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Low power optical measurements

Abstract

Methods, systems, and devices for adjusting a power output level of a light source on a wearable device are described. A photodetector on the wearable device may measure a first photoplethysmography (PPG) signal derived from an ambient light source that is powered externally to the wearable device. The wearable device may calculate a quality metric of the first PPG signal based on measuring the first PPG signal. The wearable device may adjust the power output level of the light source powered by the wearable device based on the quality metric of the first PPG signal.

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Background/Summary

FIELD OF TECHNOLOGY
(1) The following relates to wearable devices and data processing, including low power optical measurements.
BACKGROUND
(2) Some wearable devices may be configured to collect physiological data from users, including heart rate, motion data, temperature data, photoplethysmogram (PPG) data, and the like. In some cases, some wearable devices may include light sources that operate at constant power levels regardless of the quality of the physiological data signals, thereby reducing the overall battery life of the wearable device.

Description

BRIEF DESCRIPTION OF THE DRAWINGS
(1) FIG. **1** illustrates an example of a system that supports low power optical measurements in accordance with aspects of the present disclosure.
(2) FIG. **2** illustrates an example of a system that supports low power optical measurements in accordance with aspects of the present disclosure.
(3) FIG. **3** shows an example of a wearable device diagram that supports low power optical measurements in accordance with aspects of the present disclosure.
(4) FIG. **4** shows an example of a wearable device diagram that supports low power optical measurements in accordance with aspects of the present disclosure.
(5) FIG. **5** shows an example of a process flow that supports low power optical measurements in accordance with aspects of the present disclosure.
(6) FIG. **6** shows an example of timing diagrams that supports low power optical measurements in accordance with aspects of the present disclosure.
(7) FIG. **7** shows a block diagram of an apparatus that supports low power optical measurements in accordance with aspects of the present disclosure.
(8) FIG. **8** shows a block diagram of a wearable device manager that supports low power optical measurements in accordance with aspects of the present disclosure.

(9) FIG. **9** shows a diagram of a system including a device that supports low power optical measurements in accordance with aspects of the present disclosure.

(10) FIGS. **10** and **11** show flowcharts illustrating methods that support low power optical measurements in accordance with aspects of the present disclosure.

DETAILED DESCRIPTION

(11) Some wearable devices may be configured to collect physiological data from users, including photoplethysmogram (PPG) signals. In order to efficiently and accurately track physiological data, a wearable device may be configured to collect data continuously while the user wears the device. The wearable device may use the light propagation that travels from one or more light emitting diodes (LED), through the tissue, and to the photodetectors (PDs) for physiological measurements such as the PPG measurements. In such cases, the wearable device may use light emitted from a light source powered within the wearable device to measure physiological data signals. The light sources of a wearable device (e.g., LEDs or the like) may be configured to operate at relatively high and constant power levels regardless of the quality of the PPG signals or the presence of alternative or supplemental light sources. As such, the battery performance may suffer, which may reduce the overall operating battery life.

(12) Conventional wearable devices have been unable to efficiently, accurately, and reliably perform measurements using light sources outside of the wearable device for a variety of reasons. For example, alternative light sources other than the LEDs of the sensor, may create new optical interfaces that couple light into the tissue of the user from uncontrolled positions and with uncontrolled intensity. The new optical interfaces may behave differently as compared to cases where there is a controlled contact between the skin of the user and the LEDs allowing control over the light input to the skin of the user and over an optical measurement path through intended physiological structures. In such cases, the new optical interfaces may change a critical angle due to reflections, reduce perfusion index due to internal stray light, cause variations in distribution of light, and the like. The variation in optical interface and variation in wavelength may cause inaccurate readings from an alternative, external light source, which may result in inaccurate measurements.

(13) In some cases, the wearable device may be unable to efficiently and dynamically adjust a power of the LEDs, such as increasing or decreasing the brightness of an LED, to account for the variation in readings, which may increase power consumption at the wearable device. Taken together, these issues with wearable devices may result in inaccurate physiological data readings, which may lead to a distorted picture of the user's overall health (e.g., distorted PPG measurements), as well as increased power consumption and decreased battery life.

(14) Accordingly, techniques described herein are directed to systems and methods for dynamically adjusting the power output of the LEDs based on real-time signal quality metrics. More specifically, aspects of the present disclosure are directed to techniques for operating the LEDs at lower power levels (or completely turning the LEDs off) by using ambient light as an additional or alternative light source as compared to using only LEDs (or other light sources within the wearable device). The wearable device may use ambient light external from the wearable device (e.g., sunlight, indoor fluorescent lights, etc.) as a signal source to capture PPG signals or as an additional source to allow lowering the power outputted by the LEDs. In some cases, using ambient light external from the wearable device as the signal source to capture PPG signals may maximize the PD signals.

(15) The wearable device may determine the quality of the signal (e.g., the PPG signal) that is derived from the ambient light and determine whether to deactivate the LEDs and use the ambient light as the single light source or, alternatively, to operate the LEDs at a lower power level and refrain from using the ambient light as a light source. By dynamically adjusting the power output of the LEDs based on real-time signal quality metrics, techniques described herein may perform the same physiological measurements while consuming less power, which may lead to more accurate

measurements. In such cases, utilizing ambient light as an external light source and optimizing the LED power based on one or more quality metrics may decrease a power consumption at the wearable device, which may lead to longer battery life.

(16) The wearable device may perform a PPG measurement using a baseline power output of LEDs and perform a PPG measurement using ambient light. The wearable device may determine the quality of the signal measured with ambient light and adjust the power of the LEDs based on the quality of the signal. As described herein, the wearable device may adjust a power output level of a light source on the wearable device (e.g., the LED or vertical cavity surface-emitting laser (VCSEL)). The PD on the wearable device may measure a PPG signal derived from an ambient light source that is powered externally to the wearable device. The wearable device may calculate a quality metric of the PPG signal after measuring the PPG signal. In some cases, the wearable device may adjust the power output level of the light source powered by the wearable device based on the quality metric of the PPG signal to optimize the battery life of the wearable device.

(17) Aspects of the disclosure are initially described in the context of systems supporting physiological data collection from users via wearable devices. Aspects are then described in the context of wearable device diagrams, a process flow, and timing diagrams. Aspects of the disclosure are further illustrated by and described with reference to apparatus diagrams, system diagrams, and flowcharts that relate to low power optical measurements.

(18) FIG. **1** illustrates an example of a system **100** that supports low power optical measurements in accordance with aspects of the present disclosure. The system **100** includes a plurality of electronic devices (e.g., wearable devices **104**, user devices **106**) that may be worn and/or operated by one or more users **102**. The system **100** further includes a network **108** and one or more servers **110**.

(19) The electronic devices may include any electronic devices known in the art, including wearable devices **104** (e.g., ring wearable devices, watch wearable devices, etc.), user devices **106** (e.g., smartphones, laptops, tablets). The electronic devices associated with the respective users **102** may include one or more of the following functionalities: 1) measuring physiological data, 2) storing the measured data, 3) processing the data, 4) providing outputs (e.g., via GUIs) to a user **102** based on the processed data, and 5) communicating data with one another and/or other computing devices. Different electronic devices may perform one or more of the functionalities.

(20) Example wearable devices **104** may include wearable computing devices, such as a ring computing device (hereinafter "ring") configured to be worn on a user's **102** finger, a wrist computing device (e.g., a smart watch, fitness band, or bracelet) configured to be worn on a user's **102** wrist, and/or a head mounted computing device (e.g., glasses/goggles). Wearable devices **104** may also include bands, straps (e.g., flexible or inflexible bands or straps), stick-on sensors, and the like, that may be positioned in other locations, such as bands around the head (e.g., a forehead headband), arm (e.g., a forearm band and/or bicep band), and/or leg (e.g., a thigh or calf band), behind the ear, under the armpit, and the like. Wearable devices **104** may also be attached to, or included in, articles of clothing. For example, wearable devices **104** may be included in pockets and/or pouches on clothing. As another example, wearable device **104** may be clipped and/or pinned to clothing, or may otherwise be maintained within the vicinity of the user **102**. Example articles of clothing may include, but are not limited to, hats, shirts, gloves, pants, socks, outerwear (e.g., jackets), and undergarments. In some implementations, wearable devices **104** may be included with other types of devices such as training/sporting devices that are used during physical activity. For example, wearable devices **104** may be attached to, or included in, a bicycle, skis, a tennis racket, a golf club, and/or training weights.

(21) Much of the present disclosure may be described in the context of a ring wearable device **104**. Accordingly, the terms "ring **104**," "wearable device **104**," and like terms, may be used interchangeably, unless noted otherwise herein. However, the use of the term "ring **104**" is not to be regarded as limiting, as it is contemplated herein that aspects of the present disclosure may be performed using other wearable devices (e.g., watch wearable devices, necklace wearable device,

bracelet wearable devices, earring wearable devices, anklet wearable devices, and the like).

(22) In some aspects, user devices **106** may include handheld mobile computing devices, such as smartphones and tablet computing devices. User devices **106** may also include personal computers, such as laptop and desktop computing devices. Other example user devices **106** may include server computing devices that may communicate with other electronic devices (e.g., via the Internet). In some implementations, computing devices may include medical devices, such as external wearable computing devices (e.g., Holter monitors). Medical devices may also include implantable medical devices, such as pacemakers and cardioverter defibrillators. Other example user devices **106** may include home computing devices, such as internet of things (IoT) devices (e.g., IoT devices), smart televisions, smart speakers, smart displays (e.g., video call displays), hubs (e.g., wireless communication hubs), security systems, smart appliances (e.g., thermostats and refrigerators), and fitness equipment.

(23) Some electronic devices (e.g., wearable devices **104**, user devices **106**) may measure physiological parameters of respective users **102**, such as photoplethysmography waveforms, continuous skin temperature, a pulse waveform, respiration rate, heart rate, heart rate variability (HRV), actigraphy, galvanic skin response, pulse oximetry, blood oxygen saturation (SpO2), blood sugar levels (e.g., glucose metrics), and/or other physiological parameters. Some electronic devices that measure physiological parameters may also perform some/all of the calculations described herein. Some electronic devices may not measure physiological parameters, but may perform some/all of the calculations described herein. For example, a ring (e.g., wearable device **104**), mobile device application, or a server computing device may process received physiological data that was measured by other devices.

(24) In some implementations, a user **102** may operate, or may be associated with, multiple electronic devices, some of which may measure physiological parameters and some of which may process the measured physiological parameters. In some implementations, a user **102** may have a ring (e.g., wearable device **104**) that measures physiological parameters. The user **102** may also have, or be associated with, a user device **106** (e.g., mobile device, smartphone), where the wearable device **104** and the user device **106** are communicatively coupled to one another. In some cases, the user device **106** may receive data from the wearable device **104** and perform some/all of the calculations described herein. In some implementations, the user device **106** may also measure physiological parameters described herein, such as motion/activity parameters.

(25) For example, as illustrated in FIG. **1**, a first user **102**-*a* (User **1**) may operate, or may be associated with, a wearable device **104**-*a* (e.g., ring **104**-*a*) and a user device **106**-*a* that may operate as described herein. In this example, the user device **106**-*a* associated with user **102**-*a* may process/store physiological parameters measured by the ring **104**-*a*. Comparatively, a second user **102**-*b* (User **2**) may be associated with a ring **104**-*b*, a watch wearable device **104**-*c* (e.g., watch **104**-*c*), and a user device **106**-*b*, where the user device **106**-*b* associated with user **102**-*b* may process/store physiological parameters measured by the ring **104**-*b* and/or the watch **104**-*c*. Moreover, an nth user **102**-*n* (User N) may be associated with an arrangement of electronic devices described herein (e.g., ring **104**-*n*, user device **106**-*n*). In some aspects, wearable devices **104** (e.g., rings **104**, watches **104**) and other electronic devices may be communicatively coupled to the user devices **106** of the respective users **102** via Bluetooth, Wi-Fi, and other wireless protocols.

(26) In some implementations, the rings **104** (e.g., wearable devices **104**) of the system **100** may be configured to collect physiological data from the respective users **102** based on arterial blood flow within the user's finger. In particular, a ring **104** may utilize one or more light-emitting components, such as LEDs (e.g., red LEDs, green LEDs) that emit light on the palm-side of a user's finger to collect physiological data based on arterial blood flow within the user's finger. In general, the terms light-emitting components, light-emitting elements, and like terms, may include, but are not limited to, LEDs, micro LEDs, mini LEDs, laser diodes (LDs) (e.gVCSELs, and the like.

(27) In some cases, the system **100** may be configured to collect physiological data from the

respective users **102** based on blood flow diffused into a microvascular bed of skin with capillaries and arterioles. For example, the system **100** may collect PPG data based on a measured amount of blood diffused into the microvascular system of capillaries and arterioles. In some implementations, the ring **104** may acquire the physiological data using a combination of both green and red LEDs. The physiological data may include any physiological data known in the art including, but not limited to, temperature data, accelerometer data (e.g., movement/motion data), heart rate data, HRV data, blood oxygen level data, or any combination thereof.

(28) The use of both green and red LEDs may provide several advantages over other solutions, as red and green LEDs have been found to have their own distinct advantages when acquiring physiological data under different conditions (e.g., light/dark, active/inactive) and via different parts of the body, and the like. For example, green LEDs have been found to exhibit better performance during exercise. Moreover, using multiple LEDs (e.g., green and red LEDs) distributed around the ring **104** has been found to exhibit superior performance as compared to wearable devices that utilize LEDs that are positioned close to one another, such as within a watch wearable device. Furthermore, the blood vessels in the finger (e.g., arteries, capillaries) are more accessible via LEDs as compared to blood vessels in the wrist. In particular, arteries in the wrist are positioned on the bottom of the wrist (e.g., palm-side of the wrist), meaning only capillaries are accessible on the top of the wrist (e.g., back of hand side of the wrist), where wearable watch devices and similar devices are typically worn. As such, utilizing LEDs and other sensors within a ring **104** has been found to exhibit superior performance as compared to wearable devices worn on the wrist, as the ring **104** may have greater access to arteries (as compared to capillaries), thereby resulting in stronger signals and more valuable physiological data.

(29) The electronic devices of the system **100** (e.g., user devices **106**, wearable devices **104**) may be communicatively coupled to one or more servers **110** via wired or wireless communication protocols. For example, as shown in FIG. **1**, the electronic devices (e.g., user devices **106**) may be communicatively coupled to one or more servers **110** via a network **108**. The network **108** may implement transfer control protocol and internet protocol (TCP/IP), such as the Internet, or may implement other network **108** protocols. Network connections between the network **108** and the respective electronic devices may facilitate transport of data via email, web, text messages, mail, or any other appropriate form of interaction within a computer network **108**. For example, in some implementations, the ring **104**-*a* associated with the first user **102**-*a* may be communicatively coupled to the user device **106**-*a*, where the user device **106**-*a* is communicatively coupled to the servers **110** via the network **108**. In additional or alternative cases, wearable devices **104** (e.g., rings **104**, watches **104**) may be directly communicatively coupled to the network **108**.

(30) The system **100** may offer an on-demand database service between the user devices **106** and the one or more servers **110**. In some cases, the servers **110** may receive data from the user devices **106** via the network **108**, and may store and analyze the data. Similarly, the servers **110** may provide data to the user devices **106** via the network **108**. In some cases, the servers **110** may be located at one or more data centers. The servers **110** may be used for data storage, management, and processing. In some implementations, the servers **110** may provide a web-based interface to the user device **106** via web browsers.

(31) In some aspects, the system **100** may detect periods of time that a user **102** is asleep, and classify periods of time that the user **102** is asleep into one or more sleep stages (e.g., sleep stage classification). For example, as shown in FIG. **1**, User **102**-*a* may be associated with a wearable device **104**-*a* (e.g., ring **104**-*a*) and a user device **106**-*a*. In this example, the ring **104**-*a* may collect physiological data associated with the user **102**-*a*, including temperature, heart rate, HRV, respiratory rate, and the like. In some aspects, data collected by the ring **104**-*a* may be input to a machine learning classifier, where the machine learning classifier is configured to determine periods of time that the user **102**-*a* is (or was) asleep. Moreover, the machine learning classifier may be configured to classify periods of time into different sleep stages, including an awake sleep

stage, a rapid eye movement (REM) sleep stage, a light sleep stage (non-REM (NREM)), and a deep sleep stage (NREM). In some aspects, the classified sleep stages may be displayed to the user **102**-*a* via a GUI of the user device **106**-*a*. Sleep stage classification may be used to provide feedback to a user **102**-*a* regarding the user's sleeping patterns, such as recommended bedtimes, recommended wake-up times, and the like. Moreover, in some implementations, sleep stage classification techniques described herein may be used to calculate scores for the respective user, such as Sleep Scores, Readiness Scores, and the like.

(32) In some aspects, the system **100** may utilize circadian rhythm-derived features to further improve physiological data collection, data processing procedures, and other techniques described herein. The term circadian rhythm may refer to a natural, internal process that regulates an individual's sleep-wake cycle, that repeats approximately every 24 hours. In this regard, techniques described herein may utilize circadian rhythm adjustment models to improve physiological data collection, analysis, and data processing. For example, a circadian rhythm adjustment model may be input into a machine learning classifier along with physiological data collected from the user **102**-*a* via the wearable device **104**-*a*. In this example, the circadian rhythm adjustment model may be configured to "weight," or adjust, physiological data collected throughout a user's natural, approximately 24-hour circadian rhythm. In some implementations, the system may initially start with a "baseline" circadian rhythm adjustment model, and may modify the baseline model using physiological data collected from each user **102** to generate tailored, individualized circadian rhythm adjustment models that are specific to each respective user **102**.

(33) In some aspects, the system **100** may utilize other biological rhythms to further improve physiological data collection, analysis, and processing by phase of these other rhythms. For example, if a weekly rhythm is detected within an individual's baseline data, then the model may be configured to adjust "weights" of data by day of the week. Biological rhythms that may require adjustment to the model by this method include: 1) ultradian (faster than a day rhythms, including sleep cycles in a sleep state, and oscillations from less than an hour to several hours periodicity in the measured physiological variables during wake state: 2) circadian rhythms: 3) non-endogenous daily rhythms shown to be imposed on top of circadian rhythms, as in work schedules: 4) weekly rhythms, or other artificial time periodicities exogenously imposed (e.g. in a hypothetical culture with 12 day "weeks," 12 day rhythms could be used): 5) multi-day ovarian rhythms in women and spermatogenesis rhythms in men: 6) lunar rhythms (relevant for individuals living with low or no artificial lights); and 7) seasonal rhythms.

(34) The biological rhythms are not always stationary rhythms. For example, many women experience variability in ovarian cycle length across cycles, and ultradian rhythms are not expected to occur at exactly the same time or periodicity across days even within a user. As such, signal processing techniques sufficient to quantify the frequency composition while preserving temporal resolution of these rhythms in physiological data may be used to improve detection of these rhythms, to assign phase of each rhythm to each moment in time measured, and to thereby modify adjustment models and comparisons of time intervals. The biological rhythm-adjustment models and parameters can be added in linear or non-linear combinations as appropriate to more accurately capture the dynamic physiological baselines of an individual or group of individuals.

(35) In some aspects, the respective devices of the system **100** may support techniques for measuring a PPG signal using ambient light and adjusting the power output of the LEDs based on the quality of the PPG signal. For example, the system **100** may measure, at the PD on the wearable device **104**, a PPG signal derived from an ambient light source that is powered externally to the wearable device **104** (e.g., sunlight, fluorescent lights, and the like). In such cases, the system **100** may calculate a quality metric of the PPG signal derived from the ambient light source that is powered externally to the wearable device **104** in response to measuring the PPG signal derived from the ambient light source.

(36) The system **100** may adjust the power output level of the light source powered by the wearable

device **104** based on the quality metric of the PPG signal derived from the ambient light source. For example, the system **100** may deactivate (e.g., turn off) the LED or decrease the power output level of the LED while keeping the LED activated (e.g., turned on). In such cases, the system **100** may use ambient light as an external light source and optimize the LED power, thereby decreasing the power consumption at the wearable device **104** and increasing the battery life of the wearable device **104**.

(37) It should be appreciated by a person skilled in the art that one or more aspects of the disclosure may be implemented in a system **100** to additionally or alternatively solve other problems than those described above. Furthermore, aspects of the disclosure may provide technical improvements to "conventional" systems or processes as described herein. However, the description and appended drawings only include example technical improvements resulting from implementing aspects of the disclosure, and accordingly do not represent all of the technical improvements provided within the scope of the claims.

(38) FIG. **2** illustrates an example of a system **200** that supports low power optical measurements in accordance with aspects of the present disclosure. The system **200** may implement, or be implemented by, system **100**. In particular, system **200** illustrates an example of a ring **104** (e.g., wearable device **104**), a user device **106**, and a server **110**, as described with reference to FIG. **1**.

(39) In some aspects, the ring **104** may be configured to be worn around a user's finger, and may determine one or more user physiological parameters when worn around the user's finger. Example measurements and determinations may include, but are not limited to, user skin temperature, pulse waveforms, respiratory rate, heart rate, HRV, blood oxygen levels (SpO2), blood sugar levels (e.g., glucose metrics), and the like.

(40) The system **200** further includes a user device **106** (e.g., a smartphone) in communication with the ring **104**. For example, the ring **104** may be in wireless and/or wired communication with the user device **106**. In some implementations, the ring **104** may send measured and processed data (e.g., temperature data, photoplethysmogram (PPG) data, motion/accelerometer data, ring input data, and the like) to the user device **106**. The user device **106** may also send data to the ring **104**, such as ring **104** firmware/configuration updates. The user device **106** may process data. In some implementations, the user device **106** may transmit data to the server **110** for processing and/or storage.

(41) The ring **104** may include a housing **205** that may include an inner housing **205**-*a* and an outer housing **205**-*b*. In some aspects, the housing **205** of the ring **104** may store or otherwise include various components of the ring including, but not limited to, device electronics, a power source (e.g., battery **210**, and/or capacitor), one or more substrates (e.g., printable circuit boards) that interconnect the device electronics and/or power source, and the like. The device electronics may include device modules (e.g., hardware/software), such as: a processing module **230**-*a*, a memory **215**, a communication module **220**-*a*, a power module **225**, and the like. The device electronics may also include one or more sensors. Example sensors may include one or more temperature sensors **240**, a PPG sensor assembly (e.g., PPG system **235**), and one or more motion sensors **245**.

(42) The sensors may include associated modules (not illustrated) configured to communicate with the respective components/modules of the ring **104**, and generate signals associated with the respective sensors. In some aspects, each of the components/modules of the ring **104** may be communicatively coupled to one another via wired or wireless connections. Moreover, the ring **104** may include additional and/or alternative sensors or other components that are configured to collect physiological data from the user, including light sensors (e.g., LEDs), oximeters, and the like.

(43) The ring **104** shown and described with reference to FIG. **2** is provided solely for illustrative purposes. As such, the ring **104** may include additional or alternative components as those illustrated in FIG. **2**. Other rings **104** that provide functionality described herein may be fabricated. For example, rings **104** with fewer components (e.g., sensors) may be fabricated. In a specific example, a ring **104** with a single temperature sensor **240** (or other sensor), a power source, and

device electronics configured to read the single temperature sensor **240** (or other sensor) may be fabricated. In another specific example, a temperature sensor **240** (or other sensor) may be attached to a user's finger (e.g., using adhesives, wraps, clamps, spring loaded clamps, etc.). In this case, the sensor may be wired to another computing device, such as a wrist worn computing device that reads the temperature sensor **240** (or other sensor). In other examples, a ring **104** that includes additional sensors and processing functionality may be fabricated.

(44) The housing **205** may include one or more housing **205** components. The housing **205** may include an outer housing **205**-*b* component (e.g., a shell) and an inner housing **205**-*a* component (e.g., a molding). The housing **205** may include additional components (e.g., additional layers) not explicitly illustrated in FIG. **2**. For example, in some implementations, the ring **104** may include one or more insulating layers that electrically insulate the device electronics and other conductive materials (e.g., electrical traces) from the outer housing **205**-*b* (e.g., a metal outer housing **205**-*b*). The housing **205** may provide structural support for the device electronics, battery **210**, substrate(s), and other components. For example, the housing **205** may protect the device electronics, battery **210**, and substrate(s) from mechanical forces, such as pressure and impacts. The housing **205** may also protect the device electronics, battery **210**, and substrate(s) from water and/or other chemicals.

(45) The outer housing **205**-*b* may be fabricated from one or more materials. In some implementations, the outer housing **205**-*b* may include a metal, such as titanium, that may provide strength and abrasion resistance at a relatively light weight. The outer housing **205**-*b* may also be fabricated from other materials, such polymers. In some implementations, the outer housing **205**-*b* may be protective as well as decorative.

(46) The inner housing **205**-*a* may be configured to interface with the user's finger. The inner housing **205**-*a* may be formed from a polymer (e.g., a medical grade polymer) or other material. In some implementations, the inner housing **205**-*a* may be transparent. For example, the inner housing **205**-*a* may be transparent to light emitted by the PPG light emitting diodes (LEDs). In some implementations, the inner housing **205**-*a* component may be molded onto the outer housing **205**-*b*. For example, the inner housing **205**-*a* may include a polymer that is molded (e.g., injection molded) to fit into an outer housing **205**-*b* metallic shell.

(47) The ring **104** may include one or more substrates (not illustrated). The device electronics and battery **210** may be included on the one or more substrates. For example, the device electronics and battery **210** may be mounted on one or more substrates. Example substrates may include one or more printed circuit boards (PCBs), such as flexible PCB (e.g., polyimide). In some implementations, the electronics/battery **210** may include surface mounted devices (e.g., surface-mount technology (SMT) devices) on a flexible PCB. In some implementations, the one or more substrates (e.g., one or more flexible PCBs) may include electrical traces that provide electrical communication between device electronics. The electrical traces may also connect the battery **210** to the device electronics.

(48) The device electronics, battery **210**, and substrates may be arranged in the ring **104** in a variety of ways. In some implementations, one substrate that includes device electronics may be mounted along the bottom of the ring **104** (e.g., the bottom half), such that the sensors (e.g., PPG system **235**, temperature sensors **240**, motion sensors **245**, and other sensors) interface with the underside of the user's finger. In these implementations, the battery **210** may be included along the top portion of the ring **104** (e.g., on another substrate).

(49) The various components/modules of the ring **104** represent functionality (e.g., circuits and other components) that may be included in the ring **104**. Modules may include any discrete and/or integrated electronic circuit components that implement analog and/or digital circuits capable of producing the functions attributed to the modules herein. For example, the modules may include analog circuits (e.g., amplification circuits, filtering circuits, analog/digital conversion circuits, and/or other signal conditioning circuits). The modules may also include digital circuits (e.g.,

combinational or sequential logic circuits, memory circuits etc.).

(50) The memory **215** (memory module) of the ring **104** may include any volatile, non-volatile, magnetic, or electrical media, such as a random access memory (RAM), read-only memory (ROM), non-volatile RAM (NVRAM), electrically-erasable programmable ROM (EEPROM), flash memory, or any other memory device. The memory **215** may store any of the data described herein. For example, the memory **215** may be configured to store data (e.g., motion data, temperature data, PPG data) collected by the respective sensors and PPG system **235**. Furthermore, memory **215** may include instructions that, when executed by one or more processing circuits, cause the modules to perform various functions attributed to the modules herein. The device electronics of the ring **104** described herein are only example device electronics. As such, the types of electronic components used to implement the device electronics may vary based on design considerations.

(51) The functions attributed to the modules of the ring **104** described herein may be embodied as one or more processors, hardware, firmware, software, or any combination thereof. Depiction of different features as modules is intended to highlight different functional aspects and does not necessarily imply that such modules must be realized by separate hardware/software components. Rather, functionality associated with one or more modules may be performed by separate hardware/software components or integrated within common hardware/software components.

(52) The processing module **230**-*a* of the ring **104** may include one or more processors (e.g., processing units), microcontrollers, digital signal processors, systems on a chip (SOCs), and/or other processing devices. The processing module **230**-*a* communicates with the modules included in the ring **104**. For example, the processing module **230**-*a* may transmit/receive data to/from the modules and other components of the ring **104**, such as the sensors. As described herein, the modules may be implemented by various circuit components. Accordingly, the modules may also be referred to as circuits (e.g., a communication circuit and power circuit).

(53) The processing module **230**-*a* may communicate with the memory **215**. The memory **215** may include computer-readable instructions that, when executed by the processing module **230**-*a*, cause the processing module **230**-*a* to perform the various functions attributed to the processing module **230**-*a* herein. In some implementations, the processing module **230**-*a* (e.g., a microcontroller) may include additional features associated with other modules, such as communication functionality provided by the communication module **220**-*a* (e.g., an integrated Bluetooth Low Energy transceiver) and/or additional onboard memory **215**.

(54) The communication module **220**-*a* may include circuits that provide wireless and/or wired communication with the user device **106** (e.g., communication module **220**-*b* of the user device **106**). In some implementations, the communication modules **220**-*a*, **220**-*b* may include wireless communication circuits, such as Bluetooth circuits and/or Wi-Fi circuits. In some implementations, the communication modules **220**-*a*, **220**-*b* can include wired communication circuits, such as Universal Serial Bus (USB) communication circuits. Using the communication module **220**-*a*, the ring **104** and the user device **106** may be configured to communicate with each other. The processing module **230**-*a* of the ring may be configured to transmit/receive data to/from the user device **106** via the communication module **220**-*a*. Example data may include, but is not limited to, motion data, temperature data, pulse waveforms, heart rate data, HRV data, PPG data, and status updates (e.g., charging status, battery charge level, and/or ring **104** configuration settings). The processing module **230**-*a* of the ring may also be configured to receive updates (e.g., software/firmware updates) and data from the user device **106**.

(55) The ring **104** may include a battery **210** (e.g., a rechargeable battery **210**). An example battery **210** may include a Lithium-Ion or Lithium-Polymer type battery **210**, although a variety of battery **210** options are possible. The battery **210** may be wirelessly charged. In some implementations, the ring **104** may include a power source other than the battery **210**, such as a capacitor. The power source (e.g., battery **210** or capacitor) may have a curved geometry that matches the curve of the

ring **104**. In some aspects, a charger or other power source may include additional sensors that may be used to collect data in addition to, or that supplements, data collected by the ring **104** itself. Moreover, a charger or other power source for the ring **104** may function as a user device **106**, in which case the charger or other power source for the ring **104** may be configured to receive data from the ring **104**, store and/or process data received from the ring **104**, and communicate data between the ring **104** and the servers **110**.

(56) In some aspects, the ring **104** includes a power module **225** that may control charging of the battery **210**. For example, the power module **225** may interface with an external wireless charger that charges the battery **210** when interfaced with the ring **104**. The charger may include a datum structure that mates with a ring **104** datum structure to create a specified orientation with the ring **104** during charging. The power module **225** may also regulate voltage(s) of the device electronics, regulate power output to the device electronics, and monitor the state of charge of the battery **210**. In some implementations, the battery **210** may include a protection circuit module (PCM) that protects the battery **210** from high current discharge, over voltage during charging, and under voltage during discharge. The power module **225** may also include electro-static discharge (ESD) protection.

(57) The one or more temperature sensors **240** may be electrically coupled to the processing module **230**-*a*. The temperature sensor **240** may be configured to generate a temperature signal (e.g., temperature data) that indicates a temperature read or sensed by the temperature sensor **240**. The processing module **230**-*a* may determine a temperature of the user in the location of the temperature sensor **240**. For example, in the ring **104**, temperature data generated by the temperature sensor **240** may indicate a temperature of a user at the user's finger (e.g., skin temperature). In some implementations, the temperature sensor **240** may contact the user's skin. In other implementations, a portion of the housing **205** (e.g., the inner housing **205**-*a*) may form a barrier (e.g., a thin, thermally conductive barrier) between the temperature sensor **240** and the user's skin. In some implementations, portions of the ring **104** configured to contact the user's finger may have thermally conductive portions and thermally insulative portions. The thermally conductive portions may conduct heat from the user's finger to the temperature sensors **240**. The thermally insulative portions may insulate portions of the ring **104** (e.g., the temperature sensor **240**) from ambient temperature.

(58) In some implementations, the temperature sensor **240** may generate a digital signal (e.g., temperature data) that the processing module **230**-*a* may use to determine the temperature. As another example, in cases where the temperature sensor **240** includes a passive sensor, the processing module **230**-*a* (or a temperature sensor **240** module) may measure a current/voltage generated by the temperature sensor **240** and determine the temperature based on the measured current/voltage. Example temperature sensors **240** may include a thermistor, such as a negative temperature coefficient (NTC) thermistor, or other types of sensors including resistors, transistors, diodes, and/or other electrical/electronic components.

(59) The processing module **230**-*a* may sample the user's temperature over time. For example, the processing module **230**-*a* may sample the user's temperature according to a sampling rate. An example sampling rate may include one sample per second, although the processing module **230**-*a* may be configured to sample the temperature signal at other sampling rates that are higher or lower than one sample per second. In some implementations, the processing module **230**-*a* may sample the user's temperature continuously throughout the day and night. Sampling at a sufficient rate (e.g., one sample per second) throughout the day may provide sufficient temperature data for analysis described herein.

(60) The processing module **230**-*a* may store the sampled temperature data in memory **215**. In some implementations, the processing module **230**-*a* may process the sampled temperature data. For example, the processing module **230**-*a* may determine average temperature values over a period of time. In one example, the processing module **230**-*a* may determine an average

temperature value each minute by summing all temperature values collected over the minute and dividing by the number of samples over the minute. In a specific example where the temperature is sampled at one sample per second, the average temperature may be a sum of all sampled temperatures for one minute divided by sixty seconds. The memory **215** may store the average temperature values over time. In some implementations, the memory **215** may store average temperatures (e.g., one per minute) instead of sampled temperatures in order to conserve memory **215**.

(61) The sampling rate, which may be stored in memory **215**, may be configurable. In some implementations, the sampling rate may be the same throughout the day and night. In other implementations, the sampling rate may be changed throughout the day/night. In some implementations, the ring **104** may filter/reject temperature readings, such as large spikes in temperature that are not indicative of physiological changes (e.g., a temperature spike from a hot shower). In some implementations, the ring **104** may filter/reject temperature readings that may not be reliable due to other factors, such as excessive motion during exercise (e.g., as indicated by a motion sensor **245**).

(62) The ring **104** (e.g., communication module) may transmit the sampled and/or average temperature data to the user device **106** for storage and/or further processing. The user device **106** may transfer the sampled and/or average temperature data to the server **110** for storage and/or further processing.

(63) Although the ring **104** is illustrated as including a single temperature sensor **240**, the ring **104** may include multiple temperature sensors **240** in one or more locations, such as arranged along the inner housing **205**-*a* near the user's finger. In some implementations, the temperature sensors **240** may be stand-alone temperature sensors **240**. Additionally, or alternatively, one or more temperature sensors **240** may be included with other components (e.g., packaged with other components), such as with the accelerometer and/or processor.

(64) The processing module **230**-*a* may acquire and process data from multiple temperature sensors **240** in a similar manner described with respect to a single temperature sensor **240**. For example, the processing module **230** may individually sample, average, and store temperature data from each of the multiple temperature sensors **240**. In other examples, the processing module **230**-*a* may sample the sensors at different rates and average/store different values for the different sensors. In some implementations, the processing module **230**-*a* may be configured to determine a single temperature based on the average of two or more temperatures determined by two or more temperature sensors **240** in different locations on the finger.

(65) The temperature sensors **240** on the ring **104** may acquire distal temperatures at the user's finger (e.g., any finger). For example, one or more temperature sensors **240** on the ring **104** may acquire a user's temperature from the underside of a finger or at a different location on the finger. In some implementations, the ring **104** may continuously acquire distal temperature (e.g., at a sampling rate). Although distal temperature measured by a ring **104** at the finger is described herein, other devices may measure temperature at the same/different locations. In some cases, the distal temperature measured at a user's finger may differ from the temperature measured at a user's wrist or other external body location. Additionally, the distal temperature measured at a user's finger (e.g., a "shell" temperature) may differ from the user's core temperature. As such, the ring **104** may provide a useful temperature signal that may not be acquired at other internal/external locations of the body. In some cases, continuous temperature measurement at the finger may capture temperature fluctuations (e.g., small or large fluctuations) that may not be evident in core temperature. For example, continuous temperature measurement at the finger may capture minute-to-minute or hour-to-hour temperature fluctuations that provide additional insight that may not be provided by other temperature measurements elsewhere in the body.

(66) The ring **104** may include a PPG system **235**. The PPG system **235** may include one or more optical transmitters that transmit light. The PPG system **235** may also include one or more optical

receivers that receive light transmitted by the one or more optical transmitters. An optical receiver may generate a signal (hereinafter "PPG" signal) that indicates an amount of light received by the optical receiver. The optical transmitters may illuminate a region of the user's finger. The PPG signal generated by the PPG system **235** may indicate the perfusion of blood in the illuminated region. For example, the PPG signal may indicate blood volume changes in the illuminated region caused by a user's pulse pressure. The processing module **230**-*a* may sample the PPG signal and determine a user's pulse waveform based on the PPG signal. The processing module **230**-*a* may determine a variety of physiological parameters based on the user's pulse waveform, such as a user's respiratory rate, heart rate, HRV, oxygen saturation, and other circulatory parameters.

(67) In some implementations, the PPG system **235** may be configured as a reflective PPG system **235** where the optical receiver(s) receive transmitted light that is reflected through the region of the user's finger. In some implementations, the PPG system **235** may be configured as a transmissive PPG system **235** where the optical transmitter(s) and optical receiver(s) are arranged opposite to one another, such that light is transmitted directly through a portion of the user's finger to the optical receiver(s).

(68) The number and ratio of transmitters and receivers included in the PPG system **235** may vary. Example optical transmitters may include light-emitting diodes (LEDs). The optical transmitters may transmit light in the infrared spectrum and/or other spectrums. Example optical receivers may include, but are not limited to, photosensors, phototransistors, and photodiodes. The optical receivers may be configured to generate PPG signals in response to the wavelengths received from the optical transmitters. The location of the transmitters and receivers may vary. Additionally, a single device may include reflective and/or transmissive PPG systems **235**.

(69) The PPG system **235** illustrated in FIG. **2** may include a reflective PPG system **235** in some implementations. In these implementations, the PPG system **235** may include a centrally located optical receiver (e.g., at the bottom of the ring **104**) and two optical transmitters located on each side of the optical receiver. In this implementation, the PPG system **235** (e.g., optical receiver) may generate the PPG signal based on light received from one or both of the optical transmitters. In other implementations, other placements, combinations, and/or configurations of one or more optical transmitters and/or optical receivers are contemplated.

(70) The processing module **230**-*a* may control one or both of the optical transmitters to transmit light while sampling the PPG signal generated by the optical receiver. In some implementations, the processing module **230**-*a* may cause the optical transmitter with the stronger received signal to transmit light while sampling the PPG signal generated by the optical receiver. For example, the selected optical transmitter may continuously emit light while the PPG signal is sampled at a sampling rate (e.g., 250 Hz).

(71) Sampling the PPG signal generated by the PPG system **235** may result in a pulse waveform that may be referred to as a "PPG." The pulse waveform may indicate blood pressure vs time for multiple cardiac cycles. The pulse waveform may include peaks that indicate cardiac cycles. Additionally, the pulse waveform may include respiratory induced variations that may be used to determine respiration rate. The processing module **230**-*a* may store the pulse waveform in memory **215** in some implementations. The processing module **230**-*a* may process the pulse waveform as it is generated and/or from memory **215** to determine user physiological parameters described herein.

(72) The processing module **230**-*a* may determine the user's heart rate based on the pulse waveform. For example, the processing module **230**-*a* may determine heart rate (e.g., in beats per minute) based on the time between peaks in the pulse waveform. The time between peaks may be referred to as an interbeat interval (IBI). The processing module **230**-*a* may store the determined heart rate values and IBI values in memory **215**.

(73) The processing module **230**-*a* may determine HRV over time. For example, the processing module **230**-*a* may determine HRV based on the variation in the IBIs. The processing module **230**-*a* may store the HRV values over time in the memory **215**. Moreover, the processing module **230**-*a*

may determine the user's respiratory rate over time. For example, the processing module **230**-*a* may determine respiratory rate based on frequency modulation, amplitude modulation, or baseline modulation of the user's IBI values over a period of time. Respiratory rate may be calculated in breaths per minute or as another breathing rate (e.g., breaths per 30 seconds). The processing module **230**-*a* may store user respiratory rate values over time in the memory **215**.

(74) The ring **104** may include one or more motion sensors **245**, such as one or more accelerometers (e.g., 6-D accelerometers) and/or one or more gyroscopes (gyros). The motion sensors **245** may generate motion signals that indicate motion of the sensors. For example, the ring **104** may include one or more accelerometers that generate acceleration signals that indicate acceleration of the accelerometers. As another example, the ring **104** may include one or more gyro sensors that generate gyro signals that indicate angular motion (e.g., angular velocity) and/or changes in orientation. The motion sensors **245** may be included in one or more sensor packages. An example accelerometer/gyro sensor is a Bosch BM1160 inertial micro electro-mechanical system (MEMS) sensor that may measure angular rates and accelerations in three perpendicular axes.

(75) The processing module **230**-*a* may sample the motion signals at a sampling rate (e.g., 50 Hz) and determine the motion of the ring **104** based on the sampled motion signals. For example, the processing module **230**-*a* may sample acceleration signals to determine acceleration of the ring **104**. As another example, the processing module **230**-*a* may sample a gyro signal to determine angular motion. In some implementations, the processing module **230**-*a* may store motion data in memory **215**. Motion data may include sampled motion data as well as motion data that is calculated based on the sampled motion signals (e.g., acceleration and angular values).

(76) The ring **104** may store a variety of data described herein. For example, the ring **104** may store temperature data, such as raw sampled temperature data and calculated temperature data (e.g., average temperatures). As another example, the ring **104** may store PPG signal data, such as pulse waveforms and data calculated based on the pulse waveforms (e.g., heart rate values, IBI values, HRV values, and respiratory rate values). The ring **104** may also store motion data, such as sampled motion data that indicates linear and angular motion.

(77) The ring **104**, or other computing device, may calculate and store additional values based on the sampled/calculated physiological data. For example, the processing module **230** may calculate and store various metrics, such as sleep metrics (e.g., a Sleep Score), activity metrics, and readiness metrics. In some implementations, additional values/metrics may be referred to as "derived values." The ring **104**, or other computing/wearable device, may calculate a variety of values/metrics with respect to motion. Example derived values for motion data may include, but are not limited to, motion count values, regularity values, intensity values, metabolic equivalence of task values (METs), and orientation values. Motion counts, regularity values, intensity values, and METs may indicate an amount of user motion (e.g., velocity/acceleration) over time. Orientation values may indicate how the ring **104** is oriented on the user's finger and if the ring **104** is worn on the left hand or right hand.

(78) In some implementations, motion counts and regularity values may be determined by counting a number of acceleration peaks within one or more periods of time (e.g., one or more 30 second to 1 minute periods). Intensity values may indicate a number of movements and the associated intensity (e.g., acceleration values) of the movements. The intensity values may be categorized as low, medium, and high, depending on associated threshold acceleration values. METs may be determined based on the intensity of movements during a period of time (e.g., 30 seconds), the regularity/irregularity of the movements, and the number of movements associated with the different intensities.

(79) In some implementations, the processing module **230**-*a* may compress the data stored in memory **215**. For example, the processing module **230**-*a* may delete sampled data after making calculations based on the sampled data. As another example, the processing module **230**-*a* may

average data over longer periods of time in order to reduce the number of stored values. In a specific example, if average temperatures for a user over one minute are stored in memory **215**, the processing module **230**-*a* may calculate average temperatures over a five minute time period for storage, and then subsequently erase the one minute average temperature data. The processing module **230**-*a* may compress data based on a variety of factors, such as the total amount of used/available memory **215** and/or an elapsed time since the ring **104** last transmitted the data to the user device **106**.

(80) Although a user's physiological parameters may be measured by sensors included on a ring **104**, other devices may measure a user's physiological parameters. For example, although a user's temperature may be measured by a temperature sensor **240** included in a ring **104**, other devices may measure a user's temperature. In some examples, other wearable devices (e.g., wrist devices) may include sensors that measure user physiological parameters. Additionally, medical devices, such as external medical devices (e.g., wearable medical devices) and/or implantable medical devices, may measure a user's physiological parameters. One or more sensors on any type of computing device may be used to implement the techniques described herein.

(81) The physiological measurements may be taken continuously throughout the day and/or night. In some implementations, the physiological measurements may be taken during portions of the day and/or portions of the night. In some implementations, the physiological measurements may be taken in response to determining that the user is in a specific state, such as an active state, resting state, and/or a sleeping state. For example, the ring **104** can make physiological measurements in a resting/sleep state in order to acquire cleaner physiological signals. In one example, the ring **104** or other device/system may detect when a user is resting and/or sleeping and acquire physiological parameters (e.g., temperature) for that detected state. The devices/systems may use the resting/sleep physiological data and/or other data when the user is in other states in order to implement the techniques of the present disclosure.

(82) In some implementations, as described previously herein, the ring **104** may be configured to collect, store, and/or process data, and may transfer any of the data described herein to the user device **106** for storage and/or processing. In some aspects, the user device **106** includes a wearable application **250**, an operating system (OS), a web browser application (e.g., web browser **280**), one or more additional applications, and a GUI **275**. The user device **106** may further include other modules and components, including sensors, audio devices, haptic feedback devices, and the like. The wearable application **250** may include an example of an application (e.g., "app") that may be installed on the user device **106**. The wearable application **250** may be configured to acquire data from the ring **104**, store the acquired data, and process the acquired data as described herein. For example, the wearable application **250** may include a user interface (UI) module **255**, an acquisition module **260**, a processing module **230**-*b*, a communication module **220**-*b*, and a storage module (e.g., database **265**) configured to store application data.

(83) The various data processing operations described herein may be performed by the ring **104**, the user device **106**, the servers **110**, or any combination thereof. For example, in some cases, data collected by the ring **104** may be pre-processed and transmitted to the user device **106**. In this example, the user device **106** may perform some data processing operations on the received data, may transmit the data to the servers **110** for data processing, or both. For instance, in some cases, the user device **106** may perform processing operations that require relatively low processing power and/or operations that require a relatively low latency, whereas the user device **106** may transmit the data to the servers **110** for processing operations that require relatively high processing power and/or operations that may allow relatively higher latency.

(84) In some aspects, the ring **104**, user device **106**, and server **110** of the system **200** may be configured to evaluate sleep patterns for a user. In particular, the respective components of the system **200** may be used to collect data from a user via the ring **104**, and generate one or more scores (e.g., Sleep Score, Readiness Score) for the user based on the collected data. For example, as

noted previously herein, the ring **104** of the system **200** may be worn by a user to collect data from the user, including temperature, heart rate, HRV, and the like. Data collected by the ring **104** may be used to determine when the user is asleep in order to evaluate the user's sleep for a given "sleep day." In some aspects, scores may be calculated for the user for each respective sleep day, such that a first sleep day is associated with a first set of scores, and a second sleep day is associated with a second set of scores. Scores may be calculated for each respective sleep day based on data collected by the ring **104** during the respective sleep day. Scores may include, but are not limited to, Sleep Scores, Readiness Scores, and the like.

(85) In some cases, "sleep days" may align with the traditional calendar days, such that a given sleep day runs from midnight to midnight of the respective calendar day. In other cases, sleep days may be offset relative to calendar days. For example, sleep days may run from 6:00 pm (18:00) of a calendar day until 6:00 pm (18:00) of the subsequent calendar day. In this example, 6:00 pm may serve as a "cut-off time," where data collected from the user before 6:00 pm is counted for the current sleep day, and data collected from the user after 6:00 pm is counted for the subsequent sleep day. Due to the fact that most individuals sleep the most at night, offsetting sleep days relative to calendar days may enable the system **200** to evaluate sleep patterns for users in such a manner that is consistent with their sleep schedules. In some cases, users may be able to selectively adjust (e.g., via the GUI) a timing of sleep days relative to calendar days so that the sleep days are aligned with the duration of time that the respective users typically sleep.

(86) In some implementations, each overall score for a user for each respective day (e.g., Sleep Score, Readiness Score) may be determined/calculated based on one or more "contributors," "factors," or "contributing factors." For example, a user's overall Sleep Score may be calculated based on a set of contributors, including: total sleep, efficiency, restfulness, REM sleep, deep sleep, latency, timing, or any combination thereof. The Sleep Score may include any quantity of contributors. The "total sleep" contributor may refer to the sum of all sleep periods of the sleep day. The "efficiency" contributor may reflect the percentage of time spent asleep compared to time spent awake while in bed, and may be calculated using the efficiency average of long sleep periods (e.g., primary sleep period) of the sleep day, weighted by a duration of each sleep period. The "restfulness" contributor may indicate how restful the user's sleep is, and may be calculated using the average of all sleep periods of the sleep day, weighted by a duration of each period. The restfulness contributor may be based on a "wake up count" (e.g., sum of all the wake-ups (when user wakes up) detected during different sleep periods), excessive movement, and a "got up count" (e.g., sum of all the got-ups (when user gets out of bed) detected during the different sleep periods).

(87) The "REM sleep" contributor may refer to a sum total of REM sleep durations across all sleep periods of the sleep day including REM sleep. Similarly, the "deep sleep" contributor may refer to a sum total of deep sleep durations across all sleep periods of the sleep day including deep sleep. The "latency" contributor may signify how long (e.g., average, median, longest) the user takes to go to sleep, and may be calculated using the average of long sleep periods throughout the sleep day, weighted by a duration of each period and the number of such periods (e.g., consolidation of a given sleep stage or sleep stages may be its own contributor or weight other contributors). Lastly, the "timing" contributor may refer to a relative timing of sleep periods within the sleep day and/or calendar day, and may be calculated using the average of all sleep periods of the sleep day, weighted by a duration of each period.

(88) By way of another example, a user's overall Readiness Score may be calculated based on a set of contributors, including: sleep, sleep balance, heart rate, HRV balance, recovery index, temperature, activity, activity balance, or any combination thereof. The Readiness Score may include any quantity of contributors. The "sleep" contributor may refer to the combined Sleep Score of all sleep periods within the sleep day. The "sleep balance" contributor may refer to a cumulative duration of all sleep periods within the sleep day. In particular, sleep balance may indicate to a user whether the sleep that the user has been getting over some duration of time (e.g.,

the past two weeks) is in balance with the user's needs. Typically, adults need 7-9 hours of sleep a night to stay healthy, alert, and to perform at their best both mentally and physically. However, it is normal to have an occasional night of bad sleep, so the sleep balance contributor takes into account long-term sleep patterns to determine whether each user's sleep needs are being met. The "resting heart rate" contributor may indicate a lowest heart rate from the longest sleep period of the sleep day (e.g., primary sleep period) and/or the lowest heart rate from naps occurring after the primary sleep period.

(89) Continuing with reference to the "contributors" (e.g., factors, contributing factors) of the Readiness Score, the "HRV balance" contributor may indicate a highest HRV average from the primary sleep period and the naps happening after the primary sleep period. The HRV balance contributor may help users keep track of their recovery status by comparing their HRV trend over a first time period (e.g., two weeks) to an average HRV over some second, longer time period (e.g., three months). The "recovery index" contributor may be calculated based on the longest sleep period. Recovery index measures how long it takes for a user's resting heart rate to stabilize during the night. A sign of a very good recovery is that the user's resting heart rate stabilizes during the first half of the night, at least six hours before the user wakes up, leaving the body time to recover for the next day. The "body temperature" contributor may be calculated based on the longest sleep period (e.g., primary sleep period) or based on a nap happening after the longest sleep period if the user's highest temperature during the nap is at least 0.5° C. higher than the highest temperature during the longest period. In some aspects, the ring may measure a user's body temperature while the user is asleep, and the system **200** may display the user's average temperature relative to the user's baseline temperature. If a user's body temperature is outside of their normal range (e.g., clearly above or below 0.0), the body temperature contributor may be highlighted (e.g., go to a "Pay attention" state) or otherwise generate an alert for the user.

(90) In some aspects, the system **200** may support a wearable device that adjusts a power output level of a light source on the wearable device **104**. In particular, techniques described herein support a ring **104**, such as a wearable device **104** as described with reference to FIG. **1**. For example, a ring **104** may include an inner housing **205**-*a* configured to house a sensor module that includes one or more sensors that are configured to acquire physiological data from a user **102**. The one or more sensors of the ring **104** may obtain physiological measurements from the user (e.g., temperature sensors, additional LED-PD sensors used for measuring heart rate, oxygen saturation, one or more sensors that a device may use to detect whether a user is asleep, or the like).

(91) In some cases, the one or more sensors of the ring **104** are configured to acquire the physiological data from the user based on arterial blood flow, temperature, etc. In some implementations, the one or more sensors of the ring **104** are configured to acquire the physiological data (e.g., including PPG data) from the user based on blood flow that is diffused into the microvascular bed of skin with capillaries and arterioles. The one or more sensors of the ring **104** may be an example of PDs from the PPG system **235**, temperature sensors **240**, motion sensors **245**, and other sensors.

(92) As described herein, the wearable device of the system **200** may measure, at the PD, a PPG signal derived from an ambient light source that is powered externally to the wearable device (e.g., an alternative light source other than the LED). The system **200** may calculate a quality metric of the PPG signal after measuring the PPG signal. In such cases, the system **200** may adjust the power output level of the LED based on the quality metric of the PPG signal.

(93) While much of the present disclosure describes one or more components in the context of a wearable ring device, aspects of the present disclosure may additionally or alternatively be implemented in the context of other wearable devices. For example, in some implementations, the one or more components described herein may be implemented in the context of other wearable devices, such as bracelets, watches, necklaces, piercings, and the like. For example, the wearable device **104** may surround a finger, wrist, ankle, earlobe, or the like of a user.

(94) As noted previously herein, the ring **104** of the system **200** may be worn by a user to collect data from the user, including temperature data, sleep data, recovery data, activity data, heart rate data, HRV data, respiratory data, breathing rate data, blood pressure data, blood glucose data, and the like. The ring **104** of the system **200** may collect the physiological data from the user based on temperature sensors and measurements extracted from arterial blood flow (e.g., using PPG signals). In some cases, the ring **104** may collect the physiological data from the user based on measurements extracted from capillary blood flow, arteriole blood flow, or both. The physiological data may be collected continuously.

(95) In some implementations, the one or more sensors of the ring **104** may sample the user's temperature continuously throughout the day and night. Sampling at a sufficient rate (e.g., one sample per minute) throughout the day and/or night may provide sufficient temperature data for analysis described herein. In some implementations, the ring **104** may continuously acquire temperature data (e.g., at a sampling rate). In some examples, even though temperature is collected continuously, the system **200** may leverage other information about the user that it has collected or otherwise derived (e.g., sleep stage, activity levels, illness onset, etc.) to select a representative temperature for a particular day that is an accurate representation of the underlying physiological phenomenon.

(96) FIG. **3** shows an example of a wearable device diagram **300** that supports low power optical measurements in accordance with aspects of the present disclosure. The wearable device diagram **300** may implement, or be implemented by, aspects of the system **100**, system **200**, or both. For example, the wearable device diagram **300** may include a wearable device **302** that may illustrate an example of a wearable device **104** as described with reference to FIG. **1**. Although the wearable device **302** is illustrated as a ring in FIG. **3**, the wearable device **302** may be any example of any wearable device (e.g., a watch, a necklace, and the like).

(97) In some examples, the wearable device **302** may include an inner housing **305** and an outer housing **310**, which may be examples of an inner housing **205** and outer housing **205**-*b* as described with reference to FIG. **2**. One or more sensors may be embedded in the inner housing **305**, such as one or more LEDs **320** for collecting physiological measurements. In some cases, an outer opaque shell may be molded over an inner structure of the wearable device **302**.

(98) The wearable device **302** may be an example of a wearable ring device. For example, the PPG signals acquired along the respective channels illustrated in the wearable device diagram **300** may be acquired as a combination of the transmissive and reflective light transmitted through the skin of the finger. In such cases, the system may measure PPG measurements at different locations of the finger by transmitting or reflecting the light through a portion of the finger (e.g., widest portion of the finger) where the smaller arteries (e.g., arterioles) are located. Comparatively, other portions of the body (e.g., top of the wrist) may not include arterioles and may include bone and other bodily material which may interfere with physiological measurements collected by some wearable devices. As such, some other wearable devices, such as wearable devices worn around the wrist, may be unable to acquire physiological data based on blood flow within arterioles, which may result in inferior physiological measurements as compared to measurements acquired using a wearable ring device, thereby decreasing an efficiency and reliability of acquired physiological measurements.

(99) The wearable device **302** in wearable device diagram **300** may include an electronic substrate **315**, such as a printed wiring board (PWB) or PCB. The PCB may have both flexible and rigid sections. One or more sensors may be embedded in the electronic substrate **315**. For example, the electronic substrate may include one or more LEDs **320** and PDs **325**. The wearable device **302** may include LED **320**, which may emit light **330** received by PD **325**-*a* and/or PD **325**-*b*. In this regard, the LED **320** may support an optical channel for physiological data measurements. For example, the optical channel may be between the LED **320** and the PD **325**-*a.*

(100) The wearable device **302** may include any number of LEDs, PDs, and respective optical

channels for physiological data measurements. In some cases, LED **320** may be a red LED, a green LED, an infrared LED, a blue LED, or a laser diode which may emit light **330** that is scattered and absorbed by the skin of a user of the wearable device diagram **300** (e.g., reflective and/or transmissive measurements). In some cases, each of the LED **320**, PD **325**-*a*, and PD **325**-*b* may be positioned at different radial positions relative to an axis of the wearable device **302** and along an inner circumference of the wearable device **302**. In some examples, the PD **325**-*a* may be positioned at a radial position opposite of the PD **325**-*b*. The PPG signal from a green LED (e.g., LED **320**) may include a stronger signal as compared to a PPG signal from an infrared LED (e.g., LED **320**).

(101) In some cases, the inner housing **305** may include a dome structure over the one or more LEDs **320**, one or more PDs **325**, or both. For example, the wearable device **302** may include dome structures over LED **320**, PD **325**-*a*, and PD **325**-*b* to improve contact with the skin. In some other cases, there may be a window for the LED **320** to emit light **330**. An optical interface may form between the inner housing **305** and the domes or the windows (e.g., with a refractive index of ˜1.57) and the top layer of skin (e.g., with a refractive index of ˜1.55). The wearable device **302** may use the light propagation from the LEDs **320** to the PDs **325** through tissue for physiological measurements, such as PPG and SpO2 measurements. That is, the wearable device **302** may use light **330** from LED **320** to measure SpO2 or PPG.

(102) The wearable device diagram **300** may include an ambient light source **335**, which may emit light **340** received by PD **325**-*a* and/or PD **325**-*b*. In this regard, the ambient light source **335** may support an optical channel for physiological data measurements. For example, the optical channel may be between the ambient light source **335** and the PD **325**-*a*. In some cases, ambient light source **335** may be an example of a light source powered externally from the wearable device **302**. For example, the ambient light source **335** may be an example of fluorescent lights, sunlight, and the like. The ambient light source **335** may emit light **340** that is scattered and absorbed by skin of a user of the wearable device **302** (e.g., reflective and/or transmissive measurements). In some cases, the wearable device **302** may use light **340** from ambient light source **335** to measure SpO2 or PPG. Light **340** may penetrate the skin to a different depth than light **330** due to the varying wavelengths.

(103) In such cases, the system may measure the two different lights via a same PD **325**-*a* which may increase the diversity of the measurement in addition to measuring PPG measurements using two different light sources. That is, the wearable device diagram **300** may include a 2:1 relationship between the light sources (e.g., LED **320** and ambient light source **335**) and the PD **325**-*a*. In some aspects, separate PPG signals may be acquired along each of the respective optical channels. Moreover, in some implementations, the LED **320** may be configured to generate light **330** with a different wavelength as compared to the light **340** generated by the ambient light source **335**, which may further improve a diversity of measurements (e.g., PPG signals) acquired within the wearable device diagram **300**.

(104) In some implementations, a single PD **325** may be used together with multiple light sources (e.g., ambient light source **335** and LED **320**) to save cost and space. By measuring the signals (e.g., at PDs **325**), it may be possible to use LED **320** and PD **325** pairs and ambient light source **335** and PD **325** pairs that have sufficient optical paths during rapid motion and reduce battery consumption. However, the system may adjust a power level output by the LED **320** to utilize the ambient light source **335** thereby reducing the overall power consumption of the wearable device **302**. For example, using the ambient light source **335** may decrease the power consumption and increase the battery life of the wearable device **302**.

(105) The system may measure, at the PD **325**-*a*, a PPG signal derived from the LED **320**. The PPG signal may be an example of an initial measurement of PPG to use as a baseline power output level of the LED **320**. The system may measure, at the PD **325**-*a*, a PPG signal derived from the ambient light source **335**. The system may calculate a quality metric of the PPG signal derived

from the ambient light source **335** to determine whether to adjust the power output level of the LED **320**. In such cases, the system may perform a quality assessment of the PPG signal derived from the ambient light source **335** as compared to the PPG signal derived from the LED **320**.

(106) The system may determine that the quality assessment of the PPG signal derived from the ambient light source **335** satisfies a threshold. In such cases, the system may adjust the power output level of the LED **320** by turning down the power output level of the LED **320** or turning off the power output level of the LED **320** altogether. For example, the system may use the ambient light source **335** to power the PPG measurements as a single light source or in addition to the LED **320**. The ambient light source **335** may be used as a signal source to capture the PPG measurements while optimizing the power output of the LED **320** based on the quality metric of the PPG signal derived from the ambient light source **335**.

(107) The system may calculate the quality metric of the PPG signal derived from the ambient light source **335** and determine to use the ambient light source **335** for the PPG measurements. For example, the system may use the ambient light source **335** in an office environment (e.g., with fluorescent ceiling lights as the ambient light source **335**), outside on a bright, sunny day, or both. The system may decrease the power output of the LED **320** (e.g., a green LED) in cases where the ambient light source **335** is used. The light **340** may include a narrow spectrum of wavelengths in the presence of fluorescent lights as the ambient light source **335** or a wide spectrum of wavelengths in the presence of natural sunlight as the ambient light source **335**.

(108) Regardless of the wavelengths, the light **340** may penetrate the skin in several positions around the wearable device **302** such that the system may measure PPG measurements at different locations of the finger. In some cases, the LEDs **320** may use a range of 3 to 10 milliamps (mA) to perform the PPG measurements. However, utilizing the ambient light source **335** may enable the LEDs **320** to use less electrical current to perform PPG measurements. For example, the LEDs **320** may use a range of 0 to 0.5 mA to perform the same PPG measurement when utilizing the ambient light source **335**. As described herein, a combined channel selection based on a spectrogram or time domain signaling may increase the accuracy of the signaling and decrease the overall power consumption of the wearable device **302**.

(109) The wavelengths of the light **340** from the ambient light source **335** may be unknown to the system. In such cases, the system may calculate the quality metric of the PPG signal from the ambient light source **335** in order to determine whether to use the ambient light source **335**, the LED **320**, or both. In some cases, the light **340** from the ambient light source **335** may include a heart rate signal derived from the PPG signal. For example, the PPG signal may satisfy the threshold and include the heart rate signal based on satisfying the threshold. In some cases, an ambient light cancellation technique may remove the heart rate information from the PPG signal. For example, the heart rate information may be removed from the PPG signal based on the intensity of the LED **320** being lower than an intensity of the ambient light source **335**. In such cases, the system may remove heart rate information from the PPG measurement if the ambient light source **335** results in a stronger PPG signal than the LED **320**.

(110) The ambient light cancellation technique may be disabled to prevent the heart rate information from being removed from the PPG signal. In such cases, the ambient light cancellation technique may be dynamically turned on and off based on the quality metric of the PPG signal derived from the ambient light source **335**. The ambient light cancellation technique may record the PD **325**-*a* input of light received before and after the LED **320** illuminates. In such cases, the PD **325**-*a* may measure the light **330** and the light **340** before, during, and after the LED **320** illuminates regardless of whether the ambient light cancellation technique is used. By deactivating the ambient light cancellation technique when the ambient light source **335** is used, the system may save additional power consumed by the wearable device **302**. Comparing the PPG signal from the LED **320** and the PPG signal from the ambient light source **335** may determine whether the system uses the ambient light source **335** and deactivates the ambient light cancellation technique.

(111) In dark environments (e.g., environments without sunlight, fluorescent lights, and the like), the ambient light cancellation technique may be dynamically adjusted to be deactivated, thereby decreasing the power consumption of the wearable device **302**. That is, in dark environments, the ambient light may not be cancelled, so the ambient light cancellation technique may be turned off in order to save energy. For example, the system may determine that the PPG signal derived from the ambient light source **335** fails to satisfy the quality metric threshold, and the system may refrain from using the ambient light source **335**. In such cases, the system may deactivate (e.g., turn off) the ambient light cancellation technique. The ambient light cancellation technique may be deactivated to prevent measuring the light **330** before and after the LED **320** is activated which may save processing power from activating the PD **325**-*a*.

(112) In some cases, the ambient light source **335** may not emit enough light **340** to be received at the PD **325**-*a*. In such cases, the system may use the LED **320** to perform PPG measurements, and the ambient light cancellation technique may not be activated because the ambient light source **335** is not used. The LED **320** may operate at a reduced power output level such that a green LED **320** may use a low driving current. For example, previous wearable devices may use an LED operating at a range between 10 to 120 mA LED current. However, the wearable device **302** may now use an LED operating at 0.5 mA LED current to increase the efficiency of the overall wearable device **302**.

(113) In some examples, the system may remove certain physiological measurements to increase the quality of the PPG signals. For example, the system may detect longer wavelengths and remove measurements that include blood alcohol measurements to increase the quality of the PPG signals. In some cases, the ambient light source **335** may be used based on a time of day, motion associated with the user, a sleep position of the user, or a combination thereof. In some examples, the system may use the ambient light source **335** to measure daytime heart rate. For example, when a user exercises and the system measures the PPG signal, the strength of the light **340** may be greater than a strength of the light **330** from the LED **320**. The system may measure a static metric of the light **340** and determine whether the light **340** experiences a change in frequency. The system may determine that that light **340** is static and use the ambient light source **335** to power the PPG measurements. In such cases, the system may refrain from activating the LEDs **320** when the user is exercising and the outdoor, natural sunlight is the ambient light source **335**. In some cases, as described with reference to FIG. **4**, the system may measure the light **340** from a light guide to determine whether the system may use the ambient light source **335**.

(114) FIG. **4** shows an example of a wearable device diagram **400** that supports low power optical measurements in accordance with aspects of the present disclosure. The wearable device diagram **400** may implement, or be implemented by, aspects of the system **100**, system **200**, or both. For example, the wearable device diagram **400** may include a wearable device **402** that may illustrate an example of a wearable device **104** as described with reference to FIG. **1**. Although the wearable device **402** is illustrated as a ring in FIG. **4**, the wearable device **402** may be any example of a wearable device (e.g., a watch or bracelet, a necklace, and the like).

(115) The wearable device **402** may include a light guide **445**. The light guide **445** may extend from the outer housing **410** to the inner housing **405**. In such cases, the light guide **445** may extend from an external surface of the wearable device **402** to an inner surface of the wearable device **402**. The light guide **445** may be an example of a channel or a window that directs light **430**, light **440**, or both into the tissue of the user, the PD **425**-*a*, or both. The light guide **445** may include a clear, epoxy material. In some cases, the light guide **445** may be an example of a window or a pipe with TIR. For example, the light guide **445** may include a mirrored surface, a prism of various shapes, and the like. In such cases, the light guide **445** may collect light **430** and light **440** into the wearable device **402**.

(116) The light guide **445** may comprise a material that transmits and/or funnels light **430** from the LED **420** to the PD **425**-*a*, light **440** from the ambient light source **435**, or both. In some cases, the

light guide **445** may be positioned adjacent to the PD **425**-*a* to direct light **440**, light **430**, or both into the PD **425**-*a*. In other examples, a light guide **445** may be positioned adjacent to the LED **420**, the PD **425**-*b*, or both. The wearable device **402** may include one or more light guides **445**. For example, the PD **425**-*a* may include a light guide **445** positioned on either side of the PD **425**-*a*. In some cases, the outer cover **410** may include a channel (e.g., a groove throughout the material of the outer cover **410**) that guides the light from outside of the wearable device **402** and into the wearable device **402**.

(117) In some cases, a light guide sensor (e.g., a PD) may be attached to the light guide **445** such that the light guide sensor may measure an amount of light **440** received at the PD **425**-*a* and measure an amount of light **430** received at the PD **425**-*a*. In such cases, the light guide sensor may compare the amount of light **440** to an amount of light **430** received at the PD **425**-*a*. In some cases, the light guide sensor may signal, to the wearable device **302**, to deactivate the LED **420** based on an amount of light **440** received from the ambient light source **435**. In other examples, the light guide sensor may signal, to the wearable device **402**, to deactivate the LED **420** or lower the power output level of the LED **420** based on a quality metric of the PPG signal derived from the ambient light source **435**. For example, the light guide sensor may measure an amount of light **440** coming into the light guide **445** and determine that an amount of light **440** received at the PD **425**-*a* and a quality of light **440** satisfies a threshold to use the ambient light source **435** as opposed to the LED **420** or in addition to the LED **420**, thereby reducing the power consumption of the LED **420**.

(118) In some cases, the wearable device **402** may include a filter disposed over the PD **425**-*a*. For example, the filter may be an example of a film disposed on top of the dome over the PD **425**-*a*. Because the ambient light source **435** may emit a wide spectrum of light **440**, the light **440** may be filtered to omit the noise from the PPG signal. In such cases, the PPG signal may include less noise after the light **440** travels through the filter disposed over the PD **425**-*a*. In some cases, an amount of light may be filtered on the detector side (e.g., PD **425**-*a*), the source side (e.g., LED **420**, ambient light source **435**), or both. In some cases, spectral filtering may be used in addition to light guide filtering via light guide **445**. The filter may be an example of an absorption filter that includes a transmission window with a filter for certain wavelengths. In some cases, the sensors may include a filter on the pixels of the sensors. In such cases, a pixelated sensor may be used for different wavelengths, different spectrum peaks, different spectrum windows, or a combination thereof.

(119) In some cases, the wearable device **402** may store light **440** for future use. The light **440** may be stored within the wearable device **402**. For example, the light **440** may be stored within the light guide **445**. In some cases, the light **440** may be stored and released at a later time as a PPG sensor source. The wearable device **402**, including at least the PD **425**-*a*, the light guide **445**, or both, may use a phosphorescent material that stores the light **440** and releases the light **440** to the PD **425**-*a* after a duration of time expires based on the material properties of the phosphorescent material. In some cases, an electrically activated component (e.g., a liquid crystal shutter) may release the light **440** to the PD **425**-*a* after the wearable device **402** determines that the signal derived from the LED **420** fails to satisfy a threshold. For example, the phosphorescent material may store the light **440**, and the electrically activated component may release the light **440** to disable the LED **420** and conserve power of the wearable device **402**. In some examples, the phosphorescent material of the wearable device **402** may store the light **440**, and the electrically activated component may release the light **440** during the night such that the LED **420** may be deactivated. In such cases, the wearable device **402** may optically gather light **440** to determine the optimal timing to use the light **440** via the light guide **445**, a filter on the sensors, or both.

(120) FIG. **5** shows an example of a process flow **500** that supports low power optical measurements in accordance with aspects of the present disclosure. The process flow **500** may be implemented by the system **100** and system **200** including at least a server **110**, a user device **106**, a wearable device **104**, or some combination of components from these devices The process flow

500 may be implemented by the wearable device diagram **300**, wearable device diagram **400**, or both. Alternative examples of the following may be implemented, where some steps are performed in a different order than described or not performed at all. In some cases, steps may include additional features not mentioned below, or further steps may be added.

(121) Much of the present disclosure may be described in the context of a first PPG signal and a second PPG signal. Accordingly, the terms "first," "second," and like terms, may be used interchangeably, unless noted otherwise herein, as the terms "first" and "second" may be used to differentiate between two signals derived from two different light sources. However, the use of the terms "first" and "second" are not to be regarded as limiting, as it is contemplated herein that aspects of the present disclosure may measure two different signals derived from two different light sources.

(122) In some cases, at **505**, the wearable device may measure a first PPG signal. For example, a PD on the wearable device may measure a first PPG signal derived from the light source powered by the wearable device. The light source powered by the wearable device may be an example of an LED. For example, the first PPG signal may be acquired using the LED and one or more PDs. In some cases, receiving the first PPG signal may be based on the motion data satisfying a threshold motion metric, the temperature data satisfying a threshold temperature metric, or both. In some examples, the system may receive the first PPG signal based on the heart rate satisfying a threshold heart rate metric, the PPG signal feature data satisfying a threshold metric, or both. The received first PPG signal may be saved to a local memory storage. As described herein, the wearable device may determine whether to use the ambient light source as a single source based on the quality of the measurement derived from the ambient light source, regardless of measuring the first PPG signal derived from the light source powered by the wearable device.

(123) At **510**, the wearable device may measure a second PPG signal. For example, the PD on the wearable device may measure the second PPG signal. The second PPG signal may be derived from an ambient light source that is powered externally to the wearable device. In some cases, the wearable device may measure the second PPG signal before measuring the first PPG signal, after measuring the first PPG signal, or at a same time as measuring the first PPG signal.

(124) For example, the second PPG signal may be acquired using the ambient light source and one or more PDs. In some cases, receiving the second PPG signal may be based on the motion data satisfying a threshold motion metric, the temperature data satisfying a threshold temperature metric, or both. In some examples, the system may receive the second PPG signal based on the heart rate satisfying a threshold heart rate metric, the PPG signal feature data satisfying a threshold metric, or both. The received second PPG signal may be saved to a local memory storage.

(125) At **515**, the wearable device may calculate a quality metric. For example, the wearable device may calculate the quality metric of the second PPG signal based on measuring the second PPG signal. The wearable device may compare a morphology of the first PPG signal and a morphology of the second PPG signal in response to measuring the second PPG signal and measuring the first PPG signal. In such cases, the wearable device may compare the morphology of the first PPG signal and the morphology of the second PPG signal to calculate the quality metric of the second PPG signal. As such, the wearable device may compare the morphology of the signal derived from ambient light to the signal derived from LEDs.

(126) The morphology of the first PPG signal and the morphology of the second PPG signal may each include a pulse amplitude, a systolic gradient, a signal to noise ratio, or a combination thereof, as described with reference to FIG. **6**. For example, the wearable device may calculate the pulse amplitude of the second PPG signal in response to measuring the second PPG signal. The wearable device may calculate the quality metric of the second PPG signal based on calculating the pulse amplitude of the second PPG signal. In such cases, the wearable device may determine the quality metric of the pulse amplitude to determine whether to use the ambient light, the LEDs, or both as the light source to measure the PPG signal.

(127) In some cases, the wearable device may calculate a signal to noise ratio of the second PPG signal in response to measuring the second PPG signal. The wearable device may calculate the quality metric of the second PPG signal based on calculating the signal to noise ratio of the second PPG signal. In such cases, the wearable device may determine the quality metric of the signal to noise ratio to determine whether to use the ambient light, the LEDs, or both as the light source to measure the PPG signal.

(128) In some examples, the wearable device may calculate a systolic gradient of the second PPG signal after measuring the second PPG signal. The wearable device may calculate the quality metric of the second PPG signal based on calculating the systolic gradient of the second PPG signal. In such cases, the wearable device may determine the quality metric of the systolic gradient to determine whether to use the light source of ambient light, the LEDs, or both.

(129) The wearable device may calculate the quality metric of the first PPG signal based on measuring the first PPG signal. The wearable device may compare the morphology of the first PPG signal and the morphology of the second PPG signal to calculate the quality metric of the first PPG signal. In some cases, the wearable device may calculate the pulse amplitude of the first PPG signal in response to measuring the first PPG signal. The wearable device may calculate the quality metric of the first PPG signal based on calculating the pulse amplitude of the first PPG signal. In some cases, the wearable device may calculate a signal to noise ratio of the first PPG signal in response to measuring the first PPG signal. The wearable device may calculate the quality metric of the first PPG signal based on calculating the signal to noise ratio of the first PPG signal. In some examples, the wearable device may calculate a systolic gradient of the first PPG signal after measuring the first PPG signal. The wearable device may calculate the quality metric of the first PPG signal based on calculating the systolic gradient of the first PPG signal.

(130) At **520**, the wearable device may determine whether the quality metric of the second PPG signal satisfies a threshold based on calculating the quality metric of the second PPG signal. In some cases, the wearable device may determine whether the quality metric of the first PPG signal satisfies a threshold based on calculating the quality metric of the first PPG signal.

(131) At **525**, the wearable device may determine that the quality metric of the second PPG signal satisfies a threshold in response to calculating the quality metric of the second PPG signal. For example, the wearable device may deactivate an ambient light cancellation technique based on determining that the quality metric of the second PPG signal satisfies the threshold. In such cases, the wearable device may determine that the signal measured with ambient light (e.g., the second PPG signal) has a higher quality than the signal measured with the LED (e.g., the first PPG signal). For example, the PPG signal quality with ambient light may be adequate (e.g., satisfy the threshold), and the ambient light cancellation technique may be deactivated such that the ambient light may be used alone for measurements or together with LEDs in sensor measurements.

(132) The wearable device may disable (e.g., turn off) the ambient light cancellation technique after determining that the signal measured using ambient (e.g., the second PPG signal) has a higher quality metric than the signal measured using the LEDs (e.g., the first PPG signal). For example, the wearable device may determine that ambient light includes adequate quality with respect to the calculated quality metrics threshold. In such cases, the wearable device may use ambient light as the light source in heart rate measurement. In some examples, the wearable device may determine that the quality metric of the second PPG signal satisfies a threshold during the day.

(133) At **525**, the wearable device may determine that the quality metric of the first PPG signal fails to satisfy a threshold in response to calculating the quality metric of the first PPG signal. For example, the wearable device may deactivate an ambient light cancellation technique based on determining that the quality metric of the first PPG signal fails to satisfy the threshold. Ambient light cancellation works by recording the PD input just before and after lighting up the LED, and then removing the ambient light input from the LED-illuminated data sample.

(134) At **530**, the wearable device may adjust the power output level of the light source powered by

the wearable device. For example, the wearable device may deactivate the light source powered by the wearable device in response to determining that the quality metric of the second PPG signal satisfies the threshold. The wearable device may deactivate (e.g., turn off) the LEDs based on determining that the signal measured with ambient light is a better quality than the signal measured with the LED, that the ambient light includes adequate quality with respect to the calculated quality metrics, or both.

(135) For example, the wearable device may adjust the power output level of the light source powered by the wearable device based on the quality metric of the second PPG signal. The wearable device may adjust the power output level of the light source powered by the wearable device based on determining that the quality metric of the second PPG signal satisfies the threshold, deactivating the ambient light cancellation technique, or both. The power output level of the light source powered by the wearable device may be adjusted to be less than a baseline power output level of the light source powered by the wearable device. The wearable device may perform the PPG measurement using a low power LED or without using the LED altogether.

(136) In some cases, the power output level of the LED may be adjusted based on calculating the pulse amplitude of the second PPG signal, calculating the signal to noise ratio of the second PPG signal, calculating the systolic gradient of the second PPG signal, or a combination thereof. For example, the power output of the LED may be adjusted based on comparing the morphology of the first PPG signal and comparing the morphology of the second PPG signal. In some examples, the power output level of the LED may be adjusted based on deactivating the light source powered by the wearable device.

(137) In some examples, the power output level of the LED may be adjusted based on calculating the pulse amplitude of the first PPG signal, calculating the signal to noise ratio of the first PPG signal, calculating the systolic gradient of the first PPG signal, or a combination thereof. In some examples, the power output level of the LED may be adjusted based on deactivating the ambient light cancellation technique.

(138) At **535**, the wearable device may determine that the quality metric associated with the second PPG signal fails to satisfy a threshold. For example, the wearable device may determine that the quality metric of the second PPG signal fails to satisfy the threshold in response to calculating the quality metric. In such cases, the wearable device may activate the ambient light cancellation technique in response to determining that the quality metric of the second PPG signal fails to satisfy the threshold. For example, some ambient light may be present, but the PPG signal quality measured with ambient light may be too low (e.g., fails to satisfy the threshold), and the ambient light cancellation technique may be activated as the LEDs are used for sensor measurements. The wearable device may determine that the signal measured with ambient light is worse quality than the signal measured with the LED. In such cases, the wearable device may enable (e.g., turn on) ambient light cancellation technique to cancel out the ambient light and use the LED to measure the PPG signal.

(139) At **535**, the wearable device may determine that the quality metric associated with the first PPG signal satisfies a threshold. For example, the wearable device may determine that the quality metric of the first PPG signal satisfies the threshold in response to calculating the quality metric of the first PPG signal. In such cases, the wearable device may activate the ambient light cancellation technique in response to determining that the quality metric of the first PPG signal satisfies the threshold.

(140) At **530**, the wearable device may adjust the power output level of the light source powered by the wearable device based on activating the ambient light cancellation technique. For example, the power output level of the light source powered by the wearable device may be adjusted to be less than a baseline power output level of the light source powered by the wearable device after determining that the quality metric of the second PPG signal fails to satisfy the threshold. In such cases, the wearable device may perform the PPG measurement using a low powered LED. The

wearable device may adjust the power output of the LED in response to activating the ambient light cancellation technique. For example, a low powered green LED and a low powered IR LED may be utilized while the ambient light cancellation technique is turned on (e.g., cancelling out the ambient light).

(141) At **540**, the wearable device may determine that the quality metric associated with the second PPG signal fails to satisfy a threshold in response to calculating the quality metric of the second PPG signal. In such cases, the wearable device may determine that the quality metric associated with the second PPG signal (e.g. the ambient light level) is below the threshold. For example the wearable device may deactivate the ambient light cancellation technique in response to determining that the ambient light level (e.g., the quality metric of the second PPG signal) is below the threshold. The ambient light may not be cancelled because of the lack of ambient light present in dark environments, and the ambient light cancellation technique may be turned off (e.g., deactivated). In such cases, the wearable device may turn off the ambient light cancellation technique if there is no ambient light or a very low level of ambient light (e.g., during the night or in a dark day-time environment).

(142) During the night, the wearable device may use a low driving current for green LEDs for heart rate measurements. The sleep heart rate measurements with low light green PPG may be more efficient than IR with very low power settings. The low power settings may be an example of 0.5 mA LED current. In some cases, the night-time heart rate using an IR LED may use a range of 10 to 120 mA LED current. In the dark, the ambient light cancellation may be switched off dynamically to save battery power as the ambient light source may not emit enough ambient light to measure the PPG signal. In cases where there is no ambient light, or very low level of ambient light, there may not be improvement from using ambient light cancellation.

(143) For example, at night, the wearable device may measure the second PPG signal derived from the ambient light source. The wearable device may take initial measurements of ambient light to determine whether there is any or enough ambient light to measure the PPG signal. If the wearable device determines that there is little to no ambient light, the wearable device may deactivate the ambient light cancellation technique at **540**. After deactivating the ambient light cancellation technique, the wearable device may periodically measure the second PPG signal derived from the ambient light source to determine whether to activate the ambient light cancellation technique. In some cases, after deactivating the ambient light cancellation technique, the wearable device may refrain from periodically measuring the second PPG signal derived from the ambient light source until the wearable device detects motion. In such cases, the wearable device may identify movement and measure the PPG signals derived from the LED and the ambient light source.

(144) For example, at **540**), the wearable device may identify movement of a user wearing the wearable device after deactivating the ambient light cancellation technique. The wearable device may identify that the user is waking up based on identifying the movement and determine whether to use ambient light or the LED as the light source. In such cases, the wearable device may measure the first PPG signal and the second PPG signal in response to identifying the movement by the user and to determine whether there is enough ambient light and the quality of the ambient light satisfies the threshold to use the ambient light as the source for PPG measurements.

(145) The wearable device may use the motion of the wearable device to determine when the user wakes up. For example, the wearable device may perform periodic checks to determine if the amount of ambient light has changed and the ambient light cancellation technique may be turned back on. The periodic checks may be performed at varying intervals to determine whether the amount of ambient light has changed. For example, the periodic checks may be performed every 30 minutes, every hour, or every 2 hours. In some cases, the wearable device may use sleep timing data from the wearable device to predict when the user is likely to sleep, thus knowing when to switch off ambient light cancellation. The wearable device may use the calendar date, time of day, user location, or a combination thereof to determine sunrise and sunset to utilize the ambient light

cancellation technique accordingly. For example, the wearable device may use a time for sunrise to predict an increase in ambient light levels.

(146) At **530**, the wearable device may adjust the power output level of the light source powered by the wearable device based on deactivating the ambient light cancellation technique. For example, the power output level of the light source powered by the wearable device may be adjusted to be less than a baseline power output level of the light source powered by the wearable device in response to determining that the quality metric of the second PPG signal fails to satisfy the threshold, the ambient light cancellation technique is deactivated, or both. In such cases, the wearable device may perform the PPG measurement using a low powered LED.

(147) FIG. **6** shows an example of timing diagrams **600** that supports low power optical measurements in accordance with aspects of the present disclosure. The timing diagrams **600** may implement, or be implemented by, aspects of the system **100**, system **200**, wearable device diagram **300**, wearable device diagram **400**, process flow **500**, or a combination thereof.

(148) The timing diagram **600**-*a* may include a first PPG signal **605**-*a*, a second PPG signal **610**-*a*, and a third PPG signal **615**-*a*. The first PPG signal **605**-*a* may be an example of a PPG signal from a light source powered external to the wearable device (e.g., an ambient light source). The second PPG signal **610**-*a* may be an example of a PPG signal from a first green LED and received at a first photodetector. The third PPG signal **615**-*a* may be an example of a PPG signal from a second green LED and received at a second photodetector. In cases where a first green LED and a second green LED fire or activate simultaneously, the behavior of green light within a user's finger may be different due to physiological characteristics of the user's skin and other tissue, which may result in different arrival times of the green light at the respective photodetectors.

(149) The timing diagram **600**-*a* may illustrate an example of PPG signal comparison in which the first PPG signal **605**-*a*, the second PPG signal **610**-*a*, and the third PPG signal **615**-*a* may be compared to each other. For example, the wearable device may compare a morphology of the first PPG signal **605**-*a* and a morphology of the second PPG signal **610**-*a*. The wearable device may compare the morphology of the first PPG signal **605**-*a* and a morphology of the third PPG signal **615**-*a*.

(150) For example, the electrical current of the first PPG signal **605**-*a* may be greater (e.g., higher) than the second PPG signal **610**-*a* and the third PPG signal **615**-*a*. The electrical current of the second PPG signal **610**-*a* may be greater than the third PPG signal **615**-*a*. The wearable device may calculate the quality metric of the first PPG signal **605**-*a* associated with the ambient light source in response to comparing the morphology of the first PPG signal **605**-*a* and the morphology of the second PPG signal **610**-*a*, the third PPG signal **615**-*a*, or both. The morphology of the first PPG signal **605**-*a* may match (e.g., align) with the morphology of the second PPG signal **610**-*a*. The morphology of the first PPG signal **605**-*a* may be different from the morphology of the third PPG signal **615**-*a*.

(151) In such cases, the wearable device may determine that the quality metric of the first PPG signal **605**-*a* may satisfy the threshold based on determining that the morphology of the first PPG signal **605**-*a* aligns with the morphology of the second PPG signal **610**-*a*. The wearable device may adjust the power outlet level of the first green LED associated with the second PPG signal **610**-*a* and utilize the ambient light source to perform the PPG measurements in response to calculating the quality metric of the first PPG signal **605**-*a*, comparing the morphologies, or both.

(152) The morphology of the PPG signals may include a signal to noise ratio. The timing diagram **600**-*b* may include a first PPG signal **605**-*b*, a second PPG signal **610**-*b*, and a third PPG signal **615**-*b*, as described with reference to timing diagram **600**-*a*. The timing diagram **600**-*b* may illustrate an example of the signal to noise ratio of each PPG signal. For example, the wearable device may calculate the signal to noise ratio of the first PPG signal **605**-*b*, the second PPG signal **610**-*b*, and the third PPG signal **615**-*b*.

(153) The signal to noise ratio of the first PPG signal **605**-*b* may be greater than the second PPG

signal **610**-*b* and the third PPG signal **615**-*b*. The signal to noise ratio of the second PPG signal **610**-*b* may be greater than the third PPG signal **615**-*b*. The wearable device may calculate the quality metric of the first PPG signal **605**-*b* associated with the ambient light source in response to calculating the signal to noise ratio of the first PPG signal **605**-*b*. In some cases, the wearable device may calculate the quality metric of the second PPG signal **610**-*b* and the third PPG signal **615**-*b* in response to calculating the signal to noise ratio of the second PPG signal **610**-*b* and the third PPG signal **615**-*b*, respectively.

(154) The ambient light source (e.g., the first PPG signal **605**-*b*) may include the highest signal to noise ratio due to the least amount of electronic noise being present, the external noise is less attenuated and/or amplified, or both. In some cases, a dynamic range of measurements may change in different portions of the wearable device. For example, the external noise may be more attenuated and/or amplified in different portions of the wearable device where the photodetectors, the LEDs, or both are located. In such cases, when measuring with an asymmetrical PPG multichannel system, the wearable device may choose the optimal channel to perform the PPG measurements to lower the power consumption of the wearable device and maintain signal quality of the PPG measurements.

(155) The morphology of the signal to noise ratio of the first PPG signal **605**-*b* may match (e.g., align) with the morphology of the signal to noise ratio of the second PPG signal **610**-*b*. The morphology of the signal to noise ratio of the first PPG signal **605**-*b* may be different from the signal to noise ratio of the third PPG signal **615**-*b*. For example, the morphology of the signal to noise ratio of the first PPG signal **605**-*b* does not align with the morphology of the signal to noise ratio of the third PPG signal **615**-*b*.

(156) The wearable device may determine that the quality metric of the first PPG signal **605**-*b* satisfies the threshold based on calculating the signal to noise ratio of the first PPG signal **605**-*b*. The wearable device may adjust the power outlet level of the first green LED associated with the second PPG signal **610**-*b* and utilize the ambient light source associated with the first PPG signal **605**-*b* to perform the PPG measurements. For example, the wearable device may adjust the power output level of the first green LED in response to calculating the quality metric of the first PPG signal **605**-*b*, calculating the signal to noise ratio of the first PPG signal **605**-*b*, calculating the signal to noise ratio of the second PPG signal **610**-*b*, calculating the signal to noise ratio of the third PPG signal **615**-*b*, or a combination thereof. In such cases, the wearable device may determine the quality metric of the signal to noise ratio to determine whether to use the light source as ambient light or the LEDs.

(157) In some cases, the morphology of the PPG signals may include systolic gradient. Systolic gradient may be an example of a steepness of the rising edge of each pulse wave. As described with reference to the signal to noise ratio calculations of timing diagram **600**-*b*, the wearable device may calculate the systolic gradient of the first PPG signal **605**-*c*, the second PPG signal **610**-*c*, and the third PPG signal **615**-*c*.

(158) For example, the wearable device may determine that the systolic gradient of the first PPG signal **605**-*c* is greater than the third PPG signal **615**-*c* and the second PPG signal **610**-*c*. The wearable device may determine that the systolic gradient of the first PPG signal **605**-*c* is greater than the second PPG signal **610**-*c*. In such case, the wearable device may determine that the morphology of the systolic gradient of the first PPG signal **605**-*c* aligns with the systolic gradient of the third PPG signal **615**-*c*, and the wearable device may determine that the systolic gradient of the first PPG signal **605**-*c* may be different than the systolic gradient of the second PPG signal **610**-*c*. For example, the wearable device may determine that the systolic gradient of the first PPG signal **605**-*c* is greater than the systolic gradient of the second PPG signal **610**-*c*.

(159) The wearable device may adjust the power outlet level of the second green LED associated with the third PPG signal **615**-*c* and utilize the ambient light source to perform the PPG measurements in response to calculating the systolic gradient. For example, the wearable device

may adjust the power output level of the second green LED in response to calculating the quality metric (e.g., the systolic gradient) of the first PPG signal **605**-*c*, the second PPG signal **610**-*c*, the third PPG signal **615**-*c*, or a combination thereof.

(160) The morphology of the PPG signals may include a pulse wave amplitude. The pulse amplitude may be an example of a difference between a maximum of the PPG pulse waveform and a minimum of the PPG pulse waveform. The wearable device may calculate the pulse wave amplitude of the first PPG signal **605**-*d*, the second PPG signal **610**-*d*, and the third PPG signal **615**-*d*, as described with reference to the timing diagrams **600**.

(161) Based on the calculations, the pulse wave amplitude of the third PPG signal **615**-*d* may be determined to be greater than the first PPG signal **605**-*d* and the second PPG signal **610**-*d*. For example, the wearable device may determine that the pulse wave amplitude of the first PPG signal **605**-*d* is greater than the second PPG signal **610**-*d*. The wearable device may determine that the pulse wave amplitude of the first PPG signal **605**-*d* is similar to the third PPG signal **615**-*d*. For example, the wearable device may determine that morphology of the pulse wave amplitude of the first PPG signal **605**-*d* may match with the pulse wave amplitude of the third PPG signal **615**-*d*, and that the morphology of the pulse wave amplitude of the first PPG signal **605**-*d* is different than the pulse wave amplitude of the second PPG signal **610**-*d*.

(162) In response to calculating the pulse wave amplitudes of the respective PPG signals, the wearable device may adjust the power outlet level of the second green LED associated with the third PPG signal **615**-*d* and utilize the ambient light source to perform the PPG measurements. For example, the wearable device may adjust the power output level of the second green LED in response to calculating the quality metric (e.g., the pulse wave amplitude) of the first PPG signal **605**-*d*, the second PPG signal **610**-*d*, the third PPG signal **615**-*d*, or a combination thereof.

(163) For example, the wearable device may analyze the pulse wave amplitude of the PPG signals and optimize the LED current based on the pulse wave amplitudes. In some cases, the wearable device may increase the LED current if the pulse wave amplitude is too low. For example, the current of the LED associated with the second PPG signal **610**-*d* may be increased. In some cases, a pulsating source may be located closest to the third PPG signal **615**-*d*. In such cases, the third PPG signal **615**-*d* may include the greatest pulse wave amplitude. The ambient light source may include a pulse wave amplitude similar to the pulse wave amplitude of the second green LED due to the least amount of electronic noise being present, the external noise is less attenuated and/or amplified, or both.

(164) FIG. **7** shows a block diagram **700** of a device **705** that supports low power optical measurements in accordance with aspects of the present disclosure. The device **705** may include an input module **710**, an output module **715**, and a wearable device manager **720**. The device **705** may also include a processor. Each of these components may be in communication with one another (e.g., via one or more buses).

(165) For example, the wearable device manager **720** may include a signal component **725**, a quality metric component **730**, a power component **735**, or any combination thereof. In some examples, the wearable device manager **720**, or various components thereof, may be configured to perform various operations (e.g., receiving, monitoring, transmitting) using or otherwise in cooperation with the input module **710**, the output module **715**, or both. For example, the wearable device manager **720** may receive information from the input module **710**, send information to the output module **715**, or be integrated in combination with the input module **710**, the output module **715**, or both to receive information, transmit information, or perform various other operations as described herein.

(166) The signal component **725** may be configured as or otherwise support a means for measuring, at a photodetector on the wearable device, a first photoplethysmography (PPG) signal derived from an ambient light source that is powered externally to the wearable device. The quality metric component **730** may be configured as or otherwise support a means for calculating, by the wearable

device, a quality metric of the first PPG signal based at least in part on measuring the first PPG signal. The power component **735** may be configured as or otherwise support a means for adjusting, by the wearable device, the power output level of the light source powered by the wearable device based at least in part on the quality metric of the first PPG signal.

(167) FIG. **8** shows a block diagram **800** of a wearable device manager **820** that supports low power optical measurements in accordance with aspects of the present disclosure. The wearable device manager **820** may be an example of aspects of a wearable device manager or a wearable device manager **720**, or both, as described herein. The wearable device manager **820**, or various components thereof, may be an example of means for performing various aspects of low power optical measurements as described herein. For example, the wearable device manager **820** may include a signal component **825**, a quality metric component **830**, a power component **835**, or any combination thereof. Each of these components may communicate, directly or indirectly, with one another (e.g., via one or more buses).

(168) The signal component **825** may be configured as or otherwise support a means for measuring, at a photodetector on the wearable device, a first photoplethysmography (PPG) signal derived from an ambient light source that is powered externally to the wearable device. The quality metric component **830** may be configured as or otherwise support a means for calculating, by the wearable device, a quality metric of the first PPG signal based at least in part on measuring the first PPG signal. The power component **835** may be configured as or otherwise support a means for adjusting, by the wearable device, the power output level of the light source powered by the wearable device based at least in part on the quality metric of the first PPG signal.

(169) In some examples, the quality metric component **830** may be configured as or otherwise support a means for measuring, at the photodetector on the wearable device, a second PPG signal derived from the light source powered by the wearable device and comparing, by the wearable device, a morphology of the first PPG signal and a morphology of the second PPG signal based at least in part on measuring the first PPG signal, wherein calculating the quality metric is based at least in part on comparing the morphology of the first PPG signal and the morphology of the second PPG signal, wherein the morphology of the first PPG signal and the morphology of the second PPG signal each comprise a pulse amplitude, a systolic gradient, a signal to noise ratio, or a combination thereof.

(170) In some examples, to support calculating the quality metric, the signal component **825** may be configured as or otherwise support a means for calculating a pulse amplitude of the first PPG signal based at least in part on measuring the first PPG signal, wherein adjusting the power output level is based at least in part on calculating the pulse amplitude of the first PPG signal.

(171) In some examples, to support calculating the quality metric, the signal component **825** may be configured as or otherwise support a means for calculating a signal to noise ratio of the first PPG signal based at least in part on measuring the first PPG signal, wherein adjusting the power output level is based at least in part on calculating the signal to noise ratio of the first PPG signal.

(172) In some examples, to support calculating the quality metric, the signal component **825** may be configured as or otherwise support a means for calculating a systolic gradient of the first PPG signal based at least in part on measuring the first PPG signal, wherein adjusting the power output level is based at least in part on calculating the systolic gradient of the first PPG signal.

(173) In some examples, the quality metric component **830** may be configured as or otherwise support a means for determining that the quality metric of the first PPG signal satisfies a threshold based at least in part on calculating the quality metric. In some examples, the power component **840** may be configured as or otherwise support a means for deactivating an ambient light cancellation technique based at least in part on determining that the quality metric satisfies the threshold.

(174) In some examples, the power component **835** may be configured as or otherwise support a means for deactivating the light source powered by the wearable device based at least in part on

determining that the quality metric satisfies the threshold, wherein adjusting the power output level is based at least in part on deactivating the light source powered by the wearable device.

(175) In some examples, the quality metric component **830** may be configured as or otherwise support a means for determining that the quality metric associated with the first PPG signal fails to satisfy a threshold based at least in part on calculating the quality metric. In some examples, the power component **835** may be configured as or otherwise support a means for activating an ambient light cancellation technique based at least in part on determining that the quality metric fails to satisfy the threshold.

(176) In some examples, the quality metric component **830** may be configured as or otherwise support a means for determining that the quality metric associated with the first PPG signal fails to satisfy a threshold based at least in part on calculating the quality metric. In some examples, the power component **835** may be configured as or otherwise support a means for deactivating an ambient light cancellation technique based at least in part on determining that the quality metric fails to satisfy the threshold.

(177) In some examples, the signal component **825** may be configured as or otherwise support a means for identifying movement of a user wearing the wearable device after deactivating the ambient light cancellation technique, wherein measuring the first PPG signal is based at least in part on identifying the movement by the user.

(178) In some examples, the power output level of the light source powered by the wearable device is adjusted to be less than a baseline power output level of the light source powered by the wearable device.

(179) FIG. **9** shows a diagram of a system **900** including a device **905** that supports low power optical measurements in accordance with aspects of the present disclosure. The device **905** may be an example of or include the components of a device **705** as described herein. The device **905** may include an example of a wearable device **104**, as described previously herein. The device **905** may include components for bi-directional communications including components for transmitting and receiving communications with a user device **106** and a server **110**, such as a wearable device manager **920**, a communication module **910**, an antenna **915**, a sensor component **925**, a power module **930**, a memory **935**, a processor **940**, and a wireless device **950**. These components may be in electronic communication or otherwise coupled (e.g., operatively, communicatively, functionally, electronically, electrically) via one or more buses (e.g., a bus **945**).

(180) For example, the wearable device manager **920** may be configured as or otherwise support a means for measuring, at a photodetector on the wearable device, a first photoplethysmography (PPG) signal derived from an ambient light source that is powered externally to the wearable device. The wearable device manager **920** may be configured as or otherwise support a means for calculating, by the wearable device, a quality metric of the first PPG signal based at least in part on measuring the first PPG signal. The wearable device manager **920** may be configured as or otherwise support a means for adjusting, by the wearable device, the power output level of the light source powering by the wearable device based at least in part on the quality metric of the first PPG signal.

(181) By including or configuring the wearable device manager **920** in accordance with examples as described herein, the device **905** may support techniques improved communication reliability, reduced latency, improved user experience related to reduced processing, reduced power consumption, more efficient utilization of communication resources, improved coordination between devices, longer battery life, improved utilization of processing capability, and the like.

(182) FIG. **10** shows a flowchart illustrating a method **1000** that supports low power optical measurements in accordance with aspects of the present disclosure. The operations of the method **1000** may be implemented by a wearable device or its components as described herein. For example, the operations of the method **1000** may be performed by a wearable device as described with reference to FIGS. **1** through **9**. In some examples, a wearable device may execute a set of

instructions to control the functional elements of the wearable device to perform the described functions. Additionally, or alternatively, the wearable device may perform aspects of the described functions using special-purpose hardware.

(183) At **1005**, the method may include measuring, at a photodetector on the wearable device, a first photoplethysmography (PPG) signal derived from an ambient light source that is powered externally to the wearable device. The operations of block **1005** may be performed in accordance with examples as disclosed herein. In some examples, aspects of the operations of **1005** may be performed by a signal component **825** as described with reference to FIG. **8**.

(184) At **1010**, the method may include calculating, by the wearable device, a quality metric of the first PPG signal based at least in part on measuring the first PPG signal. The operations of block **1010** may be performed in accordance with examples as disclosed herein. In some examples, aspects of the operations of **1010** may be performed by a quality metric component **830** as described with reference to FIG. **8**.

(185) At **1015**, the method may include adjusting, by the wearable device, the power output level of the light source powered by the wearable device based at least in part on the quality metric of the first PPG signal. The operations of block **1015** may be performed in accordance with examples as disclosed herein. In some examples, aspects of the operations of **1015** may be performed by a power component **835** as described with reference to FIG. **8**.

(186) FIG. **11** shows a flowchart illustrating a method **1100** that supports low power optical measurements in accordance with aspects of the present disclosure. The operations of the method **1100** may be implemented by a wearable device or its components as described herein. For example, the operations of the method **1100** may be performed by a wearable device as described with reference to FIGS. **1** through **9**. In some examples, a wearable device may execute a set of instructions to control the functional elements of the wearable device to perform the described functions. Additionally, or alternatively, the wearable device may perform aspects of the described functions using special-purpose hardware.

(187) At **1105**, the method may include measuring, at a photodetector on the wearable device, a first photoplethysmography (PPG) signal derived from an ambient light source that is powered externally to the wearable device. The operations of block **1105** may be performed in accordance with examples as disclosed herein. In some examples, aspects of the operations of **1105** may be performed by a signal component **825** as described with reference to FIG. **8**.

(188) At **1110**, the method may include measuring, at the photodetector on the wearable device, a second PPG signal derived from the light source powered by the wearable device. The operations of block **1110** may be performed in accordance with examples as disclosed herein. In some examples, aspects of the operations of **1110** may be performed by a quality metric component **830** as described with reference to FIG. **8**.

(189) At **1115**, the method may include comparing, by the wearable device, a morphology of the first PPG signal and a morphology of the second PPG signal based at least in part on measuring the first PPG signal, wherein calculating the quality metric is based at least in part on comparing the morphology of the first PPG signal and the morphology of the second PPG signal, wherein the morphology of the first PPG signal and the morphology of the second PPG signal each comprise a pulse amplitude, a systolic gradient, a signal to noise ratio, or a combination thereof. The operations of block **1115** may be performed in accordance with examples as disclosed herein. In some examples, aspects of the operations of **1115** may be performed by a quality metric component **830** as described with reference to FIG. **8**.

(190) At **1120**, the method may include calculating, by the wearable device, a quality metric of the first PPG signal based at least in part on measuring the first PPG signal. The operations of block **1120** may be performed in accordance with examples as disclosed herein. In some examples, aspects of the operations of **1120** may be performed by a quality metric component **830** as described with reference to FIG. **8**.

(191) At **1125**, the method may include adjusting, by the wearable device, the power output level of the light source powered by the wearable device based at least in part on the quality metric of the first PPG signal. The operations of block **1125** may be performed in accordance with examples as disclosed herein. In some examples, aspects of the operations of **1125** may be performed by a power component **835** as described with reference to FIG. **8**.

(192) It should be noted that the methods described above describe possible implementations, and that the operations and the steps may be rearranged or otherwise modified and that other implementations are possible. Furthermore, aspects from two or more of the methods may be combined.

(193) A method is described. The method may include measuring, at a photodetector on the wearable device, a first PPG signal derived from an ambient light source that is powered externally to the wearable device, calculating, by the wearable device, a quality metric of the first PPG signal based at least in part on measuring the first PPG signal, and adjusting, by the wearable device, the power output level of the light source powered by the wearable device based at least in part on the quality metric of the first PPG signal.

(194) An apparatus is described. The apparatus may include a processor, memory coupled with the processor, and instructions stored in the memory. The instructions may be executable by the processor to cause the apparatus to measure, at a photodetector on the wearable device, a first PPG signal derived from an ambient light source that is powered externally to the wearable device, calculate, by the wearable device, a quality metric of the first PPG signal based at least in part on measuring the first PPG signal, and adjusting, by the wearable device, the power output level of the light source power by the wearable device based at least in part on the quality metric of the first PPG signal.

(195) Another apparatus is described. The apparatus may include means for measuring, at a photodetector on the wearable device, a first PPG signal derived from an ambient light source that is powered externally to the wearable device, means for calculating, by the wearable device, a quality metric of the first PPG signal based at least in part on measuring the first PPG signal, and means for adjusting, by the wearable device, the power output level of the light source powered by the wearable device based at least in part on the quality metric of the first PPG signal.

(196) A non-transitory computer-readable medium storing code is described. The code may include instructions executable by a processor to measure, at a photodetector on the wearable device, a first PPG signal derived from an ambient light source that is powered externally to the wearable device, calculate, by the wearable device, a quality metric of the first PPG signal based at least in part on measuring the first PPG signal, and adjusting, by the wearable device, the power output level of the light source power by the wearable device based at least in part on the quality metric of the first PPG signal.

(197) Some examples of the method, apparatuses, and non-transitory computer-readable medium described herein may further include operations, features, means, or instructions for measuring, at the photodetector on the wearable device, a second PPG signal derived from the light source powered by the wearable device and comparing, by the wearable device, a morphology of the first PPG signal and a morphology of the second PPG signal based at least in part on measuring the first PPG signal, wherein calculating the quality metric may be based at least in part on comparing the morphology of the first PPG signal and the morphology of the second PPG signal, wherein the morphology of the first PPG signal and the morphology of the second PPG signal each comprise a pulse amplitude, a systolic gradient, a signal to noise ratio, or a combination thereof.

(198) In some examples of the method, apparatuses, and non-transitory computer-readable medium described herein, calculating the quality metric may include operations, features, means, or instructions for calculating a pulse amplitude of the first PPG signal based at least in part on measuring the first PPG signal, wherein adjusting the power output level may be based at least in part on calculating the pulse amplitude of the first PPG signal.

(199) In some examples of the method, apparatuses, and non-transitory computer-readable medium described herein, calculating the quality metric may include operations, features, means, or instructions for calculating a signal to noise ratio of the first PPG signal based at least in part on measuring the first PPG signal, wherein adjusting the power output level may be based at least in part on calculating the signal to noise ratio of the first PPG signal.

(200) In some examples of the method, apparatuses, and non-transitory computer-readable medium described herein, calculating the quality metric may include operations, features, means, or instructions for calculating a systolic gradient of the first PPG signal based at least in part on measuring the first PPG signal, wherein adjusting the power output level may be based at least in part on calculating the systolic gradient of the first PPG signal.

(201) Some examples of the method, apparatuses, and non-transitory computer-readable medium described herein may further include operations, features, means, or instructions for determining that the quality metric of the first PPG signal satisfies a threshold based at least in part on calculating the quality metric and deactivating an ambient light cancellation technique based at least in part on determining that the quality metric satisfies the threshold.

(202) Some examples of the method, apparatuses, and non-transitory computer-readable medium described herein may further include operations, features, means, or instructions for deactivating the light source powered by the wearable device based at least in part on determining that the quality metric satisfies the threshold, wherein adjusting the power output level may be based at least in part on deactivating the light source powered by the wearable device.

(203) Some examples of the method, apparatuses, and non-transitory computer-readable medium described herein may further include operations, features, means, or instructions for determining that the quality metric associated with the first PPG signal fails to satisfy a threshold based at least in part on calculating the quality metric and activating an ambient light cancellation technique based at least in part on determining that the quality metric fails to satisfy the threshold.

(204) Some examples of the method, apparatuses, and non-transitory computer-readable medium described herein may further include operations, features, means, or instructions for determining that the quality metric associated with the first PPG signal fails to satisfy a threshold based at least in part on calculating the quality metric and deactivating an ambient light cancellation technique based at least in part on determining that the quality metric fails to satisfy the threshold.

(205) Some examples of the method, apparatuses, and non-transitory computer-readable medium described herein may further include operations, features, means, or instructions for identifying movement of a user wearing the wearable device after deactivating the ambient light cancellation technique, wherein measuring the first PPG signal may be based at least in part on identifying the movement by the user.

(206) In some examples of the method, apparatuses, and non-transitory computer-readable medium described herein, the power output level of the light source powered by the wearable device may be adjusted to be less than a baseline power output level of the light source powered by the wearable device.

(207) The description set forth herein, in connection with the appended drawings, describes example configurations and does not represent all the examples that may be implemented or that are within the scope of the claims. The term "exemplary" used herein means "serving as an example, instance, or illustration," and not "preferred" or "advantageous over other examples." The detailed description includes specific details for the purpose of providing an understanding of the described techniques. These techniques, however, may be practiced without these specific details. In some instances, well-known structures and devices are shown in block diagram form in order to avoid obscuring the concepts of the described examples.

(208) In the appended figures, similar components or features may have the same reference label. Further, various components of the same type may be distinguished by following the reference label by a dash and a second label that distinguishes among the similar components. If just the first

reference label is used in the specification, the description is applicable to any one of the similar components having the same first reference label irrespective of the second reference label.

(209) Information and signals described herein may be represented using any of a variety of different technologies and techniques. For example, data, instructions, commands, information, signals, bits, symbols, and chips that may be referenced throughout the above description may be represented by voltages, currents, electromagnetic waves, magnetic fields or particles, optical fields or particles, or any combination thereof.

(210) The various illustrative blocks and modules described in connection with the disclosure herein may be implemented or performed with a general-purpose processor, a DSP, an ASIC, an FPGA or other programmable logic device, discrete gate or transistor logic, discrete hardware components, or any combination thereof designed to perform the functions described herein. A general-purpose processor may be a microprocessor, but in the alternative, the processor may be any conventional processor, controller, microcontroller, or state machine. A processor may also be implemented as a combination of computing devices (e.g., a combination of a DSP and a microprocessor, multiple microprocessors, one or more microprocessors in conjunction with a DSP core, or any other such configuration).

(211) The functions described herein may be implemented in hardware, software executed by a processor, firmware, or any combination thereof. If implemented in software executed by a processor, the functions may be stored on or transmitted over as one or more instructions or code on a computer-readable medium. Other examples and implementations are within the scope of the disclosure and appended claims. For example, due to the nature of software, functions described above can be implemented using software executed by a processor, hardware, firmware, hardwiring, or combinations of any of these. Features implementing functions may also be physically located at various positions, including being distributed such that portions of functions are implemented at different physical locations. Also, as used herein, including in the claims, "or" as used in a list of items (for example, a list of items prefaced by a phrase such as "at least one of" or "one or more of") indicates an inclusive list such that, for example, a list of at least one of A, B, or C means A or B or C or AB or AC or BC or ABC (i.e., A and B and C). Also, as used herein, the phrase "based on" shall not be construed as a reference to a closed set of conditions. For example, an exemplary step that is described as "based on condition A" may be based on both a condition A and a condition B without departing from the scope of the present disclosure. In other words, as used herein, the phrase "based on" shall be construed in the same manner as the phrase "based at least in part on."

(212) Computer-readable media includes both non-transitory computer storage media and communication media including any medium that facilitates transfer of a computer program from one place to another. A non-transitory storage medium may be any available medium that can be accessed by a general purpose or special purpose computer. By way of example, and not limitation, non-transitory computer-readable media can comprise RAM, ROM, electrically erasable programmable ROM (EEPROM), compact disk (CD) ROM or other optical disk storage, magnetic disk storage or other magnetic storage devices, or any other non-transitory medium that can be used to carry or store desired program code means in the form of instructions or data structures and that can be accessed by a general-purpose or special-purpose computer, or a general-purpose or special-purpose processor. Also, any connection is properly termed a computer-readable medium. For example, if the software is transmitted from a website, server, or other remote source using a coaxial cable, fiber optic cable, twisted pair, digital subscriber line (DSL), or wireless technologies such as infrared, radio, and microwave, then the coaxial cable, fiber optic cable, twisted pair, DSL, or wireless technologies such as infrared, radio, and microwave are included in the definition of medium. Disk and disc, as used herein, include CD, laser disc, optical disc, digital versatile disc (DVD), floppy disk and Blu-ray disc where disks usually reproduce data magnetically, while discs reproduce data optically with lasers. Combinations of the above are also included within the scope

of computer-readable media.

(213) The description herein is provided to enable a person skilled in the art to make or use the disclosure. Various modifications to the disclosure will be readily apparent to those skilled in the art, and the generic principles defined herein may be applied to other variations without departing from the scope of the disclosure. Thus, the disclosure is not limited to the examples and designs described herein, but is to be accorded the broadest scope consistent with the principles and novel features disclosed herein.

Claims

1. A method of adjusting a power output level of a light source on a wearable device, comprising: measuring, at a photodetector on the wearable device, a first photoplethysmography (PPG) signal derived from an ambient light source that is powered externally to the wearable device; identifying one or more features of a morphology of the first PPG signal derived from the ambient light source based at least in part on measuring the first PPG signal, wherein the one or more features of the morphology comprises a pulse amplitude, a systolic gradient, a signal to noise ratio, or a combination thereof; calculating, by the wearable device, a quality metric of the first PPG signal based at least in part on the one or more features of the morphology of the first PPG signal; and adjusting, by the wearable device, the power output level of the light source powered by the wearable device based at least in part on the quality metric of the first PPG signal.

2. The method of claim 1, further comprising: measuring, at the photodetector on the wearable device, a second PPG signal derived from the light source powered by the wearable device; and comparing, by the wearable device, the morphology of the first PPG signal and a morphology of the second PPG signal based at least in part on measuring the first PPG signal, wherein calculating the quality metric is based at least in part on comparing the morphology of the first PPG signal and the morphology of the second PPG signal, the morphology of the second PPG signal comprises a pulse amplitude, a systolic gradient, a signal to noise ratio, or a combination thereof.

3. The method of claim 1, wherein calculating the quality metric further comprises: calculating the pulse amplitude of the first PPG signal based at least in part on measuring the first PPG signal, wherein adjusting the power output level is based at least in part on calculating the pulse amplitude of the first PPG signal.

4. The method of claim 1, wherein calculating the quality metric further comprises: calculating the signal to noise ratio of the first PPG signal based at least in part on measuring the first PPG signal, wherein adjusting the power output level is based at least in part on calculating the signal to noise ratio of the first PPG signal.

5. The method of claim 1, wherein calculating the quality metric further comprises: calculating the systolic gradient of the first PPG signal based at least in part on measuring the first PPG signal, wherein adjusting the power output level is based at least in part on calculating the systolic gradient of the first PPG signal.

6. The method of claim 1, further comprising: determining that the quality metric of the first PPG signal satisfies a threshold based at least in part on calculating the quality metric; and deactivating an ambient light cancellation technique based at least in part on determining that the quality metric satisfies the threshold.

7. The method of claim 6, further comprising: deactivating the light source powered by the wearable device based at least in part on determining that the quality metric satisfies the threshold, wherein adjusting the power output level is based at least in part on deactivating the light source powered by the wearable device.

8. The method of claim 1, further comprising: determining that the quality metric associated with the first PPG signal fails to satisfy a threshold based at least in part on calculating the quality metric; and activating an ambient light cancellation technique based at least in part on determining

that the quality metric fails to satisfy the threshold.

9. The method of claim 1, further comprising: determining that the quality metric associated with the first PPG signal fails to satisfy a threshold based at least in part on calculating the quality metric; and deactivating an ambient light cancellation technique based at least in part on determining that the quality metric fails to satisfy the threshold.

10. The method of claim 9, further comprising: identifying movement of a user wearing the wearable device after deactivating the ambient light cancellation technique, wherein measuring the first PPG signal is based at least in part on identifying the movement by the user.

11. The method of claim 1, wherein the power output level of the light source powered by the wearable device is adjusted to be less than a baseline power output level of the light source powered by the wearable device.

12. An apparatus, comprising: a processor; memory coupled with the processor; and instructions stored in the memory and executable by the processor to cause the apparatus to: measure, at a photodetector on a wearable device, a first photoplethysmography (PPG) signal derived from an ambient light source that is powered externally to the wearable device; identify one or more features of a morphology of the first PPG signal derived from the ambient light source based at least in part on measuring the first PPG signal, wherein the one or more features of the morphology comprises a pulse amplitude, a systolic gradient, a signal to noise ratio, or a combination thereof; calculate, by the wearable device, a quality metric of the first PPG signal based at least in part on the one or more features of the morphology of the first PPG signal; and adjust, by the wearable device, a power output level of a light source powered by the wearable device based at least in part on the quality metric of the first PPG signal.

13. The apparatus of claim 12, wherein the instructions are further executable by the processor to cause the apparatus to: measure, at the photodetector on a wearable device, a second PPG signal derived from a light source powered by the wearable device; and compare, by the wearable device, the morphology of the first PPG signal and a morphology of the second PPG signal based at least in part on measuring the first PPG signal, wherein calculating the quality metric is based at least in part on comparing the morphology of the first PPG signal and the morphology of the second PPG signal, the morphology of the second PPG signal comprises a pulse amplitude, a systolic gradient, a signal to noise ratio, or a combination thereof.

14. The apparatus of claim 12, wherein the instructions to calculate the quality metric are further executable by the processor to cause the apparatus to: calculate the pulse amplitude of the first PPG signal based at least in part on measuring the first PPG signal, wherein adjusting the power output level is based at least in part on calculating the pulse amplitude of the first PPG signal.

15. The apparatus of claim 12, wherein the instructions to calculate the quality metric are further executable by the processor to cause the apparatus to: calculate the signal to noise ratio of the first PPG signal based at least in part on measuring the first PPG signal, wherein adjusting the power output level is based at least in part on calculating the signal to noise ratio of the first PPG signal.

16. The apparatus of claim 12, wherein the instructions to calculate the quality metric are further executable by the processor to cause the apparatus to: calculate the systolic gradient of the first PPG signal based at least in part on measuring the first PPG signal, wherein adjusting the power output level is based at least in part on calculating the systolic gradient of the first PPG signal.

17. A non-transitory computer-readable medium storing code, the code comprising instructions executable by a processor to: measure, at a photodetector on a wearable device, a first photoplethysmography (PPG) signal derived from an ambient light source that is powered externally to the wearable device; identify one or more features of a morphology of the first PPG signal derived from the ambient light source based at least in part on measuring the first PPG signal, wherein the one or more features of the morphology comprises a pulse amplitude, a systolic gradient, a signal to noise ratio, or a combination thereof; calculate, by the wearable device, a quality metric of the first PPG signal based at least in part on the one or more features of the

morphology of the first PPG signal; and adjust, by the wearable device, a power output level of the light source powered by the wearable device based at least in part on the quality metric of the first PPG signal.

18. The non-transitory computer-readable medium of claim 17, wherein the instructions are further executable by the processor to: measure, at the photodetector on the wearable device, a second PPG signal derived from a light source powered by the wearable device; and compare, by the wearable device, the morphology of the first PPG signal and a morphology of the second PPG signal based at least in part on measuring the first PPG signal, wherein calculating the quality metric is based at least in part on comparing the morphology of the first PPG signal and the morphology of the second PPG signal, the morphology of the second PPG signal comprises a pulse amplitude, a systolic gradient, a signal to noise ratio, or a combination thereof.

19. The non-transitory computer-readable medium of claim 17, wherein the instructions to calculate the quality metric are further executable by the processor to: calculate the pulse amplitude of the first PPG signal based at least in part on measuring the first PPG signal, wherein adjusting the power output level is based at least in part on calculating the pulse amplitude of the first PPG signal.

20. The non-transitory computer-readable medium of claim 17, wherein the instructions to calculate the quality metric are further executable by the processor to: calculate the signal to noise ratio of the first PPG signal based at least in part on measuring the first PPG signal, wherein adjusting the power output level is based at least in part on calculating the signal to noise ratio of the first PPG signal.