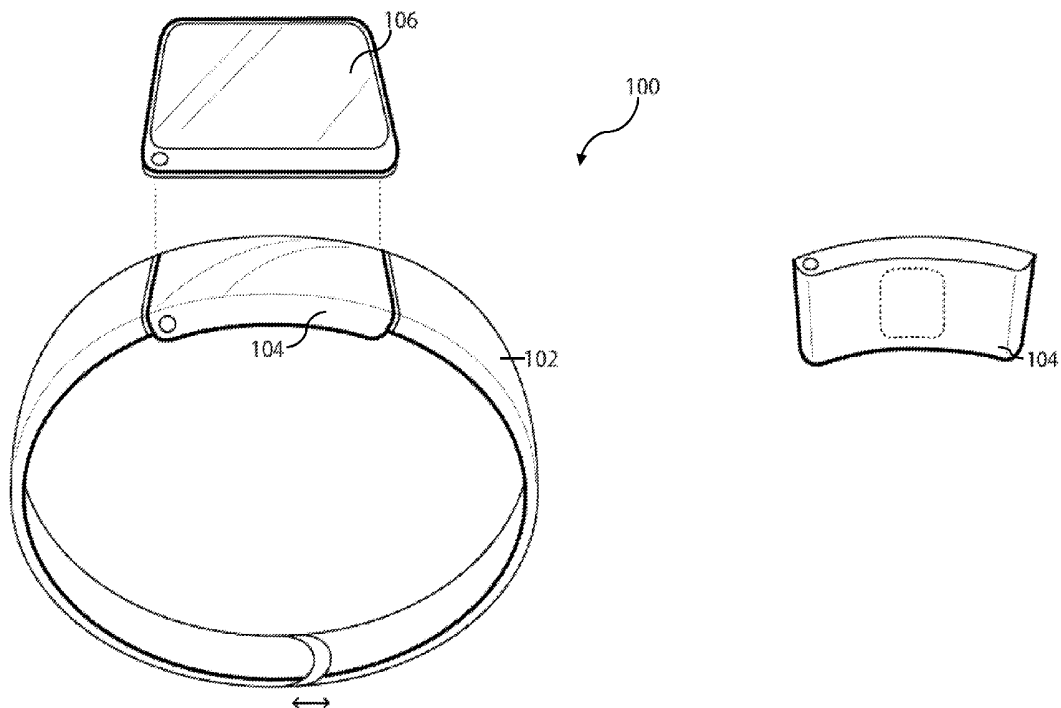




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Ritscher et al.(10) **Pub. No.: US 2018/0070839 A1**(43) **Pub. Date: Mar. 15, 2018**(54) **VARIABLE BRIGHTNESS AND GAIN FOR
OPTIMIZING SIGNAL ACQUISITION**(71) Applicant: **Whoop, Inc.**, Boston, MA (US)(72) Inventors: **David E. Ritscher**, Framingham, MA
(US); **Behnoosh Tavakoli**, Needham,
MA (US); **Mostafa Ghannad-Rezaie**,
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5/681 (2013.01); **A61B 5/7435** (2013.01);
A61B 5/4809 (2013.01)(57) **ABSTRACT**

A physiological monitoring device controls an optical signal acquisition system within a number of discrete operating states, each providing values for controllable parameters such as illumination intensity for a light source and the gain for an optical detector. Using this technique, a small number of operating states may be defined, such as operating states that are known to work well within expected use scenarios. This approach advantageously facilitates optimal or near optimal operation across a range of most likely use cases while avoiding complex or continuous optimization problems. The list of operating states may further be prioritized so that a best operating state can be selected based on, e.g., signal quality or environmental conditions.



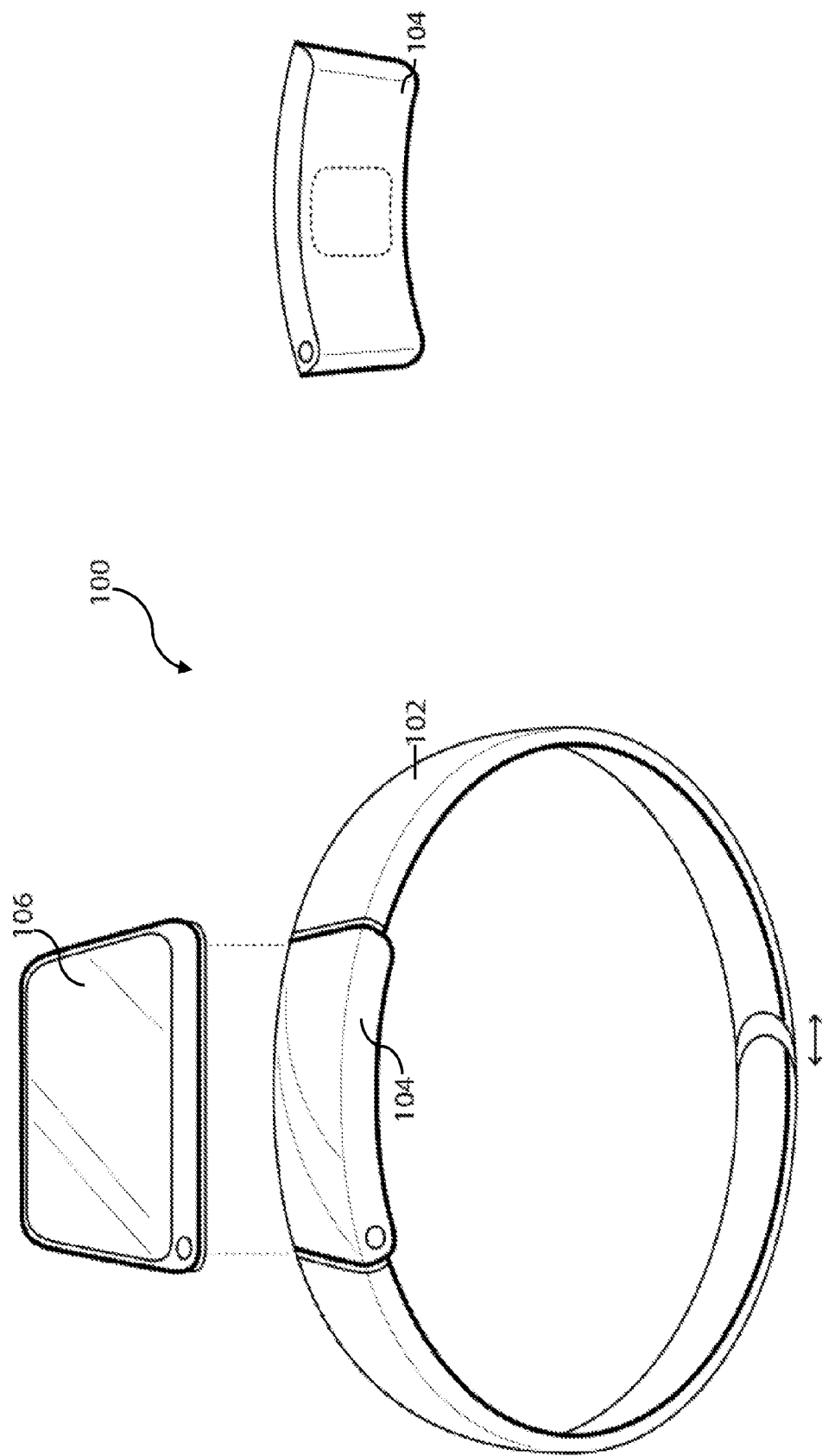


Fig. 1

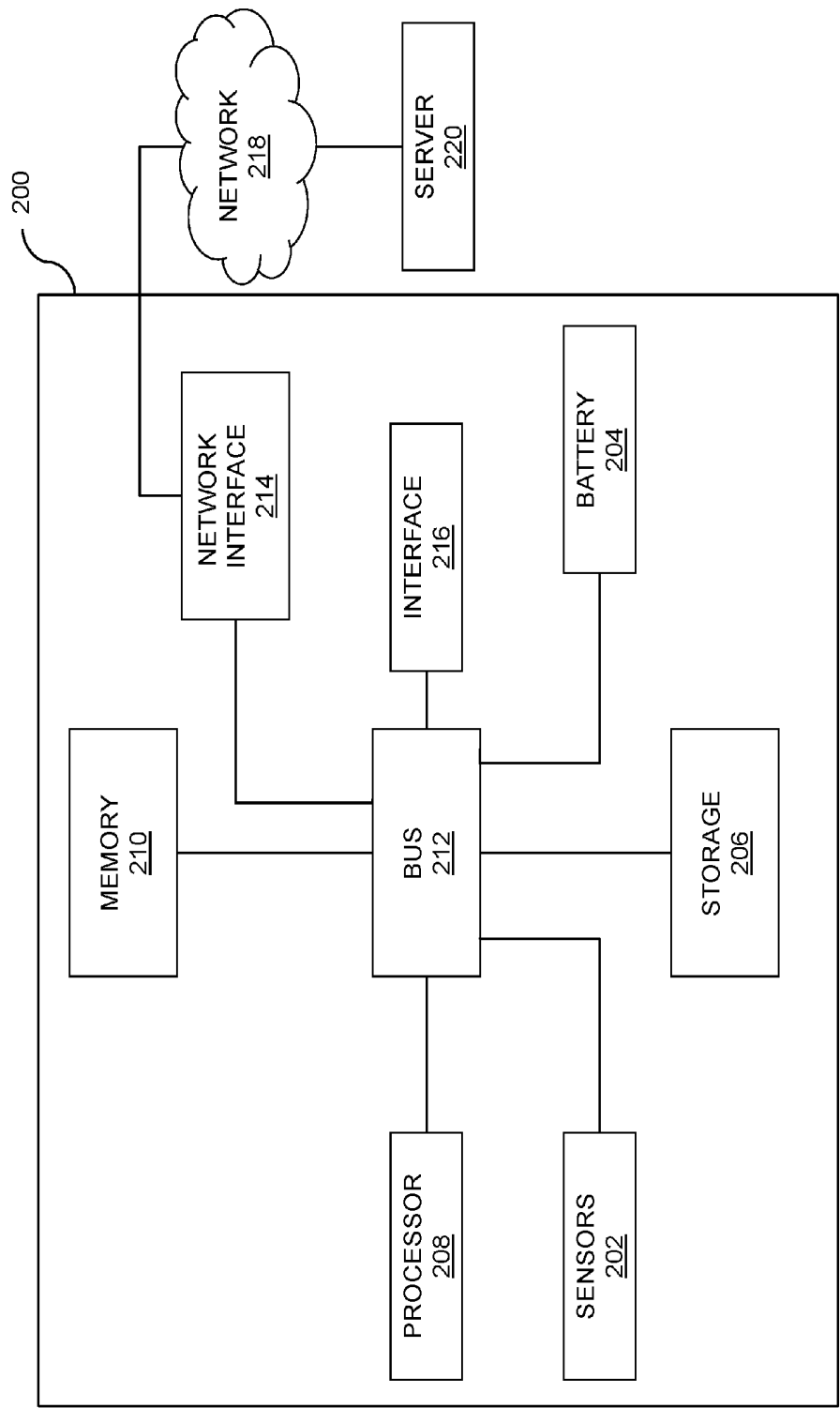


Fig. 2

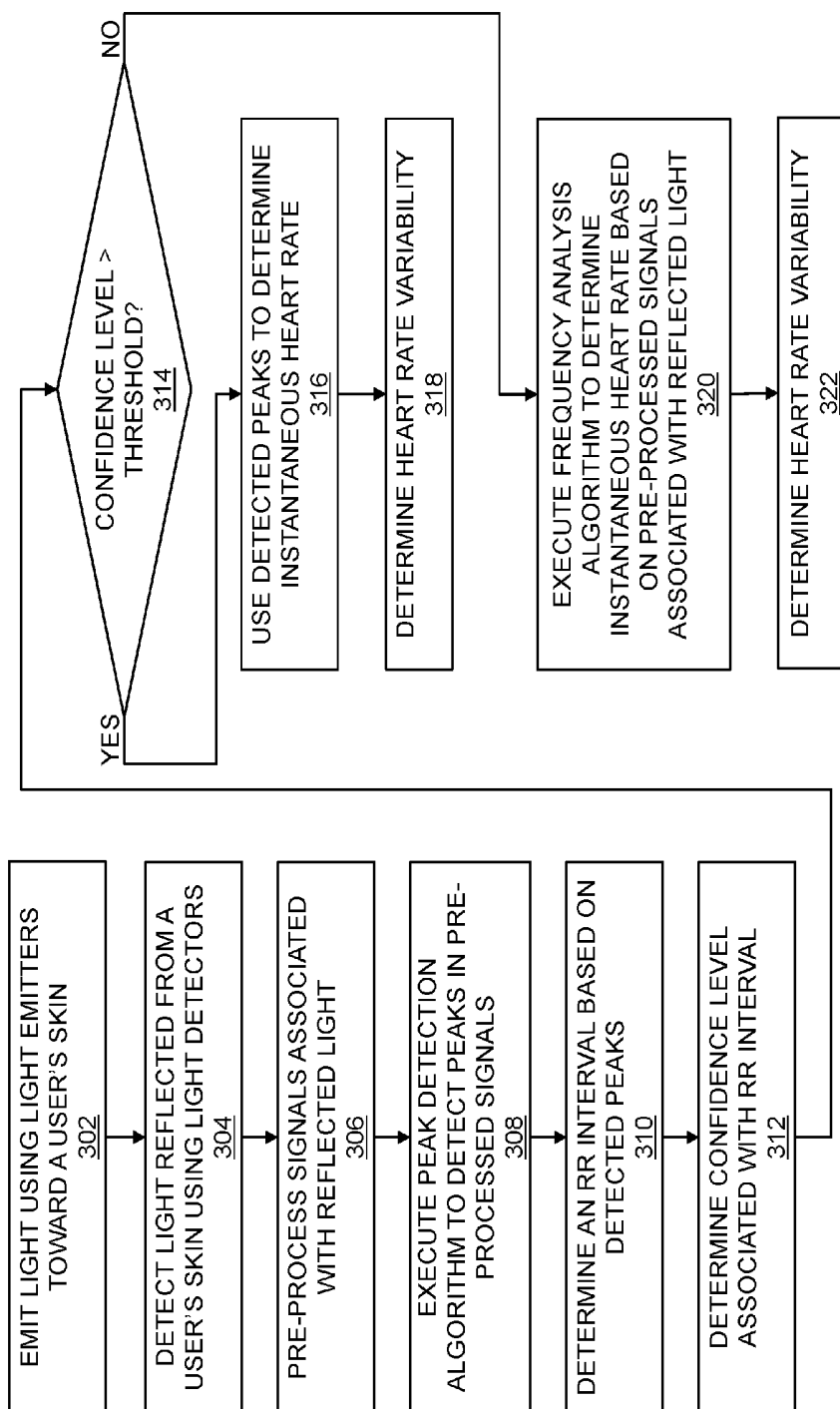


Fig. 3

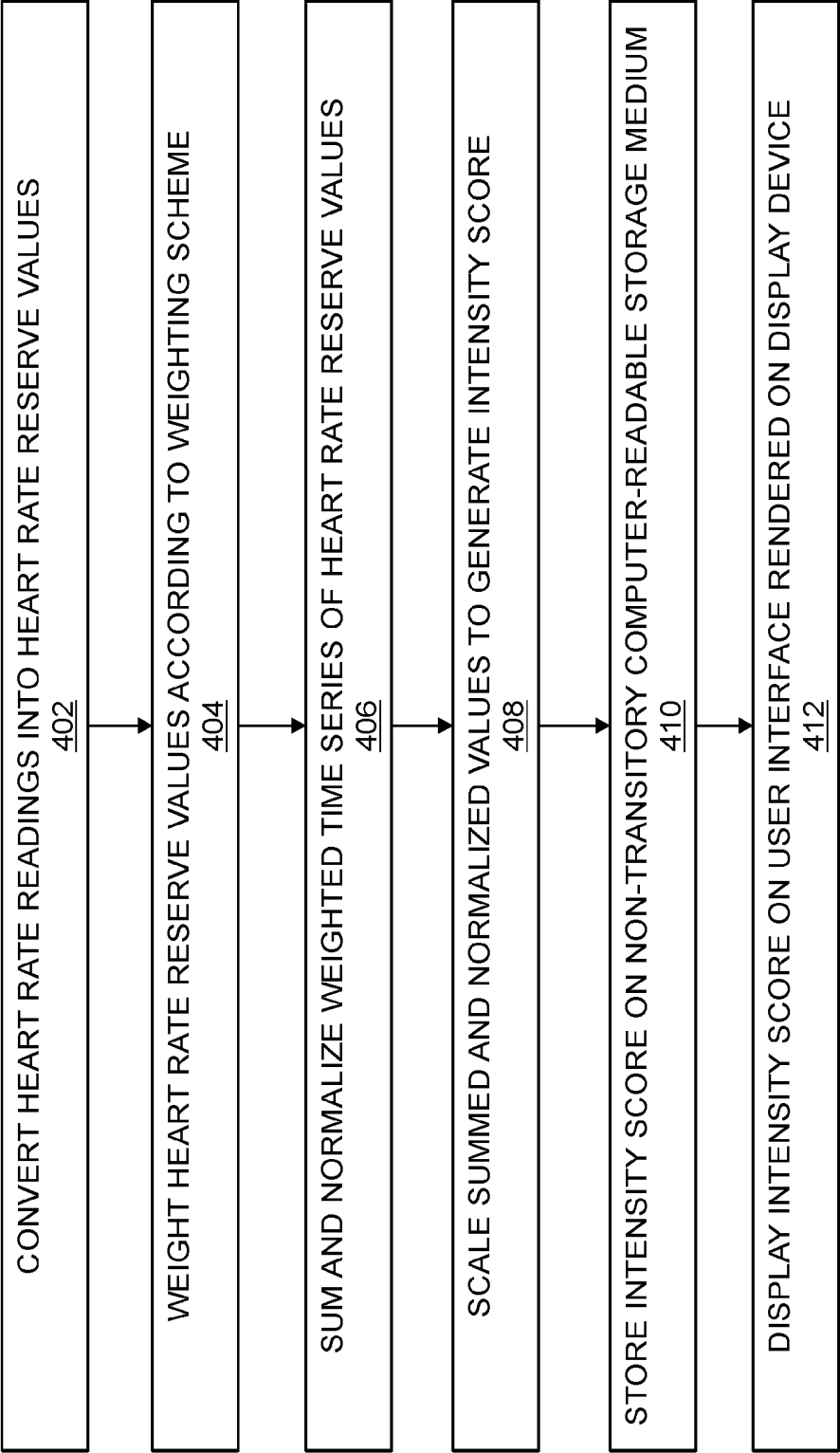


Fig. 4

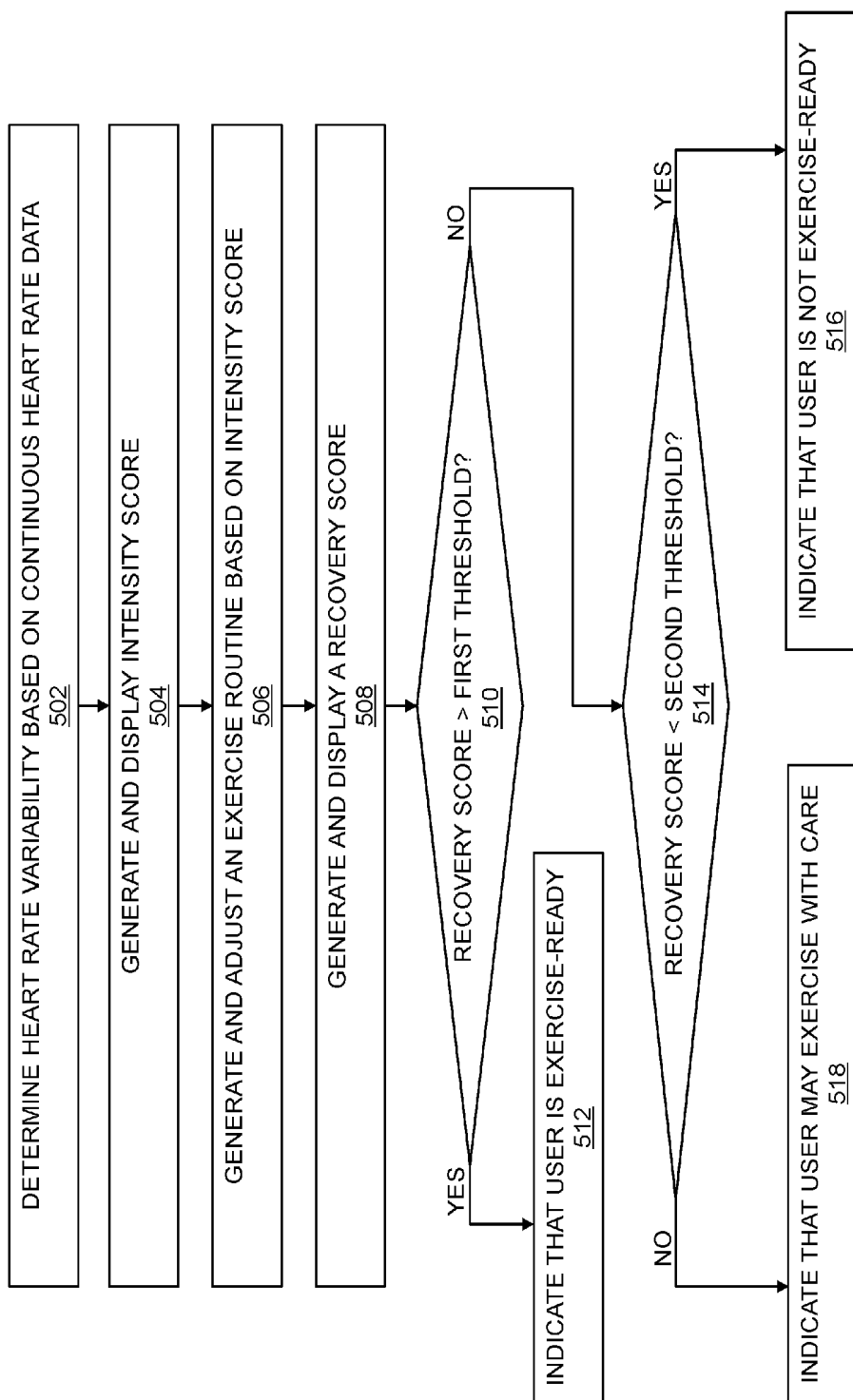


Fig. 5

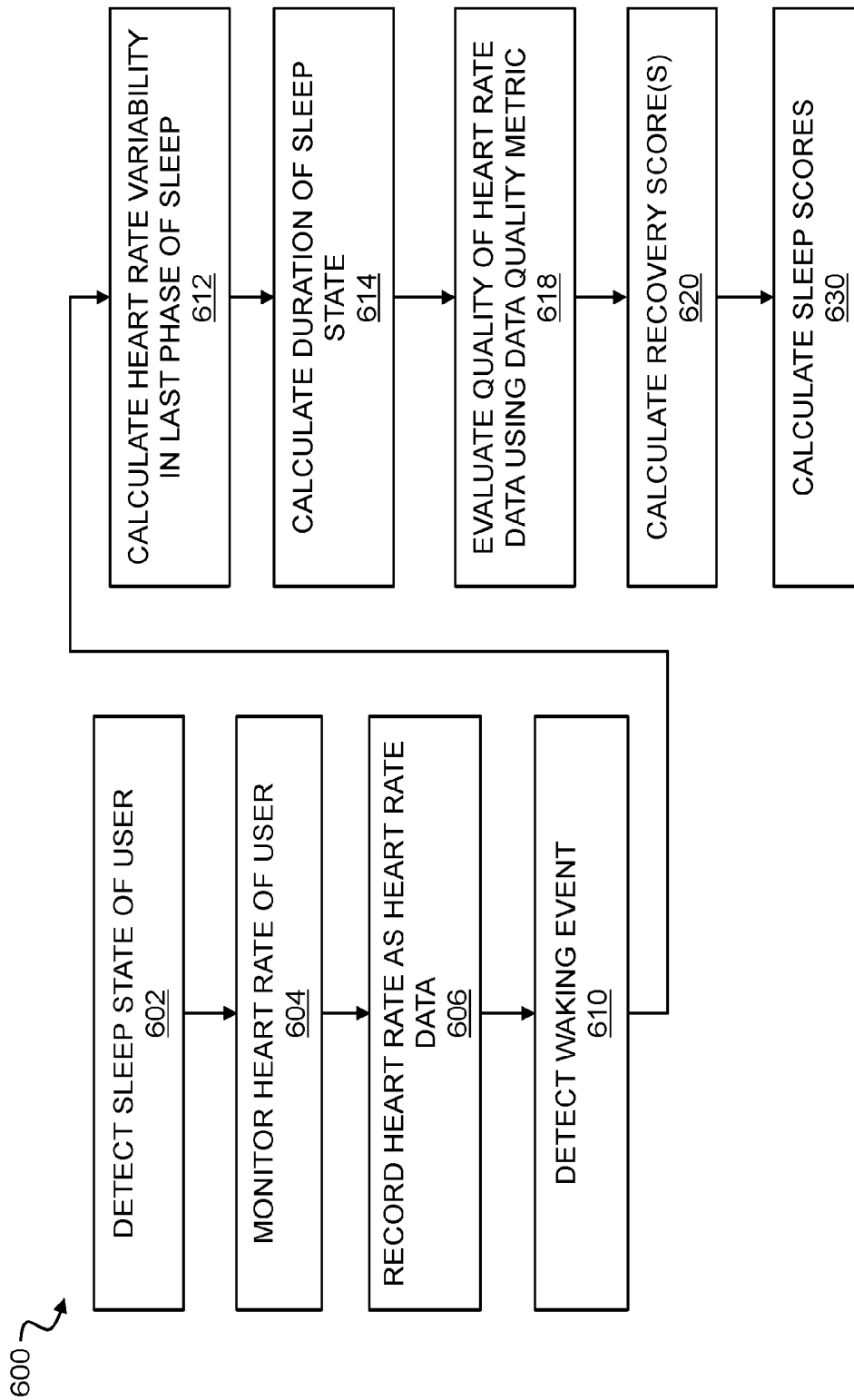


Fig. 6

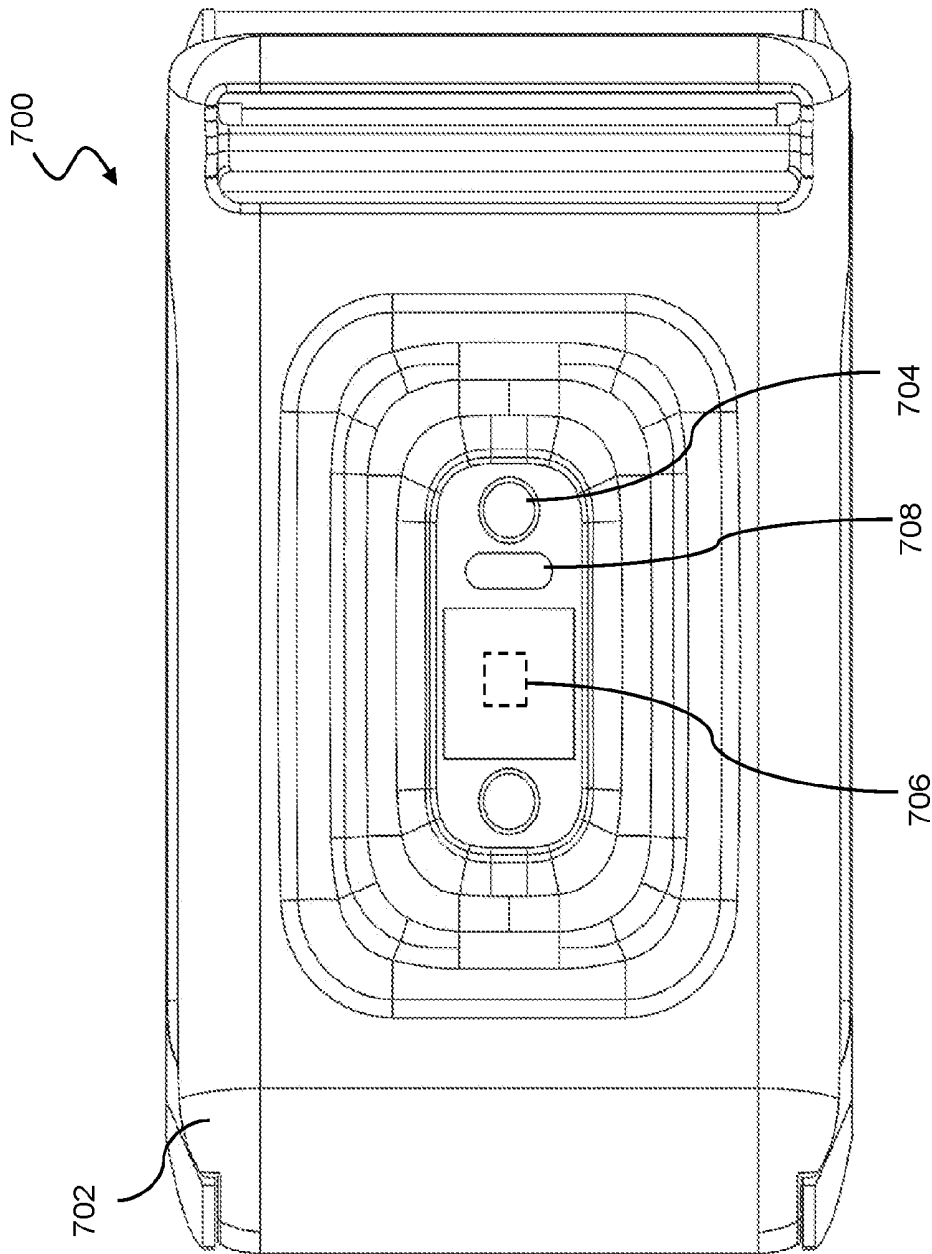


Fig. 7

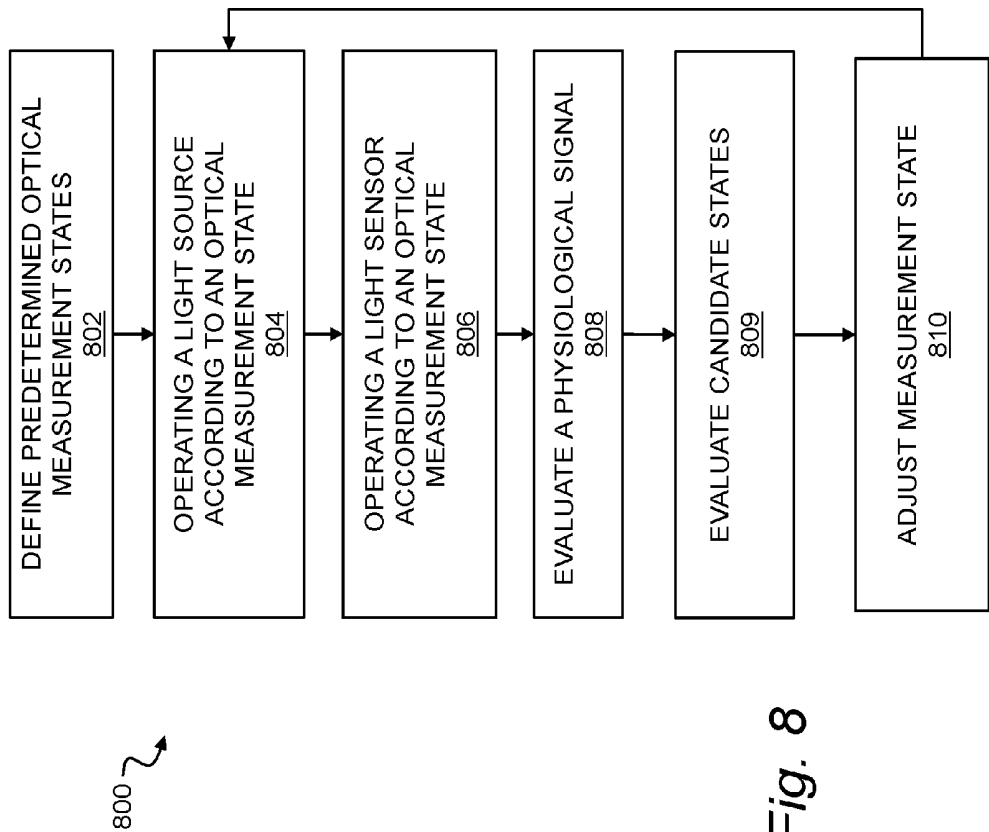


Fig. 8

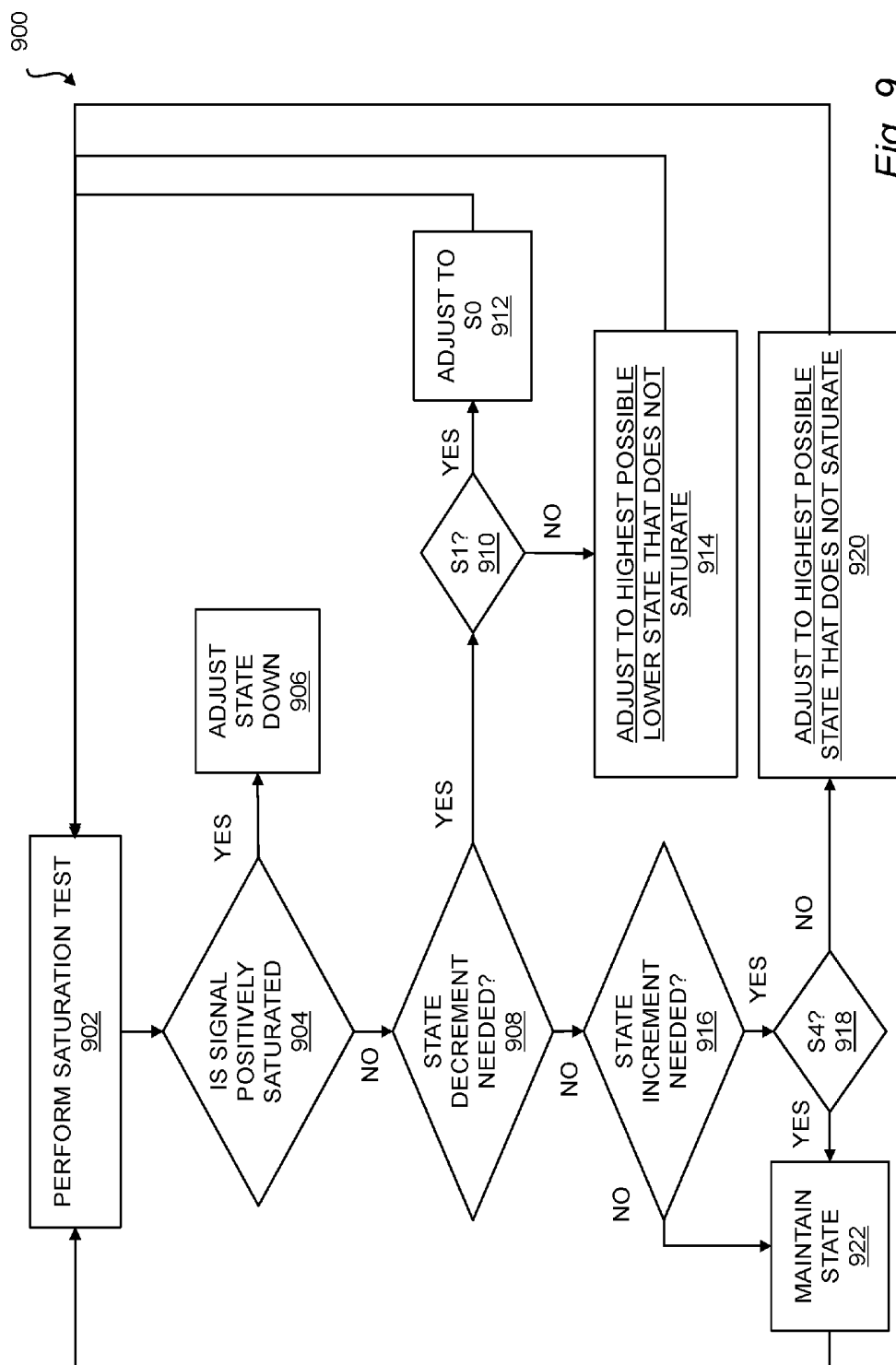


Fig. 9

VARIABLE BRIGHTNESS AND GAIN FOR OPTIMIZING SIGNAL ACQUISITION

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of U.S. Prov. Application No. 62/394,829 filed on Sep. 15, 2016, the contents of which are hereby incorporated by reference in its entirety.

BACKGROUND

[0002] Techniques such as photoplethysmography can provide useful physiological signals for evaluating workout intensity, recovery, sleep quality and so forth. However, the control parameters for an optical instrumentation system, such as illumination intensity and detector gain, can present complex optimization challenges for a physiological monitor. There remains a need for improved techniques to control the operating parameters of a physiological signal acquisition system.

SUMMARY

[0003] A physiological monitoring device controls an optical signal acquisition system within a number of discrete operating states, each providing values for controllable parameters such as illumination intensity for a light source and the gain for an optical detector. Using this technique, a small number of operating states may be defined, such as operating states that are known to work well within expected use scenarios. This approach advantageously facilitates optimal or near optimal operation across a range of most likely use cases while avoiding complex or continuous optimization problems. The list of operating states may further be prioritized so that a best operating state can be selected based on, e.g., signal quality or environmental conditions.

[0004] A method disclosed herein may include providing a plurality of predetermined optical measurement states. Each one of the plurality of predetermined optical measurement states may be characterized by at least a first discrete value for electronically controlling a brightness of a light source, such as a light emitting diode ("LED"), of the physiological monitoring device and a second discrete value for electronically controlling a gain of a light sensor of the physiological monitoring device. The plurality of predetermined optical measurement states may be ordered into a prioritized list according to preferred measurement states. The light source may be operated according to the first discrete value for a current one of the predetermined optical measurement states and the light sensor may be operated according to the second discrete value for the current one of the predetermined optical measurement states. The physiological signal may be evaluated based on data from the light sensor the predetermined optical measurement state may be adjusted in response to a detected condition.

[0005] The prioritized list may be ordered for monotonically increasing magnitudes of the first discrete value as a priority within the prioritized list increases to a more preferred measurement state. The prioritized list may also or instead be ordered for monotonically increasing magnitudes of the second discrete value as a priority within the prioritized list increases to a more preferred measurement state.

[0006] The detected condition may include a saturation of the light sensor, and wherein adjusting the predetermined

optical measurement state includes decrementing to a lower priority state in response to the detected condition. The detected condition may also or instead include a decrease in a quality of the physiological signal, and wherein adjusting the predetermined optical measurement state includes incrementing to a higher priority state in response to the detected condition. The detected condition may also or instead include a removal and replacement of the physiological monitoring device on a user, and wherein adjusting the predetermined optical measurement state includes changing to a highest priority state in response to the detected condition. The detected condition may also or instead include an increase in ambient light, and wherein adjusting the predetermined optical measurement state includes incrementing to a higher priority state in response to the detected condition.

[0007] The physiological monitoring device may include a wearable physiological monitoring device and may also or instead include a photoplethysmography system for measuring a heart rate of a user.

[0008] A wearable physiological monitoring system may include a housing configured to be worn on a limb of a user and a light source within the housing. The light source may include one or more light emitting diodes. The system may further include a light sensor within the housing which is positioned to receive an optical signal from the light source through the limb of the user when placed for use. A memory for storing a plurality of predetermined optical measurement states may also be included. Each one of the plurality of predetermined optical measurement states may be characterized by at least a first discrete value for electronically controlling a brightness of the light source and a second discrete value for electronically controlling a gain of the light. The plurality of predetermined optical measurement states may be ordered into a prioritized list according to preferred measurement states. The system may further include a processor within the housing and coupled in a communicating relationship with the light source, the light sensor and the memory. The processor may be configured by executable code stored in the memory to perform the steps of operating the light source according to the first discrete value for a current one of the predetermined optical measurement states, operating the light sensor according to the second discrete value for the current one of the predetermined optical measurement states, evaluating a physiological signal based on data from the light sensor, and adjusting the predetermined optical measurement state in response to a detected condition.

[0009] A computer program product for operating a physiological monitoring device that uses an optical signal to determine a physiological signal is described. The computer program product may comprise computer executable code embodied in a non-transitory computer readable medium that, when executing on the physiological monitoring device stores a plurality of predetermined optical measurement states. Each one of the plurality of predetermined optical measurement states may be characterized by at least a first discrete value for electronically controlling a brightness of a light source of the physiological monitoring device and a second discrete value for electronically controlling a gain of a light sensor of the physiological monitoring device. The plurality of predetermined optical measurement states may be ordered into a prioritized list according to preferred measurement states. The computer executable code may

operate the light source according to the first discrete value for a current one of the predetermined optical measurement states and operate the light sensor according to the second discrete value for the current one of the predetermined optical measurement states. The computer executable code may also evaluate the physiological signal based on data from the light sensor and adjust the predetermined optical measurement state in response to a detected condition.

BRIEF DESCRIPTION OF THE DRAWINGS

[0010] The foregoing and other objects, features, and advantages of the devices, systems, and methods described herein will be apparent from the following description of particular embodiments thereof, as illustrated in the accompanying figures. The figures are not necessarily to scale, emphasis instead being placed upon illustrating the principles of the devices, systems, and methods described herein.

[0011] FIG. 1 illustrates front and back perspective views of a wearable system configured as a bracelet including one or more straps.

[0012] FIG. 2 shows a block diagram illustrating components of a wearable physiological measurement system configured to provide continuous collection and monitoring of physiological data.

[0013] FIG. 3 is a flowchart illustrating a signal processing algorithm for generating a sequence of heart rates for every detected heartbeat that may be embodied in computer-executable instructions stored on one or more non-transitory computer-readable media.

[0014] FIG. 4 is a flowchart illustrating a method of determining an intensity score.

[0015] FIG. 5 is a flowchart illustrating a method by which a user may use intensity and recovery scores.

[0016] FIG. 6 is a flow chart illustrating a method for detecting heart rate variability in sleep states.

[0017] FIG. 7 is a bottom view of a wearable, continuous physiological monitoring device.

[0018] FIG. 8 is a flow chart illustrating a method 800 for controlling a signal acquisition system.

[0019] FIG. 9 is a flow chart illustrating a method of adjusting an optical measurement state.

DETAILED DESCRIPTION

[0020] The embodiments will now be described more fully hereinafter with reference to the accompanying figures, in which preferred embodiments are shown. The foregoing may, however, be embodied in many different forms and should not be construed as limited to the illustrated embodiments set forth herein. Rather, these illustrated embodiments are provided so that this disclosure will convey the scope to those skilled in the art.

[0021] All documents mentioned herein are hereby incorporated by reference in their entirety. References to items in the singular should be understood to include items in the plural, and vice versa, unless explicitly stated otherwise or clear from the text. Grammatical conjunctions are intended to express any and all disjunctive and conjunctive combinations of conjoined clauses, sentences, words, and the like, unless otherwise stated or clear from the context. Thus, the term “or” should generally be understood to mean “and/or” and so forth.

[0022] Recitations of ranges of values herein are not intended to be limiting, referring instead individually to any and all values falling within the range, unless otherwise indicated herein, and each separate value within such a range is incorporated into the specification as if it were individually recited herein. The words “about,” “approximately,” or the like, when accompanying a numerical value, are to be construed as including any deviation as would be appreciated by one of ordinary skill in the art to operate satisfactorily for an intended purpose, or where applicable, any acceptable range of deviation appropriate to a measurement of the numerical value or achievable by instrumentation used to measure the amount. Ranges of values and/or numeric values are provided herein as examples only, and do not constitute a limitation on the scope of the described embodiments. The use of any and all examples, or exemplary language (“e.g.,” “such as,” or the like) provided herein, is intended merely to better illuminate the embodiments and does not pose a limitation on the scope of the embodiments. No language in the specification should be construed as indicating any unclaimed element as essential to the practice of the embodiments.

[0023] In the following description, it is understood that terms such as “first,” “second,” “above,” “below,” and the like, are words of convenience and are not to be construed as limiting terms.

[0024] Exemplary embodiments provide physiological measurement systems, devices and methods for continuous health and fitness monitoring, and provide improvements to overcome the drawbacks of conventional heart rate monitors. One aspect of the present disclosure is directed to providing a lightweight wearable system with a strap that collects various physiological data or signals from a wearer. The strap may be used to position the system on an appendage or extremity of a user, for example, wrist, ankle, and the like. Exemplary systems are wearable and enable real-time and continuous monitoring of heart rate without the need for a chest strap or other bulky equipment which could otherwise cause discomfort and prevent continuous wearing and use. The system may determine the user's heart rate without the use of electrocardiography and without the need for a chest strap. Exemplary systems can thereby be used in not only assessing general well-being but also in continuous monitoring of fitness. Exemplary systems also enable monitoring of one or more physiological parameters in addition to heart rate including, but not limited to, body temperature, heart rate variability, motion, sleep, stress, fitness level, recovery level, effect of a workout routine on health and fitness, caloric expenditure, and the like.

[0025] A health or fitness monitor that includes bulky components may hinder continuous wear. Existing fitness monitors often include the functionality of a watch, thereby making the health or fitness monitor quite bulky and inconvenient for continuous wear. Accordingly, one aspect is directed to providing a wearable health or fitness system that does not include bulky components, thereby making the bracelet slimmer, unobtrusive and appropriate for continuous wear. The ability to continuously wear the bracelet further allows continuous collection of physiological data, as well as continuous and more reliable health or fitness monitoring. For example, embodiments of the bracelet disclosed herein allow users to monitor data at all times, not just during a fitness session. In some embodiments, the wearable system may or may not include a display screen for dis-

playing heart rate and other information. In other embodiments, the wearable system may include one or more light emitting diodes (LEDs) to provide feedback to a user and display heart rate selectively. In some embodiments, the wearable system may include a removable or releasable modular head that may provide additional features and may display additional information. Such a modular head can be releasably installed on the wearable system when additional information display is desired, and removed to improve the comfort and appearance of the wearable system. In other embodiments, the head may be integrally formed in the wearable system.

[0026] Embodiments also include computer-executable instructions that, when executed, enable automatic interpretation of one or more physiological parameters to assess the cardiovascular intensity experienced by a user (embodied in an intensity score or indicator) and the user's recovery after physical exertion or daily stress given sleep and other forms of rest (embodied in a recovery score). These indicators or scores may be stored and displayed in a meaningful format to assist a user in managing his health and exercise regimen. Computer-executable instructions may be provided in a cloud implementation. Embodiments also include a website that, e.g., allows users to monitor their own fitness results, share information with their teammates and coaches, compete with other users, and so forth. Both the wearable system and the website allow a user to provide feedback regarding his/her day, exercise and/or sleep, which enables recovery and performance ratings.

[0027] In an exemplary technique of data transmission, data collected by a wearable system may be transmitted directly to a cloud-based data storage, from which data may be downloaded for display and analysis on a website. In another exemplary technique of data transmission, data collected by a wearable system may be transmitted via a mobile communication device application to a cloud-based data storage, from which data may be downloaded for display and analysis on a website.

[0028] The term "user" as used herein, refers to any type of animal, human or non-human, whose physiological information may be monitored using an exemplary wearable physiological monitoring system. The term "body," as used herein, refers to the body of a user.

[0029] The term "continuous," as used herein in connection with heart rate data collection, refers to collection of heart rate data at a sufficient frequency to enable detection of every heart beat and also refers to collection of heart rate data continuously throughout the day and night.

[0030] The term "computer-readable medium," as used herein, refers to a non-transitory storage hardware, non-transitory storage device or non-transitory computer system memory that may be accessed by a controller, a microcontroller, a computational system or a module of a computational system to encode thereon computer-executable instructions or software programs. The "computer-readable medium" may be accessed by a computational system or a module of a computational system to retrieve and/or execute the computer-executable instructions or software programs encoded on the medium. The non-transitory computer-readable media may include, but are not limited to, one or more types of hardware memory, non-transitory tangible media (for example, one or more magnetic storage disks, one or more optical disks, one or more USB flash drives), computer

system memory or random access memory (such as, DRAM, SRAM, EDO RAM) and the like.

[0031] Exemplary embodiments provide wearable physiological measurements systems that are configured to provide continuous measurement of heart rate. Exemplary systems are configured to be continuously wearable on an appendage, for example, wrist or ankle, and do not rely on electrocardiography or chest straps in detection of heart rate. The exemplary system includes one or more light emitters for emitting light at one or more desired frequencies toward the user's skin, and one or more light detectors for received light reflected from the user's skin. The light detectors may include a photo-resistor, a photo-transistor, a photo-diode, and the like. As light from the light emitters (for example, green light) pierces through the skin of the user, the blood's natural absorbance or transmittance for the light provides fluctuations in the photo-resistor readouts. These waves have the same frequency as the user's pulse since increased absorbance or transmittance occurs only when the blood flow has increased after a heartbeat. The system includes a processing module implemented in software, hardware or a combination thereof for processing the optical data received at the light detectors and continuously determining the heart rate based on the optical data. The optical data may be combined with data from one or more motion sensors, e.g., accelerometers and/or gyroscopes, to minimize or eliminate noise in the heart rate signal caused by motion or other artifacts (or with other optical data of another wavelength).

[0032] FIG. 1 illustrates front and back perspective views of one embodiment of a wearable system configured as a bracelet **100** including one or more straps **102**. The bracelet is sleek and lightweight, thereby making it appropriate for continuous wear. The bracelet may or may not include a display screen, e.g., a screen **106** such as a light emitting diode (LED) display for displaying any desired data (e.g., instantaneous heart rate).

[0033] As shown in FIG. 1, the wearable system may include components configured to provide various functions such as data collection and streaming functions of the bracelet. In some embodiments, the wearable system may include a button underneath the wearable system. In some embodiments, the button may be configured such that, when the wearable system is properly tightened to one's wrist, the button may press down and activate the bracelet to begin storing information. In other embodiments, the button may be disposed and configured such that it may be pressed manually at the discretion of a user to begin storing information or otherwise to mark the start or end of an activity period such as sleep. In some embodiments, the button may be held to initiate a time stamp and held again to end a time stamp, which may be transmitted, directly or through a mobile communication device application, to a website as a time stamp.

[0034] The wearable system may include a heart rate monitor. In one example, the heart rate may be detected from the radial artery. Thus, the wearable system may include a pulse sensor. In one embodiment, the wearable system may be configured such that, when a user wears it around their wrist and tightens it, the sensor portion of the wearable system is secured over the user's radial artery or other blood vessel. Secure connection and placement of the pulse sensor over the radial artery or other blood vessel may allow measurement of heart rate and pulse. It will be understood that this configuration is provided by way of example only,

and that other sensors, sensor positions, and monitoring techniques may also or instead be employed without departing from the scope of this disclosure.

[0035] In some embodiments, the pulse or heart rate may be taken using an optical sensor coupled with one or more light emitting diodes (LEDs), all directly in contact with the user's wrist. The LEDs are provided in a suitable position from which light can be emitted into the user's skin. In one example, the LEDs mounted on a side or top surface of a circuit board in the system to prevent heat buildup on the LEDs and to prevent burns on the skin. The circuit board may be designed with the intent of dissipating heat, e.g., by including thick conductive layers, exposed copper, heatsink, or similar. In one aspect, the pulse repetition frequency is such that the amount of power thermally dissipated by the LED is negligible. Cleverly designed elastic wrist straps can ensure that the sensors are always in contact with the skin and that there is a minimal amount of outside light seeping into the sensors. In addition to the elastic wrist strap, the design of the strap may allow for continuous micro adjustments (no preset sizes) in order to achieve an optimal fit, and a floating sensor module. The sensor module may be free to move with the natural movements caused by flexion and extension of the wrist.

[0036] In some embodiments, the wearable system may be configured to record other physiological parameters including, but not limited to, skin temperature (using a thermometer), galvanic skin response (using a galvanic skin response sensor), motion (using one or more multi-axes accelerometers and/or gyroscope), and the like, and environmental or contextual parameters, e.g., ambient temperature, humidity, time of day, and the like. In an implementation, sensors are used to provide at least one of continuous motion detection, environmental temperature sensing, electrodermal activity (EDA) sensing, galvanic skin response (GSR) sensing, and the like. In this manner, an implementation can identify the cause of a detected physiological event. Reflectance PhotoPlethysmography (RPPG) may be used for the detection of cardiac activity, which may provide for non-intrusive data collection, usability in wet, dusty and otherwise harsh environments, and low power requirements. For example, as explained herein, using the physiological readouts of the device and the analytics described herein, an "Intensity Score" (e.g., 0-21) (e.g., that measures a user's recent exertion), a "Recovery Score" (e.g., 0-100%), and "Sleep Score" (e.g., 0-100) may together measure readiness for physical and psychological exertion.

[0037] In some embodiments, the wearable system may further be configured such that a button underneath the system may be pressed against the user's wrist, thus triggering the system to begin one or more of collecting data, calculating metrics and communicating the information to a network. In some embodiments, the sensor used for, e.g., measuring heart rate or GSR or any combination of these, may be used to indicate whether the user is wearing the wearable system or not. In some embodiments, power to the one or more LEDs may be cut off as soon as this situation is detected, and reset once the user has put the wearable system back on their wrist.

[0038] The wearable system may include one, two or more sources of battery life, e.g., two or more batteries. In some embodiments, it may have a battery that can slip in and out of the head of the wearable system and can be recharged using an included accessory. Additionally, the wearable

system may have a built-in battery that is less powerful. When the more powerful battery is being charged, the user does not need to remove the wearable system and can still record data (during sleep, for example).

[0039] In exemplary embodiments, the wearable system is enabled to automatically detect when the user is asleep, awake but at rest and exercising based on physiological data collected by the system.

[0040] FIG. 2 shows a block diagram illustrating exemplary components of a wearable physiological measurement system **200** configured to provide continuous collection and monitoring of physiological data. The wearable system **200** includes one or more sensors **202**. As discussed above, the sensors **202** may include a heart rate monitor. In some embodiments, the wearable system **200** may further include one or more of sensors for detecting calorie burn, distance and activity. Calorie burn may be based on a user's heart rate, and a calorie burn measurement may be improved if a user chooses to provide his or her weight and/or other physical parameters. In some embodiments, manual entering of data is not required in order to derive calorie burn; however, data entry may be used to improve the accuracy of the results. In some embodiments, if a user has forgotten to enter a new weight, he/she can enter it for past weeks and the calorie burn may be updated accordingly.

[0041] The sensors **202** may include one or more sensors for activity measurement. In some embodiments, the system may include one or more multi-axes accelerometers and/or gyroscope to provide a measurement of activity. In some embodiments, the accelerometer may further be used to filter a signal from the optical sensor for measuring heart rate and to provide a more accurate measurement of the heart rate. In some embodiments, the wearable system may include a multi-axis accelerometer to measure motion and calculate distance, whether it be in real terms as steps or miles or as a converted number. Activity sensors may be used, for example, to classify or categorize activity, such as walking, running, performing another sport, standing, sitting or lying down. In some embodiments, one or more of collected physiological data may be aggregated to generate an aggregate activity level. For example, heart rate, calorie burn, and distance may be used to derive an aggregate activity level. The aggregate level may be compared with or evaluated relative to previous recordings of the user's aggregate activity level, as well as the aggregate activity levels of other users.

[0042] The sensors **202** may include a thermometer for monitoring the user's body or skin temperature. In one embodiment, the sensors may be used to recognize sleep based on a temperature drop, GSR data, lack of activity according to data collected by the accelerometer, and reduced heart rate as measured by the heart rate monitor. The body temperature, in conjunction with heart rate monitoring and motion, may be used to interpret whether a user is sleeping or just resting, as body temperature drops significantly when an individual is about to fall asleep), and how well an individual is sleeping as motion indicates a lower quality of sleep. The body temperature may also be used to determine whether the user is exercising and to categorize and/or analyze activities.

[0043] The system **200** includes one or more batteries **204**. According to one embodiment, the one or more batteries may be configured to allow continuous wear and usage of the wearable system. In one embodiment, the wearable

system may include two or more batteries. The system may include a removable battery that may be recharged using a charger. In one example, the removable battery may be configured to slip in and out of a head portion of the system, attach onto the bracelet, or the like. In one example, the removable battery may be able to power the system for around a week. Additionally, the system may include a built-in battery. The built-in battery may be recharged by the removable battery. The built-in battery may be configured to power the bracelet for around a day on its own. When the more removable battery is being charged, the user does not need to remove the system and may continue collecting data using the built-in battery. In other embodiments, the two batteries may both be removable and rechargeable.

[0044] In some embodiments, the system **200** may include a battery that is a wireless rechargeable battery. For example, the battery may be recharged by placing the system or the battery on a rechargeable mat. In other example, the battery may be a long range wireless rechargeable battery. In other embodiments, the battery may be a rechargeable via motion. In yet other embodiments, the battery may be rechargeable using a solar energy source.

[0045] The wearable system **200** includes one or more non-transitory computer-readable media **206** for storing raw data detected by the sensors of the system and processed data calculated by a processing module of the system.

[0046] The system **200** includes a processor **208**, a memory **210**, a bus **212**, a network interface **214**, and an interface **216**. The network interface **214** is configured to wirelessly communicate data to an external network **218**. The network **218** may include any communication network through which computer systems may exchange data. For example, the network **218** may include, but is not limited to, the Internet, an intranet, a LAN (Local Area Network), a WAN (Wide Area Network), a MAN (Metropolitan Area Network), a wireless network, an optical network, and the like. To exchange data via the network **218**, the system **200** and the network **218** may use various methods, protocols and standards including, but not limited to, token ring, Ethernet, wireless Ethernet, Bluetooth, TCP/IP, UDP, HTTP, FTP, SNMP, SMS, MMS, SS7, JSON, XML, REST, SOAP, CORBA, IIOP, RMI, DCOM and Web Services. To ensure data transfer is secure, the system **200** may transmit data via the network using a variety of security measures including, but not limited to, TLS, SSL and VPN.

[0047] Some embodiments of the wearable system may be configured to stream information wirelessly to a social network. In some embodiments, data streamed from a user's wearable system to an external network **218** may be accessed by the user via a website. The network interface may be configured such that data collected by the system may be streamed wirelessly. In some embodiments, data may be transmitted automatically, without the need to manually press any buttons. In some embodiments, the system may include a cellular chip built into the system. In one example, the network interface may be configured to stream data using Bluetooth technology. In another example, the network interface may be configured to stream data using a cellular data service, such as via a 3G or 4G cellular network.

[0048] The system **200** may be coupled to one or more servers **220** via a communication network **218**.

[0049] In some embodiments, a physiological measurement system may be configured in a modular design to

enable continuous operation of the system in monitoring physiological information of a user wearing the system. The module design may include a strap and a separate modular head portion or housing that is removably couplable to the strap.

[0050] In the non-limiting illustrative module design, the strap **102** of a physiological measurement system may be provided with a set of components that enables continuous monitoring of at least a heart rate of the user so that it is independent and fully self-sufficient in continuously monitoring the heart rate without requiring the modular head portion **104**. In one embodiment, the strap includes a plurality of light emitters for emitting light toward the user's skin, a plurality of light detectors for receiving light reflected from the user's skin, an electronic circuit board comprising a plurality of electronic components configured for analyzing data corresponding to the reflected light to automatically and continually determine a heart rate of the user, and a first set of one or more batteries for supplying electrical power to the light emitters, the light detectors and the electronic circuit board. In some embodiments, the strap may also detect one or more other physiological characteristics of the user including, but not limited to, temperature, galvanic skin response, and the like.

[0051] Certain exemplary systems may be configured to be coupled to any desired part of a user's body so that the system may be moved from one portion of the body (e.g., wrist) to another portion of the body (e.g., ankle) without affecting its function and operation. In one embodiment, the identity of the portion of the user's body to which the wearable system is attached may be determined based on one or more parameters including, but not limited to, absorbance level of light as returned from the user's skin, reflectance level of light as returned from the user's skin, motion sensor data (e.g., accelerometer and/or gyroscope), altitude of the wearable system, and the like.

[0052] In some embodiments, the processing module is configured to determine that the wearable system is taken off from the user's body. In one example, the processing module may determine that the wearable system has been taken off if data from the galvanic skin response sensor indicates data atypical of a user's skin. If the wearable system is determined to be taken off from the user's body, the processing module is configured to deactivate the light emitters and the light detectors and cease monitoring of the heart rate of the user to conserve power.

[0053] Exemplary systems include a processing module configured to filter the raw photoplethysmography data received from the light detectors to minimize contributions due to motion, and subsequently process the filtered data to detect peaks in the data that correspond with heart beats of a user. The overall algorithm for detecting heart beats takes as input the analog signals from optical sensors (mV) and accelerometer, and outputs an implied beats per minute (heart rate) of the signal accurate within a few beats per minute as that determined by an electrocardiography machine even during motion.

[0054] In one aspect, using multiple LEDs with different wavelengths reacting to movement in different ways can allow for signal recovery with standard signal processing techniques. The availability of accelerometer information can also be used to compensate for coarse movement signal corruption. In order to increase the range of movements that the algorithm can successfully filter out, an aspect utilizes

techniques that augment the algorithm already in place. For example, filtering violent movements of the arm during very short periods of time, such as boxing as exercising, may be utilized by the system. By selective sampling and interpolating over these impulses, an aspect can account for more extreme cases of motion. Additionally, an investigation into different LED wavelengths, intensities, and configurations can allow the systems described herein to extract a signal across a wide spectrum of skin types and wrist sizes. In other words, motion filtering algorithms and signal processing techniques may assist in mitigating the risk caused by movement.

[0055] FIG. 3 is a flowchart illustrating an exemplary signal processing algorithm for generating a sequence of heart rates for every detected heartbeat that is embodied in computer-executable instructions stored on one or more non-transitory computer-readable media. In step 302, light emitters of a wearable physiological measurement system emit light toward a user's skin. In step 304, light reflected from the user's skin is detected at the light detectors in the system. In step 306, signals or data associated with the reflected light are pre-processed using any suitable technique to facilitate detection of heart beats. In step 308, a processing module of the system executes one or more computer-executable instructions associated with a peak detection algorithm to process data corresponding to the reflected light to detect a plurality of peaks associated with a plurality of beats of the user's heart. In step 310, the processing module determines an RR interval based on the plurality of peaks detected by the peak detection algorithm. In step 312, the processing module determines a confidence level associated with the RR interval.

[0056] Based on the confidence level associated with the RR interval estimate, the processing module selects either the peak detection algorithm or a frequency analysis algorithm to process data corresponding to the reflected light to determine the sequence of instantaneous heart rates of the user. The frequency analysis algorithm may process the data corresponding to the reflected light based on the motion of the user detected using, for example, an accelerometer. The processing module may select the peak detection algorithm or the frequency analysis algorithm regardless of a motion status of the user. It is advantageous to use the confidence in the estimate in deciding whether to switch to frequency-based methods as certain frequency-based approaches are unable to obtain accurate RR intervals for heart rate variability analysis. Therefore, an implementation maintains the ability to obtain the RR intervals for as long as possible, even in the case of motion, thereby maximizing the information that can be extracted.

[0057] For example, in step 314, it is determined whether the confidence level associated with the RR interval is above (or equal to or above) a threshold. In certain embodiments, the threshold may be predefined, for example, about 50%-90% in some embodiments and about 80% in one non-limiting embodiment. In other embodiments, the threshold may be adaptive, i.e., the threshold may be dynamically and automatically determined based on previous confidence levels. For example, if one or more previous confidence levels were high (i.e., above a certain level), the system may determine that a present confidence level that is relatively low compared to the previous levels is indicative of a less reliable signal. In this case, the threshold may be dynami-

cally adjusted to be higher so that a frequency-based analysis method may be selected to process the less reliable signal.

[0058] If the confidence level is above (or equal to or above) the threshold, in step 316, the processing module may use the plurality of peaks to determine an instantaneous heart rate of the user. On the other hand, in step 320, based on a determination that the confidence level associated with the RR interval is equal to or below the predetermined threshold, the processing module may execute one or more computer-executable instructions associated with the frequency analysis algorithm to determine an instantaneous heart rate of the user. The confidence threshold may be dynamically set based on previous confidence levels.

[0059] In some embodiments, in steps 318 or 322, the processing module determines a heart rate variability of the user based on the sequence of the instantaneous heart rates/beats.

[0060] The system may include a display device configured to render a user interface for displaying the sequence of the instantaneous heart rates of the user, the RR intervals and/or the heart rate variability determined by the processing module. The system may include a storage device configured to store the sequence of the instantaneous heart rates, the RR intervals and/or the heart rate variability determined by the processing module.

[0061] In one aspect, the system may switch between different analytical techniques for determining a heart rate such as a statistical technique for detecting a heart rate and a frequency domain technique for detecting a heart rate. These two different modes have different advantages in terms of accuracy, processing efficiency, and information content, and as such may be useful at different times and under different conditions. Rather than selecting one such mode or technique as an attempted optimization, the system may usefully switch back and forth between these differing techniques, or other analytical techniques, using a predetermined criterion. An exemplary statistical technique employs probabilistic peak detection. An exemplary frequency analysis algorithm used in an implementation isolates the highest frequency components of the optical data, checks for harmonics common in both the accelerometer data and the optical data, and performs filtering of the optical data. This latter algorithm may, for example, take as input raw analog signals from the accelerometer (3-axis) and pulse sensors, and output heart rate values or beats per minute (BPM) for a given period of time related to the window of the spectrogram.

[0062] The exemplary wearable system computes heart rate variability (HRV) to obtain an understanding of the recovery status of the body. These values are captured right before a user awakes or when the user is not moving, in both cases photoplethysmography (PPG) variability yielding equivalence to the ECG HRV. HRV is traditionally measured using an ECG machine and obtaining a time series of R-R intervals. Because an exemplary wearable system utilizes photoplethysmography (PPG), it does not obtain the electric signature from the heart beats; instead, the peaks in the obtained signal correspond to arterial blood volume. At rest, these peaks are directly correlated with cardiac cycles, which enables the calculation of HRV via analyzing peak-to-peak intervals (the PPG analog of RR intervals). It has

been demonstrated in medical literature that these peak-to-peak intervals, the “PPG variability,” is identical to ECG HRV while at rest.

[0063] An exemplary system may include a processing module that is configured to automatically adjust one or more operational characteristics of the light emitters and/or the light detectors to minimize power consumption while ensuring that all heart beats of the user are reliably and continuously detected. The operational characteristics may include, but are not limited to, a frequency of light emitted by the light emitters, the number of light emitters activated, a duty cycle of the light emitters, a brightness of the light emitters, a sampling rate of the light detectors, and the like. The processing module may adjust the operational characteristics based on one or more signals or indicators obtained or derived from one or more sensors in the system including, but not limited to, a motion status of the user, a sleep status of the user, historical information on the user’s physiological and/or habits, an environmental or contextual condition (e.g., ambient light conditions), a physical characteristic of the user (e.g., the optical characteristics of the user’s skin), and the like.

[0064] In one embodiment, the processing module may receive data on the motion of the user using, for example, an accelerometer. The processing module may process the motion data to determine a motion status of the user which indicates the level of motion of the user, for example, exercise, light motion (e.g., walking), no motion or rest, sleep, and the like. The processing module may adjust the duty cycle of one or more light emitters and the corresponding sampling rate of the one or more light detectors based on the motion status. For example, light emitters for PPG may be activated at a duty cycle ranging from about 1% to about 100%. In another example, the light emitters may be activated at a duty cycle ranging from about 20% to about 50% to minimize power consumption. Certain exemplary sampling rates of the light detectors may range from about 50 Hz to about 1000 Hz, but are not limited to these exemplary rates. Certain non-limiting sampling rates are, for example, about 100 Hz, 200 Hz, 500 Hz, and the like.

[0065] In one non-limiting example, the light detectors may sample continuously when the user is performing an exercise routine so that the error standard deviation is kept within 5 beats per minute (BPM). When the user is at rest, the light detectors may be activated for about a 1% duty cycle—10 milliseconds each second (i.e., 1% of the time) so that the error standard deviation is kept within 5 BPM (including an error standard deviation in the heart rate measurement of 2 BPM and an error standard deviation in the heart rate changes between measurement of 3 BPM). When the user is in light motion (e.g., walking), the light detectors may be activated for about a 10% duty cycle—100 milliseconds each second (i.e., 10% of the time) so that the error standard deviation is kept within 6 BPM (including an error standard deviation in the heart rate measurement of 2 BPM and an error standard deviation in the heart rate changes between measurement of 4 BPM).

[0066] The processing module may adjust the brightness of one or more light emitters by adjusting the current supplied to the light emitters. For example, a first level of brightness may be set by current ranging between about 1 mA to about 10 mA, but is not limited to this exemplary range. A second higher level of brightness may be set by current ranging from about 11 mA to about 30 mA, but is not

limited to this exemplary range. A third higher level of brightness may be set by current ranging from about 80 mA to about 120 mA, but is not limited to this exemplary range. In one non-limiting example, first, second and third levels of brightness may be set by current of about 5 mA, about 20 mA and about 100 mA, respectively.

[0067] Shorter-wavelength LEDs may require more power than is required by other types of heart rate sensors, such as, a piezo-sensor or an infrared sensor. Therefore, an exemplary wearable system may provide and use a unique combination of sensors—one or more light detectors for periods where motion is expected and one or more piezo and/or infrared sensors for low motion periods (e.g., sleep)—to save battery life. Certain other embodiments of a wearable system may exclude piezo-sensors and/or infrared sensors.

[0068] For example, upon determining that the motion status indicates that the user is at a first higher level of motion (e.g., exercising), one or more light emitters may be activated to emit light at a first wavelength. Upon determining that the motion status indicates that the user is at a second lower level of motion (e.g., at rest), non-light based sensors may be activated. The threshold levels of motion that trigger adjustment of the type of sensor may be based on one or more factors including, but are not limited to, skin properties, ambient light conditions, and the like.

[0069] The system may determine the type of sensor to use at a given time based on the level of motion (e.g., via an accelerometer) and whether the user is asleep (e.g., based on movement input, skin temperature and heart rate). Based on a combination of these factors the system selectively chooses which type of sensor to use in monitoring the heart rate of the user. Common symptoms of being asleep are periods of no movement or small bursts of movement (such as shifting in bed), lower skin temperature (although it is not a dramatic drop from normal), drastic GSR changes, and heart rate that is below the typical resting heart rate when the user is awake. These variables depend on the physiology of a person and thus a machine learning algorithm is trained with user-specific input to determine when he/she is awake/asleep and determine from that the exact parameters that cause the algorithm to deem someone asleep.

[0070] In an exemplary configuration, the light detectors may be positioned on the underside of the wearable system and all of the heart rate sensors may be positioned adjacent to each other. For example, the low power sensor(s) may be adjacent to the high power sensor(s) as the sensors may be chosen and placed where the strongest signal occurs. In one example configuration, a 3-axis accelerometer may be used that is located on the top part of the wearable system. In some embodiments, an operational characteristic of the microprocessor may be automatically adjusted to minimize power consumption. This adjustment may be based on a level of motion of the user’s body.

[0071] More generally, the above description contemplates a variety of techniques for sensing conditions relating to heart rate monitoring or related physiological activity either directly (e.g., confidence levels or accuracy of calculated heart rate) or indirectly (e.g., motion detection, temperature). However measured, these sensed conditions can be used to intelligently select from among a number of different modes, including hardware modes, software modes, and combinations of the foregoing, for monitoring heart rate based on, e.g., accuracy, power usage, detected activity states, and so forth. Thus there is disclosed herein

techniques for selecting from among two or more different heart rate monitoring modes according to a sensed condition.

[0072] Exemplary embodiments provide an analytics system for providing qualitative and quantitative monitoring of a user's body, health and physical training. The analytics system is implemented in computer-executable instructions encoded on one or more non-transitory computer-readable media. The analytics system relies on and uses continuous data on one or more physiological parameters including, but not limited to, heart rate. The continuous data used by the analytics system may be obtained or derived from an exemplary physiological measurement system disclosed herein, or may be obtained or derived from a derived source or system, for example, a database of physiological data. In some embodiments, the analytics system computes, stores and displays one or more indicators or scores relating to the user's body, health and physical training including, but not limited to, an intensity score and a recovery score. The scores may be updated in real-time and continuously or at specific time periods, for example, the recovery score may be determined every morning upon waking up, the intensity score may be determined in real-time or after a workout routine or for an entire day.

[0073] In certain exemplary embodiments, a fitness score may be automatically determined based on the physiological data of two or more users of exemplary wearable systems.

[0074] An intensity score or indicator provides an accurate indication of the cardiovascular intensities experienced by the user during a portion of a day, during the entire day or during any desired period of time (e.g., during a week or month). The intensity score is customized and adapted for the unique physiological properties of the user and takes into account, for example, the user's age, gender, anaerobic threshold, resting heart rate, maximum heart rate, and the like. If determined for an exercise routine, the intensity score provides an indication of the cardiovascular intensities experienced by the user continuously throughout the routine. If determined for a period of including and beyond an exercise routine, the intensity score provides an indication of the cardiovascular intensities experienced by the user during the routine and also the activities the user performed after the routine (e.g., resting on the couch, active day of shopping) that may affect their recovery or exercise readiness.

[0075] In exemplary embodiments, the intensity score is calculated based on the user's heart rate reserve (HRR) as detected continuously throughout the desired time period, for example, throughout the entire day. In one embodiment, the intensity score is an integral sum of the weighted HRR detected continuously throughout the desired time period. FIG. 4 is a flowchart illustrating an exemplary method of determining an intensity score.

[0076] In step 402, continuous heart rate readings are converted to HRR values. A time series of heart rate data used in step 402 may be denoted as:

$$H \in T$$

[0077] A time series of HRR measurements, $v(t)$, may be defined in the following expression in which MHR is the maximum heart rate and RHR is the resting heart rate of the user:

$$v(t) = \frac{H(t) - RHR}{MHR - RHR}$$

[0078] In step 404, the HRR values are weighted according to a suitable weighting scheme. Cardiovascular intensity, indicated by an intensity score, is defined in the following expression in which w is a weighting function of the HRR measurements:

$$I(t_0, t_1) = \int_{t_0}^{t_1} w(v(t)) dt$$

[0079] In step 406, the weighted time series of HRR values is summed and normalized.

$$I_T = \int_T w(v(t)) dt \leq w(1) |T|$$

[0080] Thus, the weighted sum is normalized to the unit interval, i.e., $[0, 1]$:

$$N_T = \frac{I_T}{w(1) \cdot 24hr}$$

[0081] In step 408, the summed and normalized values are scaled to generate user-friendly intensity score values. That is, the unit interval is transformed to have any desired distribution in a scale (e.g., a scale including 21 points from 0 to 21), for example, arctangent, sigmoid, sinusoidal, and the like. In certain distributions, the intensity values increase at a linear rate along the scale, and in others, at the highest ranges the intensity values increase at more than a linear rate to indicate that it is more difficult to climb in the scale toward the extreme end of the scale. In some embodiments, the raw intensity scores are scaled by fitting a curve to a selected group of "canonical" exercise routines that are predefined to have particular intensity scores.

[0082] In one embodiment, monotonic transformations of the unit interval are achieved to transform the raw HRR values to user-friendly intensity scores. An exemplary scaling scheme, expressed as $f: [0, 1] \rightarrow [0, 1]$, is performed using the following function:

$$(x, N, p) = 0.5 \left(\frac{\arctan(N(x - p))}{\pi/2} + 1 \right)$$

[0083] To generate an intensity score, the resulting value may be multiplied by a number based on the desired scale of the intensity score. For example, if the intensity score is graduated from zero to 21, then the value may be multiplied by 21.

[0084] In step 410, the intensity score values are stored on a non-transitory storage medium for retrieval, display and usage. In step 412, the intensity score values are, in some embodiments, displayed on a user interface rendered on a visual display device. The intensity score values may be displayed as numbers and/or with the aid of graphical tools, e.g., a graphical display of the scale of intensity scores with current score, and the like. In some embodiments, the intensity score may be indicated by audio. In step 412, the intensity score values are, in some embodiments, displayed along with one or more quantitative or qualitative pieces of information on the user including, but not limited to, whether the user has exceeded his/her anaerobic threshold,

the heart rate zones experienced by the user during an exercise routine, how difficult an exercise routine was in the context of the user's training, the user's perceived exertion during an exercise routine, whether the exercise regimen of the user should be automatically adjusted (e.g., made easier if the intensity scores are consistently high), whether the user is likely to experience soreness the next day and the level of expected soreness, characteristics of the exercise routine (e.g., how difficult it was for the user, whether the exercise was in bursts or activity, whether the exercise was tapering, etc.), and the like. In one embodiment, the analytics system may automatically generate, store and display an exercise regimen customized based on the intensity scores of the user.

[0085] Step 406 may use any of a number of exemplary static or dynamic weighting schemes that enable the intensity score to be customized and adapted for the unique physiological properties of the user. In one exemplary static weighting scheme, the weights applied to the HRR values are based on static models of a physiological process. The human body employs different sources of energy with varying efficiencies and advantages at different HRR levels. For example, at the anaerobic threshold (AT), the body shifts to anaerobic respiration in which the cells produce two adenosine triphosphate (ATP) molecules per glucose molecule, as opposed to 36 at lower HRR levels. At even higher HRR levels, there is a further subsequent threshold (CPT) at which creatine triphosphate (CTP) is employed for respiration with even less efficiency.

[0086] In order to account for the differing levels of cardiovascular exertion and efficiency at the different HRR levels, in one embodiment, the possible values of HRR are divided into a plurality of categories, sections or levels (e.g., three) dependent on the efficiency of cellular respiration at the respective categories. The HRR parameter range may be divided in any suitable manner, such as, piecewise, including piecewise-linear, piecewise-exponential, and the like. An exemplary piecewise-linear division of the HRR parameter range enables weighting each category with strictly increasing values. This scheme captures an accurate indication of the cardiovascular intensity experienced by the user because it is more difficult to spend time at higher HRR values, which suggests that the weighting function should increase at the increasing weight categories.

[0087] In one non-limiting example, the HRR parameter range may be considered a range from zero (0) to one (1) and divided into categories with strictly increasing weights. In one example, the HRR parameter range may be divided into a first category of a zero HRR value and may assign this category a weight of zero; a second category of HRR values falling between zero (0) and the user's anaerobic threshold (AT) and may assign this category a weight of one (1); a third category of HRR values falling between the user's anaerobic threshold (AT) and a threshold at which the user's body employs creatine triphosphate for respiration (CPT) and may assign this category a weight of 18; and a fourth category of HRR values falling between the creatine triphosphate threshold (CPT) and one (1) and may assign this category a weight of 42, although other numbers of HRR categories and different weight values are possible. That is, in this example, the weights are defined as:

$$w(v) = \begin{cases} 0 & : v = 0 \\ 1 & : v \in (0, AT] \\ 18 & : v \in (AT, CPT] \\ 42 & : v \in (CPT, 1] \end{cases}$$

[0088] In another exemplary embodiment of the weighting scheme, the HRR time series is weighted iteratively based on the intensity scores determined thus far (e.g., the intensity score accrued thus far) and the path taken by the HRR values to get to the present intensity score. In another exemplary embodiment of the weighting scheme, a predictive approach is used by modeling the weights or coefficients to be the coefficient estimates of a logistic regression model. One of ordinary skill in the art will recognize that two or more aspects of any of the disclosed weighting schemes may be applied separately or in combination in an exemplary method for determining an intensity score.

[0089] In one aspect, heart rate zones quantify the intensity of workouts by weighing and comparing different levels of heart activity as percentages of maximum heart rate. Analysis of the amount of time an individual spends training at a certain percentage of his/her MHR may reveal his/her state of physical exertion during a workout. This intensity, developed from the heart rate zone analysis, motion, and activity, may then indicate his/her need for rest and recovery after the workout, e.g., to minimize delayed onset muscle soreness (DOMS) and prepare him/her for further activity. As discussed above, MEM, heart rate zones, time spent above the anaerobic threshold, and HRV in RSA (Respiratory Sinus Arrhythmia) regions—as well as personal information (gender, age, height, weight, etc.) may be utilized in data processing.

[0090] A recovery score or indicator provides an accurate indication of the level of recovery of a user's body and health after a period of physical exertion. The human autonomic nervous system controls the involuntary aspects of the body's physiology and is typically subdivided into two branches: parasympathetic (deactivating) and sympathetic (activating). Heart rate variability (HRV), i.e., the fluctuation in inter-heartbeat interval time, is a commonly studied result of the interplay between these two competing branches. Parasympathetic activation reflects inputs from internal organs, causing a decrease in heart rate. Sympathetic activation increases in response to stress, exercise and disease, causing an increase in heart rate. For example, when high intensity exercise takes place, the sympathetic response to the exercise persists long after the completion of the exercise. When high intensity exercise is followed by insufficient recovery, this imbalance lasts typically until the next morning, resulting in a low morning HRV. This result should be taken as a warning sign as it indicates that the parasympathetic system was suppressed throughout the night. While suppressed, normal repair and maintenance processes that ordinarily would occur during sleep were suppressed as well. Suppression of the normal repair and maintenance processes results in an unprepared state for the next day, making subsequent exercise attempts more challenging.

[0091] The recovery score is customized and adapted for the unique physiological properties of the user and takes into account, for example, the user's heart rate variability (HRV), resting heart rate, sleep quality and recent physiological

strain (indicated, in one example, by the intensity score of the user). In one exemplary embodiment, the recovery score is a weighted combination of the user's heart rate variability (HRV), resting heart rate, sleep quality indicated by a sleep score, and recent strain (indicated, in one example, by the intensity score of the user). In an exemplar, the sleep score combined with performance readiness measures (such as, morning heart rate and morning heart rate variability) provides a complete overview of recovery to the user. By considering sleep and HRV alone or in combination, the user can understand how exercise-ready he/she is each day and to understand how he/she arrived at the exercise-readiness score each day, for example, whether a low exercise-readiness score is a predictor of poor recovery habits or an inappropriate training schedule. This insight aids the user in adjusting his/her daily activities, exercise regimen and sleeping schedule therefore obtain the most out of his/her training.

[0092] In some cases, the recovery score may take into account perceived psychological strain experienced by the user. In some cases, perceived psychological strain may be detected from user input via, for example, a questionnaire on a mobile device or web application. In other cases, psychological strain may be determined automatically by detecting changes in sympathetic activation based on one or more parameters including, but not limited to, heart rate variability, heart rate, galvanic skin response, and the like.

[0093] With regard to the user's HRV used in determining the recovery score, suitable techniques for analyzing HRV include, but are not limited to, time-domain methods, frequency-domain methods, geometric methods and non-linear methods. In one embodiment, the HRV metric of the root-mean-square of successive differences (RMSSD) of RR intervals is used. The analytics system may consider the magnitude of the differences between 7-day moving averages and 3-day moving averages of these readings for a given day. Other embodiments may use Poincaré Plot analysis or other suitable metrics of HRV.

[0094] The recovery score algorithm may take into account RHR along with history of past intensity and recovery scores.

[0095] With regard to the user's resting heart rate, moving averages of the resting heart rate are analyzed to determine significant deviations. Consideration of the moving averages is important since day-to-day physiological variation is quite large even in healthy individuals. Therefore, the analytics system may perform a smoothing operation to distinguish changes from normal fluctuations.

[0096] Although an inactive condition, sleep is a highly active recovery state during which a major portion of the physiological recovery process takes place. Nonetheless, a small, yet significant, amount of recovery can occur throughout the day by rehydration, macronutrient replacement, lactic acid removal, glycogen re-synthesis, growth hormone production and a limited amount of musculoskeletal repair. In assessing the user's sleep quality, the analytics system generates a sleep score using continuous data collected by an exemplary physiological measurement system regarding the user's heart rate, skin conductivity, ambient temperature and accelerometer/gyroscope data throughout the user's sleep. Collection and use of these four streams of data enable an understanding of sleep previously only accessible through invasive and disruptive over-night laboratory testing. For example, an increase in skin conductivity when

ambient temperature is not increasing, the wearer's heart rate is low, and the accelerometer/gyroscope shows little motion, may indicate that the wearer has fallen asleep. The sleep score indicates and is a measure of sleep efficiency (how good the user's sleep was) and sleep duration (if the user had sufficient sleep). Each of these measures is determined by a combination of physiological parameters, personal habits and daily stress/strain (intensity) inputs. The actual data measuring the time spent in various stages of sleep may be combined with the wearer's recent daily history and a longer-term data set describing the wearer's personal habits to assess the level of sleep sufficiency achieved by the user. The sleep score is designed to model sleep quality in the context of sleep duration and history. It thus takes advantage of the continuous monitoring nature of the exemplary physiological measurement systems disclosed herein by considering each sleep period in the context of biologically-determined sleep needs, pattern-determined sleep needs and historically-determined sleep debt.

[0097] The recovery and sleep score values are stored on a non-transitory storage medium for retrieval, display and usage. The recovery and/or sleep score values are, in some embodiments, displayed on a user interface rendered on a visual display device. The recovery and/or sleep score values may be displayed as numbers and/or with the aid of graphical tools, e.g., a graphical display of the scale of recovery scores with current score, and the like. In some embodiments, the recovery and/or sleep score may be indicated by audio. The recovery score values are, in some embodiments, displayed along with one or more quantitative or qualitative pieces of information on the user including, but not limited to, whether the user has recovered sufficiently, what level of activity the user is prepared to perform, whether the user is prepared to perform an exercise routine a particular desired intensity, whether the user should rest and the duration of recommended rest, whether the exercise regimen of the user should be automatically adjusted (e.g., made easier if the recovery score is low), and the like. In one embodiment, the analytics system may automatically generate, store and display an exercise regimen customized based on the recovery scores of the user alone or in combination with the intensity scores.

[0098] As discussed above, the sleep performance metric may be based on parameters like the number of hours of sleep, sleep onset latency, and the number of sleep disturbances. In this manner, the score may compare a tactical athlete's duration and quality of sleep in relation to the tactical athlete's evolving sleep need (e.g., a number of hours based on recent strain, habitual sleep need, signs of sickness, and sleep debt). By way of example, a soldier may have a dynamically changing need for sleep, and it may be important to consider the total hours of sleep in relation to the amount of sleep that may have been required. By providing an accurate sensor for sleep and sleep performance, an aspect may evaluate sleep in the context of the overall day and lifestyle of a specific user.

[0099] FIG. 5 is a flowchart illustrating an exemplary method by which a user may use intensity and recovery scores. In step 502, the wearable physiological measurement system begins determining heart rate variability (HRV) measurements based on continuous heart rate data collected by an exemplary physiological measurement system. In some cases, it may take the collection of several days of heart rate data to obtain an accurate baseline for the HRV. In

step **504**, the analytics system may generate and display intensity score for an entire day or an exercise routine. In some cases, the analytics system may display quantitative and/or qualitative information corresponding to the intensity score.

[0100] In step **506**, in an exemplary embodiment, the analytics system may automatically generate or adjust an exercise routine or regimen based on the user's actual intensity scores or desired intensity scores. For example, based on inputs of the user's actual intensity scores, a desired intensity score (that is higher than the actual intensity scores) and a first exercise routine currently performed by the user (e.g., walking), the analytics system may recommend a second different exercise routine that is typically associated with higher intensity scores than the first exercise routine (e.g., running).

[0101] In step **508**, at any given time during the day (e.g., every morning), the analytics system may generate and display a recovery score. In some cases, the analytics system may display quantitative and/or qualitative information corresponding to the intensity score. For example, in step **510**, in an exemplary embodiment, the analytics system may determine if the recovery is greater than (or equal to or greater than) a first predetermined threshold (e.g., about 60% to about 80% in some examples) that indicates that the user is recovered and is ready for exercise. If this is the case, in step **512**, the analytics system may indicate that the user is ready to perform an exercise routine at a desired intensity or that the user is ready to perform an exercise routine more challenging than the past day's routine. Otherwise, in step **514**, the analytics system may determine if the recovery is lower than (or equal to or lower than) a second predetermined threshold (e.g., about 10% to about 40% in some examples) that indicates that the user has not recovered. If this is the case, in step **516**, the analytics system may indicate that the user should not exercise and should rest for an extended period. The analytics system may, in some cases, the duration of recommended rest. Otherwise, in step **518**, the analytics system may indicate that the user may exercise according to his/her exercise regimen while being careful not to overexert him/herself. The thresholds may, in some cases, be adjusted based on a desired intensity at which the user desires to exercise. For example, the thresholds may be increased for higher planned intensity scores.

[0102] FIG. 6 is a flow chart illustrating a method for detecting heart rate variability in sleep states. The method **600** may be used in cooperation with any of the devices, systems, and methods described herein, such as by operating a wearable, continuous physiological monitoring device to perform the following steps. The wearable, continuous physiological monitoring system may for example include a processor, one or more light emitting diodes, one or more light detectors configured to obtain heart rate data from a user, and one or more other sensors to assist in detecting stages of sleep. In general, the method **600** aims to measure heart rate variability in the last phase of sleep before waking in order to provide a consistent and accurate basis for calculating a physical recovery score.

[0103] As shown in step **602**, the method **600** may include detecting a sleep state of a user. This may, for example, include any form of continuous or periodic monitoring of sleep states using any of a variety of sensors or algorithms as generally described herein.

[0104] Sleep states (also be referred to as "sleep phases," "sleep cycles," "sleep stages," or the like) may include rapid eye movement (REM) sleep, non-REM sleep, or any states/stages included therein. The sleep states may include different phases of non-REM sleep, including Stages 1-3. Stage 1 of non-REM sleep generally includes a state where a person's eyes are closed, but the person can be easily awakened; Stage 2 of non-REM sleep generally includes a state where a person is in light sleep, i.e., where the person's heart rate slows and their body temperature drops in preparation for deeper sleep; and Stage 3 of non-REM sleep generally includes a state of deep sleep, where a person is not easily awakened. Stage 3 is often referred to as delta sleep, deep sleep, or slow wave sleep (i.e., from the high amplitude but small frequency brain waves typically found in this stage). Slow wave sleep is thought to be the most restful form of sleep, which relieves subjective feelings of sleepiness and restores the body.

[0105] REM sleep on the other hand typically occurs 1-2 hours after falling asleep. REM sleep may include different periods, stages, or phases, all of which may be included within the sleep states that are detected as described herein. During REM sleep, breathing may become more rapid, irregular and shallow, eyes may jerk rapidly (thus the term "Rapid Eye Movement" or "REM"), and limb muscles may be temporarily paralyzed. Brain waves during this stage typically increase to levels experienced when a person is awake. Also, heart rate, cardiac pressure, cardiac output, and arterial pressure may become irregular when the body moves into REM sleep. This is the sleep state in which most dreams occur, and, if awoken during REM sleep, a person can typically remember the dreams. Most people experience three to five intervals of REM sleep each night.

[0106] Homeostasis is the balance between sleeping and waking, and having proper homeostasis may be beneficial to a person's health. Lack of sleep is commonly referred to as sleep deprivation, which tends to cause slower brain waves, a shorter attention span, heightened anxiety, impaired memory, mood disorders, and general mental, emotional, and physical fatigue. Sleep debt (the effect of not getting enough sleep) may result in the diminished abilities to perform high-level cognitive functions. A person's circadian rhythms (i.e., biological processes that display an endogenous, entrainable oscillation of about 24 hours) may be a factor in a person's optimal amount of sleep. Thus, sleep may in general be usefully monitored as a proxy for physical recovery. However, a person's heart rate variability at a particular moment during sleep—during the last phase of sleep preceding a waking event—can further provide an accurate and consistent basis for objectively calculating a recovery score following a period of sleep.

[0107] According to the foregoing, sleep of a user may be monitored to detect various sleep states, transitions, and other sleep-related information. For example, the device may monitor/detect the duration of sleep states, the transitions between sleep states, the number of sleep cycles or particular states, the number of transitions, the number of waking events, the transitions to an awake state, and so forth. Sleep states may be monitored and detected using a variety of strategies and sensor configurations according to the underlying physiological phenomena. For example, body temperature may be usefully correlated to various sleep states and transitions. Similarly, galvanic skin response may be correlated to sweating activity and various sleep

states, any of which may also be monitored, e.g., with a galvanic skin response sensor, to determine sleep states. Physical motion can also be easily monitored using accelerometers or the like, which can be used to detect waking or other activity involving physical motion. In another aspect, heart rate activity itself may be used to infer various sleep states and transitions, either alone or in combination with other sensor data. Other sensors may also or instead be used to monitor sleep activity, such as brain wave monitors, pupil monitors, and so forth, although the ability to incorporate these types of detection into a continuously wearable physiological monitoring device may be somewhat limited depending on the contemplated configuration.

[0108] As shown in step 604, the method 600 may include monitoring a heart rate of the user substantially continuously with the continuous physiological monitoring system. Continuous heart rate monitoring is described above in significant detail, and the description is not repeated here except to note generally that this may include raw sensor data, heart rate data or peak data, and heart rate variability data over some historical period that can be subsequently correlated to various sleep states and activities.

[0109] As shown in step 606, the method 600 may include recording the heart rate as heart rate data. This may include storing the heart rate data in any raw or processed form on the device, or transmitting the data to a local or remote location for storage. In one aspect, the data may be stored as peak-to-peak data or in some other semi-processed form without calculating heart rate variability. This may be useful as a technique for conserving processing resources in a variety of contexts, for example where only the heart rate variability at a particular time is of interest. Data may be logged in some unprocessed or semi-processed form, and then the heart rate variability at a particular point in time can be calculated once the relevant point in time has been identified.

[0110] As shown in step 610, the method 600 may include detecting a waking event at a transition from the sleep state of the user to an awake state. It should be appreciated that the waking event may be a result of a natural termination of sleep, e.g., after a full night's rest, or in response to an external stimulus that causes awakening prior to completion of a natural sleep cycle. Regardless of the precipitating event(s), the waking event may be detected via the various physiological changes described above, or using any other suitable techniques. While the emphasis herein is on a wearable, continuous monitoring device, it will be understood that the device may also receive inputs from an external device such as a camera (for motion detection) or an infrared camera (for body temperature detection) that can be used to aid in accurately assessing various sleep states and transitions.

[0111] Thus the wearable, continuous physiological monitoring system may generally detect a waking event using one or more sensors including, for example, one or more of an accelerometer, a galvanic skin response sensor, a light sensor, and so forth. For example, in one aspect, the waking event may be detected using a combination of motion data and heart rate data.

[0112] As shown in step 612, the method 600 may include calculating a heart rate variability of the user at a moment in a last phase of sleep preceding the waking event based upon the heart rate data. While a waking event and a history of sleep states are helpful information for assessing recovery,

the method 600 described herein specifically contemplates use of the heart rate variability in a last phase of sleep as a consistent foundation for calculating recovery scores for a device user. Thus step 612 may also include detecting a slow wave sleep period immediately prior to the waking event, or otherwise determining the end of a slow wave or deep sleep episode immediately preceding the waking event.

[0113] It will be appreciated that the last phase of sleep preceding a natural waking event may be slow wave sleep. However, where a sleeper is awakened prematurely, this may instead include a last recorded episode of REM sleep or some other phase of sleep immediately preceding the waking event. This moment—the end of the last phase of sleep before waking—is the point at which heart rate variability data provides the most accurate and consistent indicator of physical recovery. Thus, with the appropriate point of time identified, the historical heart rate data (in whatever form) may be used with the techniques described above to calculate the corresponding heart rate variability. It will be further noted that the time period for this calculation may be selected with varying degrees of granularity depending on the ability to accurately detect the last phase of sleep and an end of the last phase of sleep. Thus for example, the time may be a predetermined amount of time before waking, or at the end of slow wave sleep, or some predetermined amount of time before the end of slow wave sleep is either detected or inferred. In another aspect, an average heart rate variability or similar metric may be determined for any number of discrete measurements within a window around the time of interest.

[0114] As shown in step 614, the method 600 may include calculating a duration of the sleep state. The quantity and quality of sleep may be highly relevant to physical recovery, and as such the duration of the sleep state may be used to calculate a recovery score.

[0115] As shown in step 618, the method 600 may include evaluating a quality of heart rate data using a data quality metric for a slow wave sleep period, e.g., the slow wave sleep period occurring most recently before the waking event. As noted above, the quality of heart rate measurements may vary over time for a variety of reasons. Thus the quality of heart rate data may be evaluated prior to selecting a particular moment or window of heart rate data for calculating heart rate variability, and the method 600 may include using this quality data to select suitable values for calculating a recovery score. For example, the method 600 may include calculating the heart rate variability for a window of predetermined duration within the slow wave sleep period having the highest quality of heart rate data according to the data quality metric.

[0116] As shown in step 620, the method 600 may include calculating a recovery score for the user based upon the heart rate variability from the last phase of sleep. The calculation may be based on other sources of data. For example, the calculation of recovery score may be based on the duration of sleep, the stages of sleep detected or information concerning the stages (e.g., amount of time in certain stages), information regarding the most recent slow wave sleep period or another sleep period/state, information from the GSR sensor or other sensor(s), and so on. The method 600 may further include calculating additional recovery scores after one or more other waking events of the user for comparison to the previously calculated recovery score. The actual calculation of a discovery score is described in

substantial detail above, and this description is not repeated here except to note that the use of a heart rate variability measurement from the last phase of sleep provides an accurate and consistent basis for evaluating the physical recovery state of a user following a period of sleep.

[0117] As shown in step 630, the method 600 may include calculating a sleep score and communicating this score to a user.

[0118] In one aspect, the sleep score may be a measure of prior sleep performance. For example, a sleep performance score may quantify, on a scale of 0-100, the ratio of the hours of sleep during a particular resting period compared to the sleep needed. On this scale, if a user sleeps six hours and needed eight hours of sleep, then the sleep performance may be calculated as 75%. The sleep performance score may begin with one or more assumptions about needed sleep, based on, e.g., age, gender, health, fitness level, habits, genetics, and so forth and may be adapted to actual sleep patterns measured for an individual over time.

[0119] The sleep score may also or instead include a sleep need score or other objective metric that estimates an amount of sleep needed by the user of the device in a next sleep period. In general, the score may be any suitable quantitative representation including, e.g., a numerical value over some predetermined scale (e.g., 0-10, 1-100, or any other suitable scale) or a representation of a number of hours of sleep that should be targeted by the user. In another aspect, the sleep score may be calculated as the number of additional hours of sleep needed beyond a normal amount of sleep for the user.

[0120] The score may be calculated using any suitable inputs that capture, e.g., a current sleep deficit, a measure of strain or exercise intensity over some predetermined prior interval, an accounting for any naps or other resting, and so forth. A variety of factors may affect the actual sleep need, including physiological attributes such as age, gender, health, genetics and so forth, as well as daytime activities, stress, napping, sleep deficit or deprivation, and so forth. The sleep deficit may itself be based on prior sleep need and actual sleep performance (quality, duration, waking intervals, etc.) over some historical window. In one aspect, an objective scoring function for sleep need may have a model of the form:

$$\text{SleepNeed} = \text{Baseline} + f_1(\text{strain}) + f_2(\text{debt}) - \text{Naps}$$

[0121] In general, this calculation aims to estimate the ideal amount of sleep for best rest and recovery during a next sleep period. When accounting for time falling asleep, periods of brief wakefulness, and so forth, the actual time that should be dedicated to sleep may be somewhat higher, and this may be explicitly incorporated into the sleep need calculation, or left for a user to appropriately manage sleep habits.

[0122] In general, the baseline sleep may represent a standard amount of sleep needed by the user on a typical rest day (e.g., with no strenuous exercise or workout). As noted above, this may depend on a variety of factors, and may be estimated or measured for a particular individual in any suitable manner. The strain component, $f_1(\text{strain})$, may be assessed based on a previous day's physical intensity, and will typically increase the sleep need. Where intensity or strain is measured on an objective scale from 0 to 21, the strain calculation may take the following form, which yields an additional sleep time needed in minutes for a strain, i:

$$f(i) = \frac{1.7}{1 + e^{\frac{17-i}{3.5}}}$$

[0123] The sleep debt, $f_2(\text{debt})$, may generally measure a carryover of needed sleep that was not attained in a previous day. This may be scaled, and may be capped at a maximum, according to individual sleep characteristics or general information about long term sleep deficit and recovery. Naps may also be accounted for directly by correcting the sleep need for any naps that have been taken, or by calculating a nap factor that is scaled or otherwise manipulated or calculated to more accurately track the actual effect of naps on prospective sleep need.

[0124] However calculated, the sleep need may be communicated to a user, such as by displaying a sleep need on a wrist-worn physiological monitoring device, or by sending an e-mail, text message or other alert to the user for display on any suitable device.

[0125] FIG. 7 is a bottom view of a wearable, continuous physiological monitoring device (the side facing a user's skin). As shown in the figure, the wearable, continuous physiological monitoring system 700 includes a wearable housing 702, one or more sensors 704, a processor 706, and a light source 708.

[0126] The wearable housing 702 may be configured such that a user can wear a continuous physiological monitoring device as part of the wearable, continuous physiological monitoring system 700. The wearable housing 702 may be configured for cooperation with a strap or the like, e.g., for engagement with an appendage of a user.

[0127] The one or more sensors 704 may be disposed in the wearable housing 702. In one aspect, the one or more sensors 704 include a light detector configured to provide data to the processor 706 for calculating a heart rate variability. The one or more sensors 704 may also or instead include an accelerometer configured to provide data to the processor 706 for detecting a sleep state or a waking event. In an implementation, the one or more sensors 704 measure a galvanic skin response of the user.

[0128] The processor 706 may be disposed in the wearable housing 702. The processor 706 may be configured to operate the one or more sensors 704 to detect a sleep state of a user wearing the wearable housing 702. The processor 706 may be further configured to monitor a heart rate of the user substantially continuously, and to record the heart rate as heart rate data without calculating a heart rate variability for the user. The processor 706 may also or instead be configured to detect a waking event at a transition from the sleep state of the user to an awake state, and to calculate the heart rate variability of the user at a moment in the last phase of sleep preceding the waking event based upon the heart rate data. The processor 706 may further be configured to calculate a recovery score for the user based upon the heart rate variability from the last phase of sleep.

[0129] The light source 708 may be coupled to the wearable housing 702 and controlled by the processor 706. The light source 708 may be directed toward the skin of a user's appendage. Light from the light source 708 may be detected by the one or more sensors 704.

[0130] According to one aspect of the invention, signal acquisition from a wearable device may be optimized through the selection and adjustment of a variety of mea-

surement states. As stated above, in some embodiments, physiological data may be obtained using an optical sensor coupled with one or more light sources, e.g., light emitting diodes (LEDs)—for example, where the optical sensor is in communication with a user's wrist through a device secured to the user's wrist. When obtaining optical samples using such sensors and LEDs, e.g., via a photoplethysmography (PPG) signal on a user's wrist for measuring a heart rate of the user, there are often saturation problems associated with the LEDs. In many environments, and for many users, the PPG signals may become easily saturated, for example, by the light emitted from the LEDs combined with environment characteristics and/or characteristics of the user's skin. When a signal is saturated information may be lost, and the gathering of useful physiological data readings may be delayed. Further, saturation of the optical signal may disrupt or otherwise impair subsequent processing algorithms, lowering the accuracy of estimators for some time after the saturation event. As such, saturation may be detrimental to the devices, systems, and methods described herein.

[0131] The saturation of a physiological signal may generally stem from the brightness of the LEDs of the wearable device. If, for example, the LEDs are too bright, the signal may become saturated, referred to herein as positive saturation. If, however, the LEDs are not bright enough, the PPG signal may be difficult or impossible to obtain, referred to herein as negative saturation. This problem may be further exacerbated when obtaining a PPG signal when a user is exercising, moving, changing environments, and the like. The saturation problem may also or instead be exacerbated when attempting to obtain a PPG signal on a user having relatively dark skin, where the PPG signal can be difficult to detect unless the LEDs are relatively bright. A useful and effective optical signal may be one that is a product of an LED brightness level and an amplified gain level that neither positively nor negatively saturates the optical signal.

[0132] Characteristics that affect saturation may also change for a user while wearing a device. For example, the action of placing the device on their wrist, may cause the PPG signal to saturate as the user does so. By way of further example, if the user is indoors or in a low-light environment, there may be no saturation of the signal, however if the user goes outside to a bright light environment, the PPG signal may become saturated.

[0133] FIG. 8 is a flow chart illustrating a method 800 for controlling a signal acquisition system. The method 800 may generally optimize signal acquisition through control of discrete states for, e.g., illumination brightness and detection gain. In general, the method provides a technical solution to the problem of identifying useful operating states for a signal acquisition system in which multiple dimensions (e.g., time, ambient light, gain and intensity) have multiple degrees of freedom (e.g., gain and intensity) over time. The solution to this problem may be realized through a simplex-type algorithm or any other technique that yields a set of corner conditions or discrete operating states, where the corner points can be further optimized over a large dataset with diverse activities, ambient conditions, skin tone, and the like and simplified to a few operating states that cover most or all of the expected operating conditions for the physiological monitoring system.

[0134] In one aspect, methods for optimizing the PPG signal may include changing at least two variables that can affect saturation of a light detector, and thus the quality of

signal acquisition: (1) the brightness of one or more LEDs that illuminate a target region, and (2) the gain of light detection for the light detector (or group of light detectors) that acquire a signal indicative of light intensity based in part on the illumination from the LEDs. The LED brightness levels and detector gain values may be included or used to define a plurality of optical measurement states characterized by discrete values for brightness and gain. The wearable device may operate under one of these optical measurement states to obtain and evaluate a physiological signal, such as a PPG signal, for potential saturation. If the state under which the device is operating is saturated, or is otherwise insufficient or impaired, the device may be adjusted to operate under a different, non-saturated optical measurement state. In one aspect, the optical measurement states may be cycled until an acceptable physiological signal is obtained, i.e., the device finds an optical measurement state with an ideal balance of LED brightness and sufficient gain level to detect and process the physiological signal from the user.

[0135] It will be understood that a degenerate case exists in which the LED is not used. More specifically, it has been demonstrated that under suitable lighting conditions, a useful PPG signal may be obtained from a physiological monitoring device based on the incident, ambient light. Thus, it is possible for at least the LED brightness to have a value of zero in at least one potentially useful operating state, and this should be understood to be one of the possible operating states contemplated herein even though no LED or other light source is being used. Similarly, pulsed or gated illumination and/or detection cycles may also be used, and may be considered discrete operating states even though the input or output signals may periodically be zero during such operating modes.

[0136] As shown in step 802, the method 800 may include defining or providing predetermined optical measurement states. Each one of a plurality of such predetermined optical measurement states may be characterized by at least a first discrete value for electronically controlling a brightness of a light source of the physiological monitoring device. Each of the plurality of predetermined optical measurement states may also or instead be characterized by a second discrete value for electronically controlling a gain of a light sensor of the physiological monitoring device. The plurality of predetermined optical measurement states may be ordered into a prioritized list according to preferred measurement states. The light source may be any light source suitable for use with a physiological monitoring device as contemplated herein, such as an LED or other light source. The light sensor (also referred to herein as a light detector or the like) may be any suitable transducer, detector, or combination of these or other components suitable for measuring an intensity of incident light and providing a corresponding electrical signal for use in the physiological monitoring system.

[0137] In one aspect, the method 800 for optimizing signal acquisition may include selecting a state from among the predetermined optical measurement states that avoids or reduces saturation of the detector, e.g., by selecting a state with a lower LED brightness or lower detection gain. In another aspect, selecting the state may include selecting a state with the greatest signal gain, e.g., by maximizing detector gain, LED brightness, or some combination of these. More generally, a wearable device using these techniques may switch between the predetermined optical measurement states that each have a certain gain level and a

certain brightness level. In an aspect, as the state increases so does the brightness, and as the state decreases the brightness similarly decreases. The optical measurement states may be defined or chosen according to known or anticipated usage scenarios, which may include, without limitation, low-light, bright light, light skin, dark skin, low activity level, high activity levels, or any combination thereof. By defining a relatively small number of operating states that are known to provide acceptable signal quality under most or all normal operating conditions, a device can avoid generalized, processing-intensive, complex optimization calculations in favor of a state machine using a limited number of discrete optical measurement states.

[0138] In one aspect, the method 800 may use five predetermined optical measurement states: S0, S1, S2, S3, and S4. The optical measurement states may be defined using three gain levels and three LED brightness levels, each of which may be specified as a digital control signal, a digital drive signal, or any other suitably definite analog or digital signal for controlling gain and intensity respectively. In the following discussion, the gain levels (e.g., transimpedance amplifier gain levels or 'tiaGain' levels) are referred to as G1, G2, and G3, and the LED brightness levels are referred to as L1, L2, and L3. The method 800 may implement the predetermined optical measurement states as discrete combinations of the gain levels and LED levels, which may be sorted or prioritized, for example, based on preferred combinations. By way of example, the pre-defined combinations of gain and LED levels may include: S4=(L3,G3); S3=(L3,G2); S2=(L2,G2); S1=(L1,G2); S0=(L1,G1).

[0139] In one aspect, the prioritized list of optical measurement states provides monotonically increasing magnitudes of the first discrete value (e.g., for LED brightness) for each higher position within the prioritized list. The prioritized list may also or instead be ordered for monotonically increasing magnitudes of the second discrete value as the priority within the prioritized list increases to a more preferred measurement state. The prioritized list may also or instead be ordered according to other conditional factors to minimize power consumption, maximize signal gain or quality, minimize processing resources and so forth. Other factors may also affect whether and when a state change occurs. For example, the method 800 may include evaluating processing resources and computational requirements required for a change in the operating state, or waiting a predetermined interval since a last change state before permitting another state change or evaluating possible state changes. In one aspect, the method 800 may include ordering the prioritized list to minimize a number of optical measurement state changes over a period of time.

[0140] As shown in step 804 the method 800 may include operating a light source according to an optical measurement state. In one aspect, the method 800 may operate the light source at a brightness that is controlled according to a first discrete value for the current predetermined optical measurement state. The light source may include one or more LEDs, as further described herein. The light source may also or instead include an LED configurable to operate at any number of discrete brightness levels. In the example given above, the light source may include an LED capable of operating at the discrete brightness levels L1, L2 and L3.

[0141] As shown in step 806, the method 800 may include operating a light sensor according to an optical measurement state. In one aspect, the method 800 may operate the light

sensor using a detection gain that is controlled according to a second discrete value for the current predetermined optical measurement state. The light sensor may include a photo-resistor, a photo-transistor, a photo-diode, or other sensor described herein for detecting and receiving reflected light from the user's skin. The light sensor may include an amplifier, such as a transimpedance amplifier, capable of amplifying the physiological signal received according to discrete gain values controlled, e.g., by a digital signal or the like.

[0142] As shown in step 808, the method 800 may include evaluating a physiological signal based on data from the light sensor. This generally includes processing the data obtained using the current optical measurement state to obtain the desired signal, such as the heart rate, heart rate variability, or other signal of interest.

[0143] As shown in step 809, the method 800 may include evaluating the candidate measurement states. In general, the optical signal, or the physiological state derived from the optical signal, may be evaluated to determine the quality of measurements from the optical measurement system. This may, for example, include general measures of signal quality, signal gain, device saturation, and so forth. For example, if the physical sensor appears saturated, e.g., operating at a physical detection limit, then the device may distort subsequent measurements as the device seeks to recover from the saturated state return to a normal operating range. This may introduce significant measurement artifacts that degrade signal quality. Similarly, where there is insufficient illumination, the signal of interest may fall below a noise threshold so that it is undetectable, or not consistently detectable in a manner that permits extraction of the corresponding physiological signal. Useful operating thresholds may be defined so that the device operates below the saturation level and above the noise floor whenever possible. In one aspect, the saturation and noise thresholds may be offset by a constant to facilitate operation of the device within the normal operating range. For example, if it is known that an optical detector becomes positively saturated at 2200 mV of output, a saturation threshold may be set to 2000 mV or lower, such that if the measured optical signal approaches 2000 mV, an adjustment of the optical measurement state may be made before the optical detector actually becomes saturated and data is lost.

[0144] It will be appreciated that a device may also have a negative saturation limit. Thus, while the foregoing discussion is cast in terms of an upper saturation limit and a lower noise floor, the minimum signal of interest may instead be a negative saturation limit for a detector or detection circuit. As such, references to a noise floor herein should be understood to also contemplate a processing or detection floor such as a negative or zero saturation limit, or any other physical or analytic operating limit that might introduce artifacts into physiological signal calculation and impede operation of a physiological monitoring device.

[0145] Evaluation of the physiological signal may also or instead take into account ambient light and brightness of the light source (i.e., light emitted from the LED), which may be measured at a predetermined rate or interval (e.g., 100 times per second). The gain may affect the ambient light signal, and both the brightness and the gain may affect the driven light signal. Changes to activity levels, ambient light levels, and other environmental conditions as well as a user putting or taking off the device may lead to a degradation of the

quality of the physiological signal, or to changes in the signal levels leading to saturation or other unfavorable operating conditions.

[0146] In one aspect, the physiological signal may be modeled to predict the signal levels expected in each of the predetermined optical measurement states under the current monitoring conditions. The predicted signal levels, for all optical measurement states, may be modeled using target levels (i.e., the predetermined levels defined by a given optical measurement state) and the current brightness and gain levels. In one aspect, a target gain level (targetGainLevel) for one of the predetermined optical measurement states, a target LED level (targetLEDLevel) for the predetermined optical measurement state, a current gain level setting (currentGainLevel) and current LED brightness settings (currentLEDLevel) for the current optical measurement state may be used together to model the predicted physiological signal (PredictedOptical Sample) at each of the predetermined optical measurement states according to the following:

PredictedOpticalSignal =

$$\frac{\text{targetGainLevel}}{\text{currentGainLevel}} \left(\left(\frac{\text{targetLEDLevel}}{\text{currentLEDLevel}} (\text{opticalSignal} - \text{ambientSignal}) + \text{ambientSignal} \right) - \text{offset} \right) + \text{offset}$$

[0147] Where opticalSignal is the current intensity of the current optical signal received by the sensor, ambientSignal is the ambient light intensity, and the offset is a measured value taken from the optical sensor when no light is being driven and no gain is being applied.

[0148] According to this exemplary model, and given the current readings measured, an output signal level can be calculated or estimated for each of the discrete optical measurement states used by the system. The predicted optical signals may be compared to a known saturation limit and noise floor, which may be determined based on device specifications, or evaluated for a design or for a specific physiological monitoring device based upon an analysis of historical usage or test data.

[0149] Thus, the method 800 may include evaluating each of the predetermined optical states to predict a signal value therefor. More specifically, the method 800 may include determining the expected optical signal in each of the predetermined optical measurement states, including the current state, in order to determine if the signal for each of those states would be within normal operating conditions for the measurement system.

[0150] As shown in step 810, the method 800 may include adjusting the optical measurement state in response to a detected condition.

[0151] In one aspect, the method 800 may include adjusting the optical measurement state according to the predicted signals for one or more of the optical measurement states. For example, the results of the signal evaluation described above may help in the identification of a preferred operating state that will improve data quality. Where the current state produces poor results or approaches processing thresholds as contemplated above, the optical measurement state may be adjusted to an adjacent optical measurement state in the prioritized list. Similarly, where another state produces a

signal that is likely to provide better overall signal quality, or is within a preferred operating window for the measurement system, then the operating state may increment or decrement in the prioritized list as appropriate to move closer to that operating state. In another aspect, the method 800 may include maintaining a current one of the optical measurement states for at least a predetermined window of time, e.g., so that the system does not continuously change between states.

[0152] In another aspect, the method 800 may include adjusting the optical measurement state according to other detected conditions. This may, for example, include directly detecting (e.g., in the current signal) potential saturation or a loss of signal. This may also include a detection of other conditions that may be relevant to state selection. For example, a detected condition may include, without limitation, signal saturation, poor signal quality, putting on or removing the device, a change to ambient light, increased or decreased activity level, waking-up a sleeping device, a power off operation, or any change in the physiological signal that may affect the accuracy of the measurement data.

[0153] In one aspect, the detected condition may include a saturation of the light sensor, and the device may be adjusted to a predetermined optical measurement state by decrementing to a lower priority state in response to the detected condition. The detected condition may also or instead include a decrease in a quality of the physiological signal, and the device may be adjusted to a predetermined optical measurement state by incrementing to a higher priority state in response to the detected condition. The detected condition may also or instead include a removal and replacement of the physiological monitoring device on a user, and the device may be adjusted to a predetermined optical measurement state by changing to a highest priority state in response to the detected condition. The detected condition may also or instead include an increase in ambient light, and the device may be adjusted to a predetermined optical measurement state by incrementing to a higher priority state in response to the detected condition.

[0154] In one aspect, if the evaluation of the physiological signal, upon evaluation, is determined to be positively saturated, a different, lower-gain optical measurement state may be used. If the data quality is below a given threshold, e.g., very weak or undetectable, then an optical measurement state having a higher-intensity LED brightness may be used. In one aspect, the adjustment of the optical measurement state may include cycling the optical measurement states, according to the prioritized list, until an appropriate optical measurement state is found. If the physiological signal is acceptable, the device may remain in that optical measurement state until a saturation, or near saturation threshold signal is measured or predicted.

[0155] FIG. 9 is a flow chart illustrating a method of adjusting an optical measurement state. To illustrate an exemplary adjustment of the optical measurement state in response to a detected or predicted saturation condition the method 900 may perform one or more tests or signal modeling operations to determine which optical measurement state, if any, provides more efficient and reliable operation of the wearable device.

[0156] As shown in step 902, the method 900 may include performing a saturation test on the signal obtained by the light sensor. As described above, the saturation level for the signal may be known from collection and analysis of his-

torical data, models or simulations, or from device specifications or any other suitable source. The intensity of the signal may be compared to the known saturation or other saturation threshold to determine if an adjustment to an alternative optical measurement state is needed or if additional signal tests should be run.

[0157] As shown in step 904, the method 900 may include determining if the signal is saturated. As shown in step 906, if the signal is saturated, the method 900 may include adjusting the optical measurement state down one state in the prioritized list, e.g., adjusting the optical measurement state from S4 to S3.

[0158] As shown in step 908, if the current signal does not indicate device saturation (e.g., is not at or near a maximum or minimum device value), the method 900 may determine if an optical measurement state decrement is needed. A decrement in the optical measurement state may be needed, even if the physiological signal is not currently saturated, if the physiological signal is predicted to become saturated at a later time, given available information such as the current gain levels, LED brightness and ambient light measurements, continued operation near a saturation limit, or an observable trend in signal values suggesting an approaching saturation condition. If, for example, the predicted optical sample is modeled to become saturated under the present state, or reach a near-saturation threshold, an adjustment to the optical measurement state may be made.

[0159] As shown in step 910, the method 900 may determine if the present state is S1. If the present state is S1, according to the present example, the only available state with a lower gain level may be S0. In such a case, as shown in step 912, the optical measurement state may be adjusted down to S0. If, however, the present state is not S1, then, as shown in step 914 the optical measurement state may be adjusted to the highest possible state that is lower than the current state and does not have a predicted optical signal higher than the saturation threshold. The method 900 may then return to step 902 where the evaluation and adjustment can be repeated. While this has been generally described as a single step increment within the prioritized list of operating states, the optical measurement state may also be adjusted more than one step in either direction where necessary or appropriate according to the predicted signals at various operating states.

[0160] As shown in step 916, if a state decrement is not needed, the method 900 may determine if a state increment is needed or available. A state increment may be needed or otherwise desired if the physiological signal is at or near zero, or otherwise undetectable. The method 900 may determine if a state increment is available by modeling the predicted optical signal for each optical measurement state. If the predicted optical signals at another operating state are within an acceptable range of signal strengths, that optical measurement state may be made available. This may result in a single step increment to a next higher operating state in the prioritized list, or this may result in a multi-step increment where a suitable one of the higher, predetermined optical measurement states is available.

[0161] As shown in step 922, if none of the other optical measurement states are available, or the predicted optical signal for the current state yields the highest state in which the predicted optical signal does not exceed the saturation threshold, the present state may be maintained. As shown in step 918, for example, if it is determined that the present

state is S4, the method 900 will maintain the present state as there are no higher available optical measurement states. The method 900 may then return to step 902 where the evaluation and adjustment is repeated.

[0162] As shown in step 920, if the present optical measurement state is not S4, the method 900 may adjust the device to the highest optical measurement state for which the predicted model does not exceed the saturation threshold. The method 900 may then return to step 902 where the evaluation and adjustment is repeated.

[0163] According to the foregoing, there is also disclosed herein a wearable physiological monitoring system comprising a housing configured to be worn on a limb of a user and a light source within the housing. The light source may include one or more light emitting diodes. The system may further include a light sensor within the housing which is positioned to receive an optical signal from the light source through the limb of the user when placed for use. A memory for storing a plurality of predetermined optical measurement states may also be included. Each one of the plurality of predetermined optical measurement states may be characterized by at least a first discrete value for electronically controlling a brightness of the light source and a second discrete value for electronically controlling a gain of the light. The plurality of predetermined optical measurement states may be ordered into a prioritized list according to preferred measurement states.

[0164] The system may further include a processor within the housing and coupled in a communicating relationship with the light source, the light sensor and the memory. The processor may be configured by executable code stored in the memory to perform the steps of operating the light source according to the first discrete value for a current one of the predetermined optical measurement states, operating the light sensor according to the second discrete value for the current one of the predetermined optical measurement states, evaluating a physiological signal based on data from the light sensor, and adjusting the predetermined optical measurement state in response to a detected condition.

[0165] According to the foregoing, there is also disclosed herein a computer program product for operating a physiological monitoring device that uses an optical signal to determine a physiological signal. The computer program product may comprise computer executable code embodied in a non-transitory computer readable medium that, when executing on the physiological monitoring device stores a plurality of predetermined optical measurement states. Each one of the plurality of predetermined optical measurement states may be characterized by at least a first discrete value for electronically controlling a brightness of a light source of the physiological monitoring device and a second discrete value for electronically controlling a gain of a light sensor of the physiological monitoring device. The plurality of predetermined optical measurement states may be ordered into a prioritized list according to preferred measurement states. The computer executable code may operate the light source according to the first discrete value for a current one of the predetermined optical measurement states and operate the light sensor according to the second discrete value for the current one of the predetermined optical measurement states. The computer executable code may also evaluate the physiological signal based on data from the light sensor and adjust the predetermined optical measurement state in response to a detected condition.

[0166] The above systems, devices, methods, processes, and the like may be realized in hardware, software, or any combination of these suitable for the control, data acquisition, and data processing described herein. This includes realization in one or more microprocessors, microcontrollers, embedded microcontrollers, programmable digital signal processors or other programmable devices or processing circuitry, along with internal and/or external memory. This may also, or instead, include one or more application specific integrated circuits, programmable gate arrays, programmable array logic components, or any other device or devices that may be configured to process electronic signals. It will further be appreciated that a realization of the processes or devices described above may include computer-executable code created using a structured programming language such as C, an object oriented programming language such as C++, or any other high-level or low-level programming language (including assembly languages, hardware description languages, and database programming languages and technologies) that may be stored, compiled or interpreted to run on one of the above devices, as well as heterogeneous combinations of processors, processor architectures, or combinations of different hardware and software.

[0167] Thus, in one aspect, each method described above and combinations thereof may be embodied in computer executable code that, when executing on one or more computing devices, performs the steps thereof. In another aspect, the methods may be embodied in systems that perform the steps thereof, and may be distributed across devices in a number of ways, or all of the functionality may be integrated into a dedicated, standalone device or other hardware. The code may be stored in a non-transitory fashion in a computer memory, which may be a memory from which the program executes (such as random access memory associated with a processor), or a storage device such as a disk drive, flash memory or any other optical, electromagnetic, magnetic, infrared or other device or combination of devices. In another aspect, any of the systems and methods described above may be embodied in any suitable transmission or propagation medium carrying computer-executable code and/or any inputs or outputs from same. In another aspect, means for performing the steps associated with the processes described above may include any of the hardware and/or software described above. All such permutations and combinations are intended to fall within the scope of the present disclosure.

[0168] It should further be appreciated that the methods above are provided by way of example. Absent an explicit indication to the contrary, the disclosed steps may be modified, supplemented, omitted, and/or re-ordered without departing from the scope of this disclosure.

[0169] The method steps of the implementations described herein are intended to include any suitable method of causing such method steps to be performed, consistent with the patentability of the following claims, unless a different meaning is expressly provided or otherwise clear from the context. So for example performing the step of X includes any suitable method for causing another party such as a remote user, a remote processing resource (e.g., a server or cloud computer) or a machine to perform the step of X. Similarly, performing steps X, Y and Z may include any method of directing or controlling any combination of such other individuals or resources to perform steps X, Y and Z

to obtain the benefit of such steps. Thus method steps of the implementations described herein are intended to include any suitable method of causing one or more other parties or entities to perform the steps, consistent with the patentability of the following claims, unless a different meaning is expressly provided or otherwise clear from the context. Such parties or entities need not be under the direction or control of any other party or entity, and need not be located within a particular jurisdiction.

[0170] It will be appreciated that the methods and systems described above are set forth by way of example and not of limitation. Numerous variations, additions, omissions, and other modifications will be apparent to one of ordinary skill in the art. In addition, the order or presentation of method steps in the description and drawings above is not intended to require this order of performing the recited steps unless a particular order is expressly required or otherwise clear from the context. Thus, while particular embodiments have been shown and described, it will be apparent to those skilled in the art that various changes and modifications in form and details may be made therein without departing from the spirit and scope of this disclosure and are intended to form a part of the invention as defined by the following claims, which are to be interpreted in the broadest sense allowable by law.

What is claimed is:

1. A method for operating a physiological monitoring device that uses an optical signal to determine a physiological signal, the method comprising:

providing a plurality of predetermined optical measurement states, each one of the plurality of predetermined optical measurement states characterized by at least a first discrete value for electronically controlling a brightness of a light source of the physiological monitoring device and a second discrete value for electronically controlling a gain of a light sensor of the physiological monitoring device, wherein the plurality of predetermined optical measurement states are ordered into a prioritized list according to preferred measurement states;

operating the light source according to the first discrete value for a current one of the predetermined optical measurement states;

operating the light sensor according to the second discrete value for the current one of the predetermined optical measurement states;

evaluating the physiological signal based on data from the light sensor; and

adjusting the predetermined optical measurement state in response to a detected condition.

2. The method of claim 1 wherein the prioritized list is ordered for monotonically increasing magnitudes of the first discrete value as a priority within the prioritized list increases to a more preferred measurement state.

3. The method of claim 1 wherein the prioritized list is ordered for monotonically increasing magnitudes of the second discrete value as a priority within the prioritized list increases to a more preferred measurement state.

4. The method of claim 1 wherein the light source includes one or more light emitting diodes.

5. The method of claim 1 wherein the detected condition includes a saturation of the light sensor, and wherein adjust-

ing the predetermined optical measurement state includes decrementing to a lower priority state in response to the detected condition.

6. The method of claim 1 wherein the detected condition includes a decrease in a quality of the physiological signal, and wherein adjusting the predetermined optical measurement state includes incrementing to a higher priority state in response to the detected condition.

7. The method of claim 1 wherein the detected condition includes a removal and replacement of the physiological monitoring device on a user, and wherein adjusting the predetermined optical measurement state includes changing to a highest priority state in response to the detected condition.

8. The method of claim 1 wherein the detected condition includes an increase in ambient light, and wherein adjusting the predetermined optical measurement state includes incrementing to a higher priority state in response to the detected condition.

9. The method of claim 1 wherein the physiological monitoring device includes a wearable physiological monitoring device.

10. The method of claim 1 wherein the physiological monitoring device includes a photoplethysmography system for measuring a heart rate of a user.

11. A computer program product for operating a physiological monitoring device that uses an optical signal to determine a physiological signal, the computer program product comprising computer executable code embodied in a non-transitory compute readable medium that, when executing on the physiological monitoring device, performs the steps of:

storing a plurality of predetermined optical measurement states, each one of the plurality of predetermined optical measurement states characterized by at least a first discrete value for electronically controlling a brightness of a light source of the physiological monitoring device and a second discrete value for electronically controlling a gain of a light sensor of the physiological monitoring device, wherein the plurality of predetermined optical measurement states are ordered into a prioritized list according to preferred measurement states;

operating the light source according to the first discrete value for a current one of the predetermined optical measurement states;

operating the light sensor according to the second discrete value for the current one of the predetermined optical measurement states;

evaluating the physiological signal based on data from the light sensor; and

adjusting the predetermined optical measurement state in response to a detected condition.

12. The computer program product of claim 11 wherein the prioritized list is ordered for monotonically increasing magnitudes of the first discrete value as a priority within the prioritized list increases to a more preferred measurement state.

13. The computer program product of claim 11 wherein the prioritized list is ordered for monotonically increasing

magnitudes of the second discrete value as a priority within the prioritized list increases to a more preferred measurement state.

14. The computer program product of claim 11 wherein the light source includes one or more light emitting diodes.

15. The computer program product of claim 11 wherein the detected condition includes a saturation of the light sensor, and wherein adjusting the predetermined optical measurement state includes decrementing to a lower priority state in response to the detected condition.

16. The computer program product of claim 11 wherein the detected condition includes a decrease in a quality of the physiological signal, and wherein adjusting the predetermined optical measurement state includes incrementing to a higher priority state in response to the detected condition.

17. The computer program product of claim 11 wherein the detected condition includes a removal and replacement of the physiological monitoring device on a user, and wherein adjusting the predetermined optical measurement state includes changing to a highest priority state in response to the detected condition.

18. The computer program product of claim 11 wherein the detected condition includes an increase in ambient light, and wherein adjusting the predetermined optical measurement state includes incrementing to a higher priority state in response to the detected condition.

19. The computer program product of claim 11 wherein the physiological monitoring device includes a wearable physiological monitoring device.

20. A wearable physiological monitoring system comprising:

a housing configured to be worn on a limb of a user;

a light source within the housing, the light source including one or more light emitting diodes;

a light sensor within the housing, the light sensor positioned to receive an optical signal from the light source through the limb of the user when placed for use;

a memory storing a plurality of predetermined optical measurement states, each one of the plurality of predetermined optical measurement states characterized by at least a first discrete value for electronically controlling a brightness of the light source and a second discrete value for electronically controlling a gain of the light, wherein the plurality of predetermined optical measurement states are ordered into a prioritized list according to preferred measurement states; and

a processor within the housing and coupled in a communicating relationship with the light source, the light sensor and the memory, the processor configured by executable code stored in the memory to perform the steps of operating the light source according to the first discrete value for a current one of the predetermined optical measurement states, operating the light sensor according to the second discrete value for the current one of the predetermined optical measurement states, evaluating a physiological signal based on data from the light sensor, and adjusting the predetermined optical measurement state in response to a detected condition.

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[标]发明人	RITSCHER DAVID E TAVAKOLI BEHNOOSH GHANNAD REZAIE MOSTAFA		
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摘要(译)

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