not limited to a processor chip, microprocessor, a microcontroller, a computer processor, a programmable logic device, a field programmable gate array, and can also include memory that is operatively connected thereto. Standard protocols and communication interfaces, such as Bluetooth, Bluetooth Low Energy or wireless communication can be used to transit the data and signals from the device by the communication module. Moreover, it is also possible that computer instructions that are configured to perform the method are recorded on a non-transitory computer readable medium, for example but not limited to a CDROM, Blu-ray disc, DVD-ROM, memory stick, memory card, portable hard drive, hard drive, thumb drive, or other type of medium that can be operatively connected to a computer device, and can execute the method of computing the Spo2 value of a user, when the computer instructions are performed on the computer device. The wearable device architecture with the electrical sensor for measuring ECG as well is shown in FIG. 3.

[0047] The device may be worn in different parts of the body, as shown in FIG. 4. Some of the locations for wearing the device are the wrist (location 1), upper arm (location 2), on upper chest (location 3) or sternum (location 4).

[0048] The snapshots of the exemplary device are shown in FIGS. 5A and 5B. More precisely, FIGS. 5A and 5B show perspective views of the wearable device that obtains multiple wavelength pulse signals and/or ECG with inbuilt accelerometer. The device may be attached using an arm band/wrist band or a chest patch. The armband has metal sensors on the band to acquire the ECG signal.

[0049] Next, the method for heart rate detection under activity is discussed, according to another aspect of the present invention. An example of the time varying pulse waveform is shown in FIG. 6, under no or very low movement of the user. One of the usual methods to determine the heart rate from the pulse signal is to perform the spectral analysis using Fast Fourier Transform (FFT). A FFT is performed on the signal, and when the pulse signal is not subject to noise sources, the peak of the FFT signifies the pulse rate (alternatively, also signified as heart rate). The FFT of the pulse signal from FIG. 6 is shown in FIG. 7. Each peak on the FFT denotes a frequency component of the signal and the amplitude of the peak (also termed as the amplitude of the frequency component) denotes the intensity of the periodicity of the signal at that frequency. When there is no motion artifact and other noise sources, the frequency component of the pulse signal corresponding to the heart rate value has the highest intensity or amplitude.

[0050] The X-axis of the FFT (in FIG. 6) is the rate, the Y-axis represents the amplitude of the signal at that rate.

Each peak of the FFT also denotes a frequency component of the underlying signal. When there is no activity and no noise, the maximum amplitude peak (or the frequency component with the highest amplitude) signifies the heart rate (around 72 bpm in FIG. 7).

[0051] When the subject is under activity, the movement artefact also appears on the pulse signal. In one of the embodiments of the invention, the accelerometer data is used to remove the movement artefact from the pulse signal. In one embodiment of the patent, the steps to determine heart rate under activity are shown in a flowchart in FIG. 8.

[0052] The method involves taking the frequency transform of the pulse and accelerometer signal (such as the FFT), defining thresholds t_1 and t_2 for accelerometer and pulse signal, removing the peaks of the FFT of the accelerometer below the threshold t_1 , removing the remaining peaks from the FFT of the pulse signal, removing the remaining peaks of the FFT of the pulse signal below the threshold t_2 and choosing one of the remaining peaks of the FFT of the pulse signal.

[0053] An example of the FFT of the pulse signal and accelerometer is shown in FIG. 9, and the method is explained using an example shown in FIGS. 9-12.

[0054] FIG. 10 shows an example of the FFT of the accelerometer signal under noise. t_1 is a pre-defined threshold. The value of t_1 *maximum peak is shown by the horizontal line in the plot. The value of t_1 is set experimentally, based on user data collection. In the above example, 6 peaks are above the threshold.

[0055] FIG. 11 shows an example of the FFT of the pulse signal, after removing the peaks from FIG. 9 (the crossed ones are peaks removed), with the threshold t_2 *maximum amplitude of remaining peaks marked by the horizontal line.

[0056] In a further embodiment of the invention, the thresholds t_1 and t_2 are based on training data, where different values in the range of [0,1] are used and the ones that lead to accurate heart rate (when compared to a gold standard measurement, for example using ECG measurement on the chest) measurements are used. In another embodiment, the accelerometer frequency components are removed from the pulse frequency components only when the raw value of the accelerometer exceeds a pre-defined threshold. This is to avoid the case of accidentally removing the real heart rate frequency component when the accelerometer does not experience any significant movement.

[0057] In the above algorithm, if multi-axis accelerometer is used (such as the 3D accelerometer), then in step 5, the peaks of the FFT of each accelerometer axis is detected and removed from the pulse FFT peaks (in step 7). The threshold t_1 can be same for all the axes of the accelerometer, or individual thresholds can be set for each axes.

[0058] In FIG. 12, we show the application of the algorithm when using a 3-axis accelerometer that measures the activity across the X-axis, Y-axis and Z-axis. We use 3 thresholds, t_{1_x} , t_{1_y} and t_{1_z} , apart from the threshold t_2 for the pulse signal. In one embodiment of the patent, the three thresholds (t_{1_x} , t_{1_y} and t_{1_z}) can be equal.

[0059] In another embodiment of the invention, the 3 different accelerometer values are combined to a single one, such as by taking a RMS (Root Mean Squared) value. The RMS signal is then used as the accelerometer signal in the algorithm of FIG. 8.

[0060] The above algorithms are defined for a single window of PPG and accelerometer signals. According to an

aspect of the present invention, the heart rate continuously computed in real-time, either on the device or on an external data processing device that receives the data, for example a mobile phone, tablet or a smart phone. Moreover, the heart rate can be displayed on a device screen or monitor.

[0061] In this case, the above algorithm can be extended as follows: processing to accumulate signals in window: A moving window is used, where in signals samples from the PPG sensor and accelerometer are stored for particular time window. Then, the above algorithms are applied. The window is then time shifted, ignoring a set of older values and using newer values.

[0062] In a further embodiment of the invention, a window of eight (8) seconds is used. The moving window is shifted by 1-second and the algorithms are implemented. In this case, the oldest 1 second values are discarded and the newest 1-second are added. Thus, the heart rate is computed every second, using the last 8-seconds of data.

[0063] In a further embodiment of the invention, from the resulting peaks in Step 9 (of FIG. 8) or Step 11 (of FIG. 12), the peak that is closest to the peak chosen in the previous window is selected.

[0064] Next, the method for detecting oxygen saturation (SpO₂) is explained with non-limiting embodiments. In order to detect the SpO₂, the following steps can be performed on a processor of a computer:

[0065] 1. Define a window of the Red and Infrared PPG signals

[0066] 2. Compute the DC value of the Red and Infrared signals (RDC and IRDC)

[0067] 3. Compute the AC value of Red and Infrared signals (RAC and IRAC)

[0068] 4. Compute the ratio of R/IR with the following Equation 3:

$$\frac{R}{IR} = \left(\frac{\frac{AC_R}{DC_R}}{\frac{AC_{IR}}{DC_{IR}}} \right) \quad (\text{Equation 3})$$

[0069] In a further embodiment of the invention, the DC value (in Step 1 above) is computed as the mean of the PPG signal. In another embodiment of the patent, the DC value is computed to be the amplitude of the FFT of the 0th component (at X-axis value of 0) of the PPG signal.

[0070] In another embodiment of the invention, the AC value (in Step 3 above) is computed as the maximum amplitude of the FFT of the signals.

[0071] Because the PPG signals can have significant baseline wander, in another embodiment of the invention, the AC values are computed as the maximum amplitude of the FFT of the signal after subtracting the mean of the signal (removing part of the baseline wander).

[0072] In another embodiment of the invention, the AC values are computed as the maximum amplitude of the FFT of the signal after filtering the signal (removing part of the baseline wander) by a band pass filter. In another embodiment, the particular bandpass filter used has a cut-off of [0.5 Hz, 4 Hz].

[0073] In a further embodiment of the invention, the heart rate (Step 9 of FIG. 8, or Step 11 of FIG. 12) is computed using one of the Red or Infrared signals in a window, and the AC values (of Red and Infrared) are calculated as the

amplitudes of the FFT of the signals (Red and Infrared, respectively) at that particular heart-rate. That is, the amplitude of the FFT with X-axis matching the heart rate.

[0074] In another embodiment of the invention, the heart rate, exemplarily shown in step 9 of FIG. 8, or step 11 of FIG. 12, is computed using one of the Red or Infrared signals in a window, and the AC values (of Red and Infrared) are calculated as the amplitudes of the FFT of the signals (Red and Infrared, respectively) after subtracting the mean, at that particular heart-rate. That is, the amplitude of the FFT with X-axis matching the heart rate.

[0075] In still another embodiment of the invention, the heart rate, for example step 9 of FIG. 8, or step 11 of FIG. 12, is computed using one of the Red or Infrared signals in a window, and the AC values (of Red and Infrared) are calculated as the amplitudes of the FFT of the signals (Red and Infrared, respectively) after filtering the signals, at that particular heart-rate. That is, the amplitude of the FFT with X-axis matching the heart rate.

[0076] In a further embodiment of the invention, we use a different signal to compute heart rate, and find the amplitude of the signal in the Red and Infrared sensor signals and compute SpO₂. As green light PPG sensor has better skin penetration than Red and Infrared PPG sensors, this is preferred to obtain heart rate.

[0077] In another embodiment of the invention, the heart rate (Step 9 of FIG. 8, or Step 11 of FIG. 12) is computed using a Green LED PPG sensor in a window, and the AC values (of Red and Infrared) are calculated as the amplitudes of the FFT of the signals (Red and Infrared, respectively) after filtering the signals, at that particular heart-rate computed from the Green LED PPG sensor. That is, the amplitude of the FFT with X-axis matching the heart rate.

[0078] In a further embodiment of the invention, the device measures ECG, Green LED PPG, Red LED PPG and Infrared LED PPG at the same time.

[0079] In another embodiment of the invention, the heart rate is computed from an ECG signal in the window, and the AC values (of Red and Infrared) are calculated as the amplitudes of the FFT of the signals (Red and Infrared, respectively) after filtering the signals, at that particular heart rate computed from the ECG. That is, the amplitude of the FFT with X-axis matching the heart rate.

[0080] Next, a device for determining the heart rate is discussed, according to another aspect of the present invention. In another embodiment of the invention, the wearable device (of FIG. 2 or FIG. 3) is used for estimating the heart rate of a user under activity including (a) means of recording a time-dependent optical waveform pulse induced by the patient's heartbeat with an optical sensor configured to attach to the user, (b) means of recording a time-dependent accelerometer waveform including using an inertial sensor configured to be in proximity with the optical sensor of (a), and (c) a processor that acquires the optical waveform and accelerometer waveform, and performs the heart rate computation according to the methods in FIG. 8 or FIG. 12. The means of recording the time dependent signals can include but are not limited to an analog-to-digital converter operatively coupled to the optical sensor or the inertial sensor or both, analog signal electronics for filtering, amplifying, and pre-processing the analog signals from the sensor, a communication line such as a cable or wireless communication between the sensor and the processor, memory buffer for

temporarily storing the converted sensor data, an interface for providing the sensor data to the processor.

[0081] In another embodiment of the invention, the wearable device (of FIG. 2 or FIG. 3) is used for estimating the heart rate of a user under activity including (a) means of recording a time-dependent optical waveform pulse induced by the patient's heartbeat with an optical sensor configured to attach to the user, (b) means of recording a time-dependent accelerometer waveform including using an inertial sensor configured to be in proximity with the pulse sensor of (a), and (c) a processor that acquires the optical waveform and accelerometer waveform in windows, and performs the heart rate computation according to the methods in FIG. 8 or FIG. 12 for each window of the acquisition.

[0082] In another embodiment of the invention, the window can be sliding in nature, where for each window, some old pulse and accelerometer values are discarded and newer ones are used, and the heart rate computation is performed.

[0083] Next a device for determining oxygen saturation is discussed, according to still another aspect of the invention.

[0084] In another embodiment of the invention, the wearable device (of FIG. 2 or FIG. 3) is used for estimating the oxygen saturation value of a user under activity including (a) means for detecting a time-dependent optical waveform including a pulse induced by the patient's heartbeat with an optical sensor configured to attach to the patient that transmits light at a first wavelength, (b) means for detecting a time-dependent optical waveform including a pulse induced by the patient's heartbeat with an optical sensor configured to attach to the patient that transmits light at a second wavelength, (c) a processor that acquires the optical waveform and accelerometer waveform, and performs the methods to determine oxygen saturation on the processor, as shown above with respect to the method for detecting oxygen saturation. The means of detecting the time-dependent signals from the optical sensor can include but are not limited to an analog-to-digital converter operatively coupled to the optical sensor, analog signal electronics for filtering, amplifying, and pre-processing the analog signals from the sensor, a communication line such as a cable or wireless communication between the sensor and the processor for data transmission, memory buffer for temporarily storing the converted sensor data, an interface for providing the sensor data to the processor.

[0085] In another embodiment of the invention, the wearable device (of FIG. 2 or FIG. 3) is used for estimating the oxygen saturation value of a user under activity including (a) means for detecting a time-dependent optical waveform including a pulse induced by the patient's heartbeat with an optical sensor configured to attach to the patient that transmits light at a first wavelength, (b) means for detecting a time-dependent optical waveform including a pulse induced by the patient's heartbeat with an optical sensor configured to attach to the patient that transmits light at a second wavelength, (c) a processor that acquires the optical waveform and accelerometer waveform in windows, and performs the methods to determine oxygen saturation on the processor on each window, as shown above with respect to the method for detecting oxygen saturation.

[0086] In another embodiment of the invention, the window can be sliding in nature, where for each window, some old pulse and accelerometer values are discarded and newer ones are used, and the oxygen saturation computation is performed.

[0087] While the invention has been disclosed with reference to certain preferred embodiments, numerous modifications, alterations, and changes to the described embodiments are possible without departing from the sphere and scope of the invention, as defined in the appended claims and their equivalents thereof. Accordingly, it is intended that the invention not be limited to the described embodiments, but that it have the full scope defined by the language of the following claims.

1. A method for computing the heart rate value of an user, comprising:

- (a) a first detecting of a time-dependent optical waveform comprising a pulse induced by the user's heartbeat, with an optical pulse sensor attached to the user;
- (b) a second detecting of a time-dependent accelerometer waveform by means of an inertial sensor arranged in proximity with the optical pulse sensor;
- (c) a first computing of frequency components of the time-dependent optical waveform by means of a mathematical transform;
- (d) a second computing of frequency components of the time-dependent accelerometer waveform by means of the mathematical transform;
- (e) a first removing of the computed frequency components of the time-dependent accelerometer waveform that are below a first pre-defined threshold of the maximum amplitude across the frequency components of the accelerometer;
- (f) a second removing of the computed frequency components of the time-dependent optical waveform that are matching to the computed frequency components of the time-dependent accelerometer waveform that remain after the first removing;
- (g) a third removing of the computed frequency components after the second removing that are below a second pre-defined threshold of the maximum amplitude across the remaining frequency components after the second removing; and
- (h) choosing one of the computed frequency components from the third removing as the heart rate.

2. The method of claim 1, wherein the inertial sensor has more than one axis, and wherein the computing of the heart rate further comprises

- (a) measuring activity across more than one dimension;
- (b) a third computing of the frequency components of the different axes of the accelerometer signal of the second detecting by means of the same mathematical transform as in the first detecting;
- (c) a fourth removing of the computed frequency components from the third computing that are below pre-defined thresholds of the maximum amplitude across the frequency components of each axis of the accelerometer;
- (d) a fifth removing of the computed frequency components of the pulse signal computed in the first computing that are matching to those frequency components of each axis of the accelerometer signal that remain after the fourth removing;
- (e) a sixth removing of the frequency components of the fifth removing that are below another pre-defined threshold of the maximum amplitude across the remaining frequency components of the pulse signal of the fifth removing; and

(f) choosing one of the frequency components from the sixth removing as the heart rate.

3. The method of claim 1 wherein the step of choosing one of the computed frequency components from the third removing as the heart rate, the frequency component with the highest amplitude is chosen as the heart rate.

4. The method of claim 1 wherein the pulse signal and accelerometer signal are divided into multiple time windows, with the steps of claim 1 executed for each window, and for a particular window, in the step of choosing one of the computed frequency components from the third removing as the heart rate, the frequency component that is closest to the one chosen as the heart rate in the previous time window is selected as the heart rate for the window.

5. The method of claim 2 wherein the pulse signal and accelerometer signals are divided into multiple time windows, with the steps of claim 2 executed for each window, and for a particular window, in the step of choosing one of the frequency components from the third removing as the heart rate, the frequency component that is closest to the one chosen as the heart rate in the previous time window is selected as the heart rate for the window.

6. A method for computing the SpO₂ value of a user, comprising:

- (a) a first detecting of a time-dependent optical waveform comprising a pulse induced by the user's heartbeat, with an optical pulse sensor attached to the user that transmits light at a first wavelength;
- (b) a second detecting of a time-dependent optical waveform comprising a pulse induced by the user's heartbeat, with an optical pulse sensor attached to the user that transmits light at a second wavelength;
- (c) a first computing of the DC value of the signal of the first detected waveform;
- (d) a second computing of the DC value of the signal of the second detected waveform;
- (e) a third computing the heart rate using steps (a)-(h) of claim 1, using the first detected waveform;
- (f) a fourth computing of the frequency components of the first detected waveform and choosing the amplitude of the frequency component that matches the heart rate computed in step of the third computing as the AC value of the first detected waveform;
- (g) a fifth computing of the frequency components of the second detected waveform and choosing the amplitude of the frequency component that matches the heart rate computed in the step of the third computing as the AC value of the second detected waveform; and
- (h) a sixth computing of the ratio of the ratio of the AC value of the fourth computing to the DC value of the first computing to ratio of the AC value of the fifth computing to the DC value of the second computing, which is then transformed by a polynomial to obtain SpO₂ value.

7. The method of SpO₂ computation of claim 6 wherein,

- (a) apart from the pulse signals at two different wavelengths computed in the steps of the first detecting and the second detecting, the method further comprises detecting a time-dependent optical waveform comprising a pulse induced by the user's heartbeat with an optical sensor configured to attach to the user that transmits light at a third wavelength; and

(b) the heart rate computation of the step of the third computing is performed using the pulse signal at the third wavelength.

8. The method of claim 6, wherein the SpO₂ computation is performed in windows, with the heart rate computation of the step of the third computing performed using the following steps:

- (a) measuring activity across more than one dimension;
- (b) third computing of the frequency components of the different axes of the accelerometer signal of the second detecting by means of the same mathematical transform as in the first detecting;
- (c) a fourth removing of the computed frequency components from the third computing that are below pre-defined thresholds of the maximum amplitude across the frequency components of each axis of the accelerometer;
- (d) a fifth removing of the computed frequency components of the pulse signal computed in the first computing that are matching to those frequency components of each axis of the accelerometer signal that remain after the fourth removing; and
- (e) a sixth removing of the frequency components of the fifth removing that are below another pre-defined threshold of the maximum amplitude across the remaining frequency components of the pulse signal of the fifth removing.

9. A device for estimating the heart rate of a user under activity comprising:

- (a) means of recording a time-dependent optical waveform pulse induced by the user's heartbeat with an optical pulse sensor configured to attach to the user;
 - (b) means of recording a time-dependent accelerometer waveform comprising using an inertial sensor configured to be in proximity with the optical pulse sensor;
 - (c) a processor that acquires the optical waveform and accelerometer waveform, with:
 - (i) first means for computing the frequency components of the optical signal using a mathematical transform;
 - (ii) second means for computing the frequency components of the accelerometer signal using the same mathematical transform as the first means for computing;
 - (iii) first means for removing all frequency components computed by the second means for removing that are below a pre-defined threshold of the maximum amplitude across the frequency components of the accelerometer;
 - (iv) second means for removing all the frequency components of the pulse signal computed by the first means for computing that are matching to those frequency components of the accelerometer signal that remain after removal by the first means for removing;
 - (v) third means for removing all frequency components resulting from the second means for removing that are below another pre-defined threshold of the maximum amplitude across the remaining frequency components of the pulse signal resulting from the second means for removing;
 - (vi) means for choosing one of the frequency components from the third means for removing as the heart rate.
10. The device of claim 9, wherein,
- (a) the accelerometer has more than one axis, measuring activity across more than one dimension;

- (b) means for computing the frequency components of the different axes of the accelerometer signal from the second means for computing use the same mathematical transform as the first means for computing; the device further comprising
 - (c) fourth means for removing all frequency components of each axis of the accelerometer in the means for computing that are below pre-defined thresholds of the maximum amplitude across the frequency components of each axis of the accelerometer;
 - (d) fifth means for removing all the frequency components of the pulse signal computed in the first means for computing that are matching to those frequency components of each axis of the accelerometer signal that remain after removal by the fourth means for removing;
 - (e) sixth means for removing all the frequency components from the second means for removing that are below another predefined threshold of the maximum amplitude across the remaining frequency components of the pulse signal in the fifth means for removing.
- 11.** The device of claim **9** where in the second means for removing, the frequency component with the highest amplitude is chosen as the heart rate.
- 12.** The device of claim **9** wherein the processor segments the pulse signal and accelerometer signal into multiple time windows, with the first and second means for computing and the first, second and third means for removing executed for each window, and for a particular window, in the means for choosing one of the frequency components, the frequency component that is closest to the one chosen as the heart rate in the previous time window is selected as the heart rate for the window.
- 13.** A device for computing the SpO₂ value of an user, comprising:
- (a) means for detecting a time-dependent optical waveform comprising a pulse induced by the user's heartbeat with an optical sensor configured to attach to the user that transmits light at a first wavelength;
 - (b) means for detecting a time-dependent optical waveform comprising a pulse induced by the user's heartbeat with an optical sensor configured to attach to the user that transmits light at a second wavelength;
 - (c) means for computing the DC value of the signal of the first wavelength;
 - (d) means for computing the DC value of the signal of the second wavelength;
 - (e) means for computing the heart rate using a processor that acquires the optical waveform and accelerometer waveform, including,
 - (i) first means for computing the frequency components of the optical signal using a mathematical transform;
 - (ii) second means for computing the frequency components of the accelerometer signal using the same mathematical transform as the first means for computing;
 - (iii) first means for removing all frequency components computed by the second means for computing that are below a pre-defined threshold of the maximum amplitude across the frequency components of the accelerometer;
 - (iv) second means for removing all the frequency components of the pulse signal computed by the first means for computing that are matching to those frequency components of the accelerometer signal that remain after removal by the first means for removing;
 - (v) third means for removing all frequency components resulting from the second means for removing that are below another pre-defined threshold of the maximum amplitude across the remaining frequency components of the pulse signal resulting from the second means for removing; and
 - (vi) means for choosing one of the frequency components from the third means for removing as the heart rate, using one of the pulse signal at the first wavelength;
 - (f) means for computing the frequency components of the signal at the first wavelength and choosing the amplitude of the frequency component that matches the heart rate computed with the means for computing the heart rate as the AC value at the first wavelength;
 - (g) means for computing the frequency components of the signal at the second wavelength and choosing the amplitude of the frequency component that matches the heart rate computed with the means for computing the heart rate as the AC value at the second wavelength; and
 - (h) means for computing the ratio of AC/DC at first wavelength to AC/DC at second wavelength, which is then used for calibration to obtain the SpO₂ values.
- 14.** The device of claim **13**, wherein,
- (a) apart from the pulse signals at two different wavelengths computed in the means for detecting a time-dependent optical waveform and the means for detecting a time-dependent optical waveform, the device further comprises means of detecting a time-dependent optical waveform comprising a pulse induced by the user's heartbeat with an optical sensor configured to attach to the user that transmits light at a third wavelength; and
 - (b) means for computing the heart rate enabled to perform using the pulse signal at the third wavelength.
- 15.** The method of claim **8**, wherein the signals are divided into time segments of activity and inactivity, based on the accelerometer values, and the SpO₂ computations are performed individually in the different segments.
- 16.** A non-transitory computer readable medium having computer instructions recorded thereon, the computer instructions configured to perform a method for computing a heart rate of a user when executed on a processor of a device, the method comprising the steps of:
- detecting a time-dependent optical waveform having a pulse induced by a heartbeat of the user with an optical pulse sensor attached to the user;
 - detecting a time-dependent accelerometer waveform with an inertial sensor arranged in proximity with the optical pulse sensor;
 - computing frequency components of the time-dependent optical waveform by a mathematical transform;
 - computing frequency components of the time-dependent accelerometer waveform by the mathematical transform;
 - first removing the computed frequency components of the time-dependent accelerometer waveform below a first pre-defined threshold of the maximum amplitude across the frequency components of the accelerometer;

second removing the computed frequency components of the time-dependent optical waveform that are matching to the computed frequency components of the time-dependent accelerometer waveform that remain after the first removing;

third removing the computed frequency components after the second removing below a second pre-defined threshold of the maximum amplitude across the remaining frequency components after the second removing; and

choosing one of the computed frequency components from the third removing as the heart rate.

* * * * *

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摘要(译)

一种用于计算用户的心率值的方法，包括利用附着到用户的光学脉冲传感器来检测包括由心跳引起的脉搏的时间相关光学波形，通过布置的惯性传感器检测时间相关加速度计波形在所述光学脉冲传感器附近，通过数学变换计算所述时间相关光学波形的频率分量，通过所述数学变换计算所述时间相关加速度计波形的频率分量，首先去除所述时间相关光学波形的计算频率分量，取决于时间相关的加速度计波形，其低于预先定义的阈值，其次去除与计算的频率分量相匹配的时间相关的光学波形的计算出的频率分量，第三次移除在第二次移除之后的计算出的频率分量，阈值，并从第三个中选择一个计算出的频率分量作为心率去除。

