



US010617912B2

(12) **United States Patent**
Narasimha Rao et al.

(10) **Patent No.:** **US 10,617,912 B2**
(45) **Date of Patent:** **Apr. 14, 2020**

(54) **SYSTEMS AND METHODS OF SWIMMING CALORIMETRY**

(52) **U.S. Cl.**
CPC *A63B 24/0062* (2013.01); *A61B 5/0205* (2013.01); *A61B 5/02438* (2013.01);
(Continued)

(71) Applicant: **Apple Inc.**, Cupertino, CA (US)

(58) **Field of Classification Search**
CPC *A63B 24/00652*; *A63B 24/0006*; *A63B 2024/0071*; *A63B 2208/03*;
(Continued)

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(73) Assignee: **Apple Inc.**, Cupertino, CA (US)

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 328 days.

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(21) Appl. No.: **15/692,237**

Primary Examiner — Manuel L Barbee

(22) Filed: **Aug. 31, 2017**

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(65) **Prior Publication Data**

(57) **ABSTRACT**

US 2018/0056129 A1 Mar. 1, 2018

The present disclosure relates to systems and methods of estimating energy expenditure of a user while swimming. A processor circuit of a user device can estimate a speed of the user based on a stroke rate and a stroke length. The processor circuit can estimate an efficiency of the user. The processor circuit can classify a swimming style of the user. The processor circuit can determine energy expenditure of the user based on the speed, the efficiency, and the style. The processor circuit can also detect glides of the user and adjust the energy expenditure.

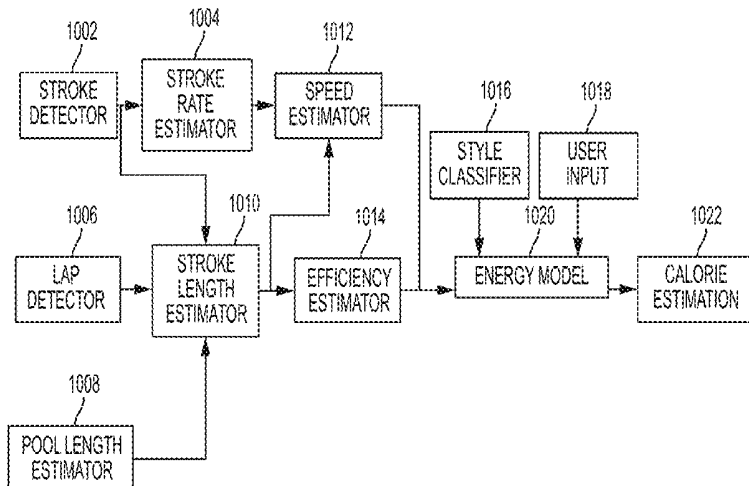
Related U.S. Application Data

(60) Provisional application No. 62/382,060, filed on Aug. 31, 2016, provisional application No. 62/478,900, filed on Mar. 30, 2017.

19 Claims, 29 Drawing Sheets

(51) **Int. Cl.**
A63B 24/00 (2006.01)
A61B 5/11 (2006.01)

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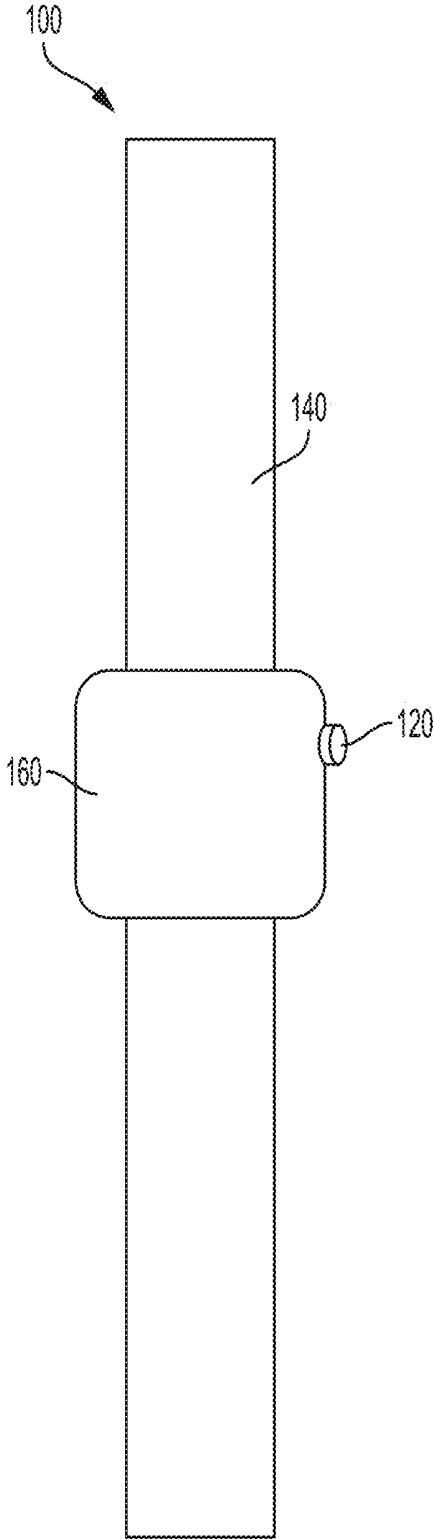


FIG. 1

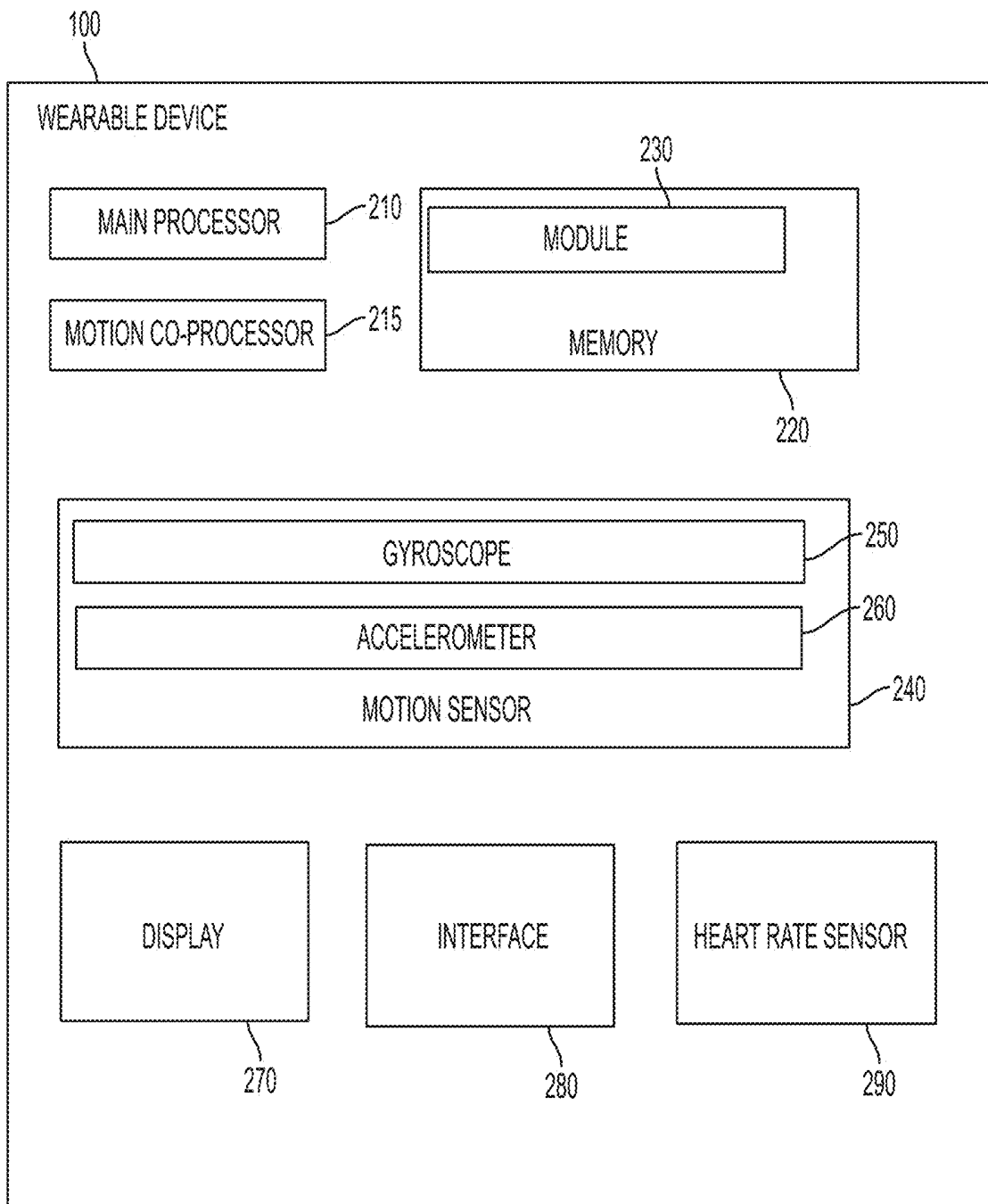


FIG. 2

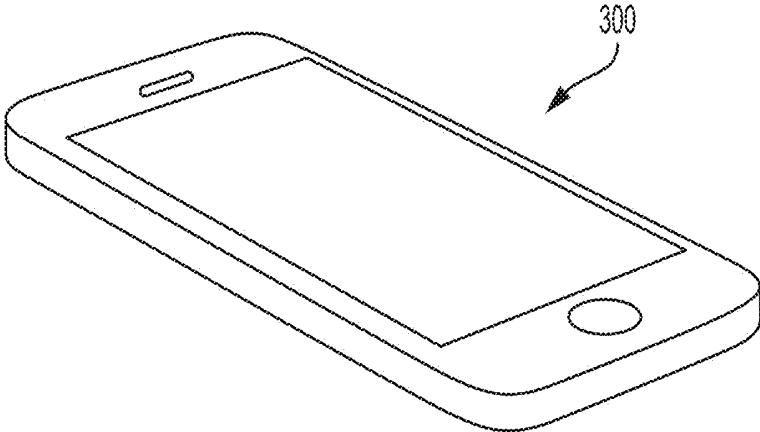


FIG. 3

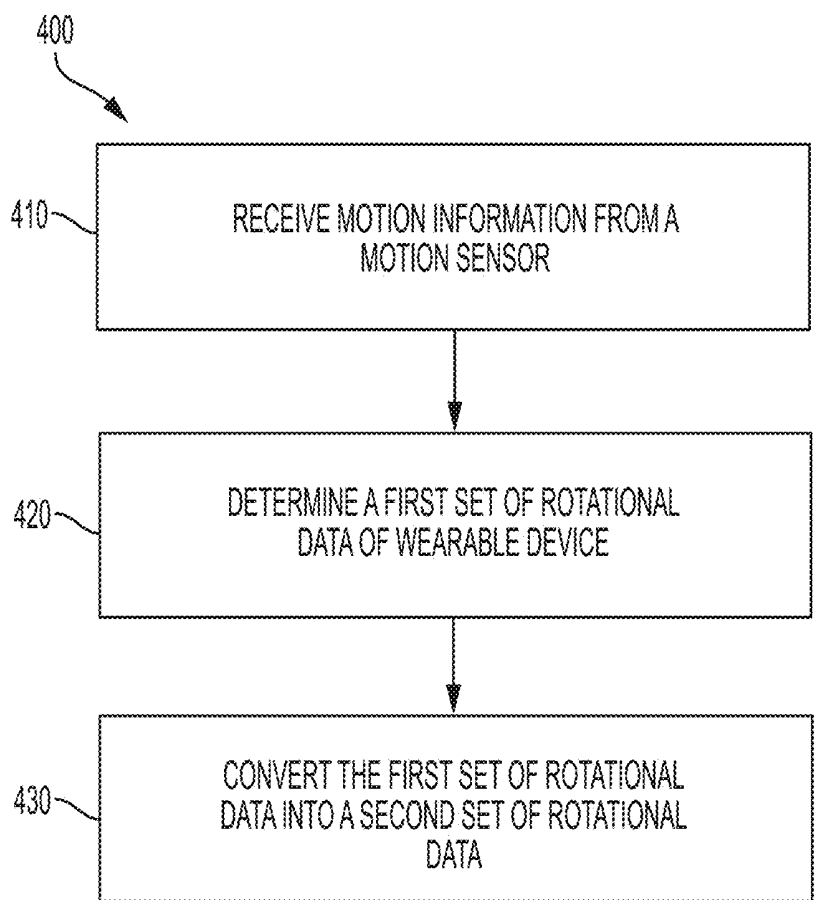


FIG. 4

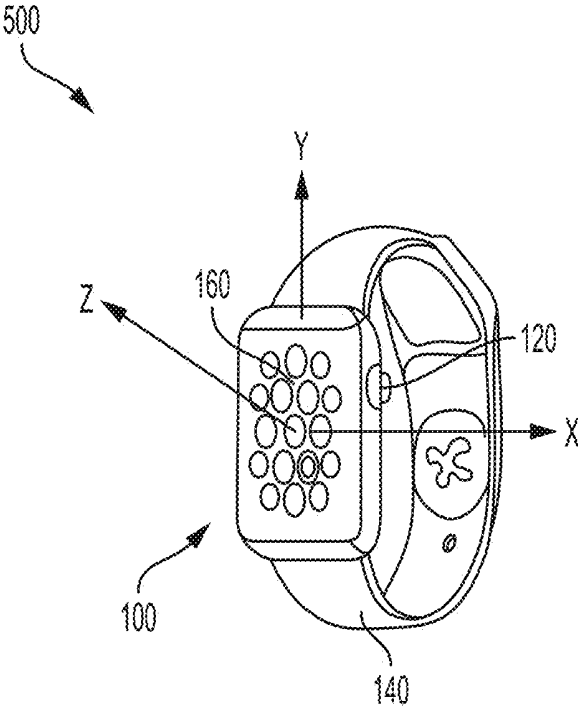


FIG. 5A

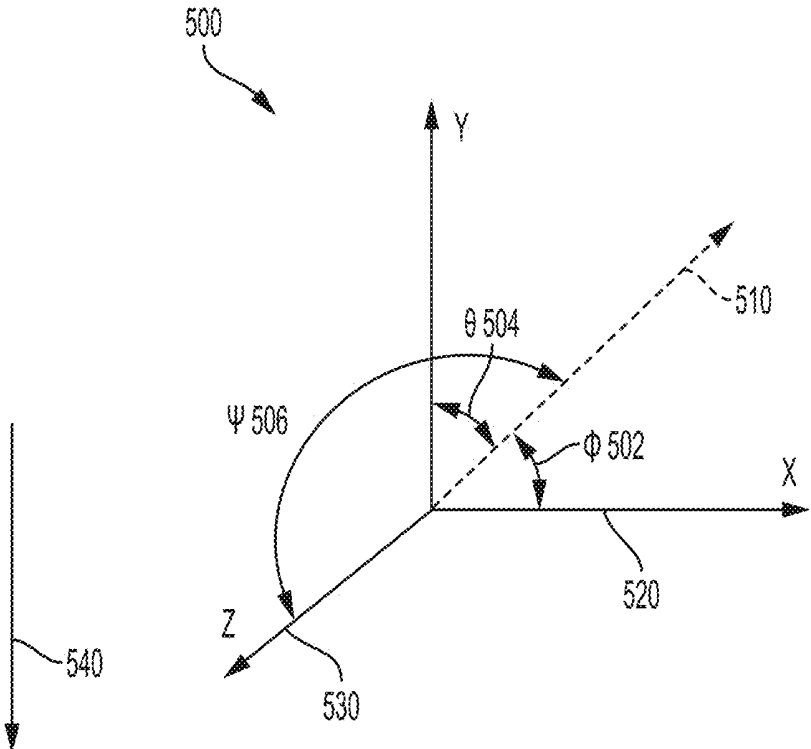


FIG. 5B

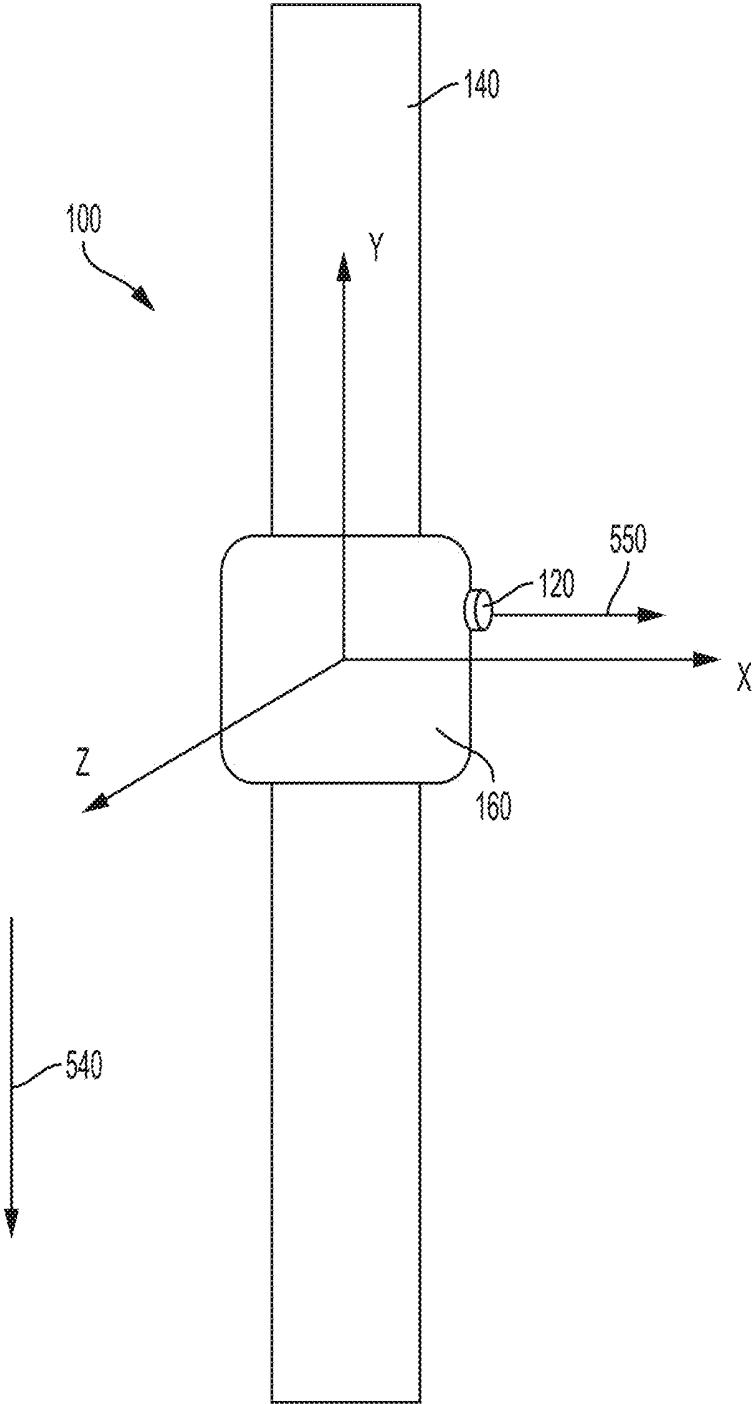


FIG. 5C

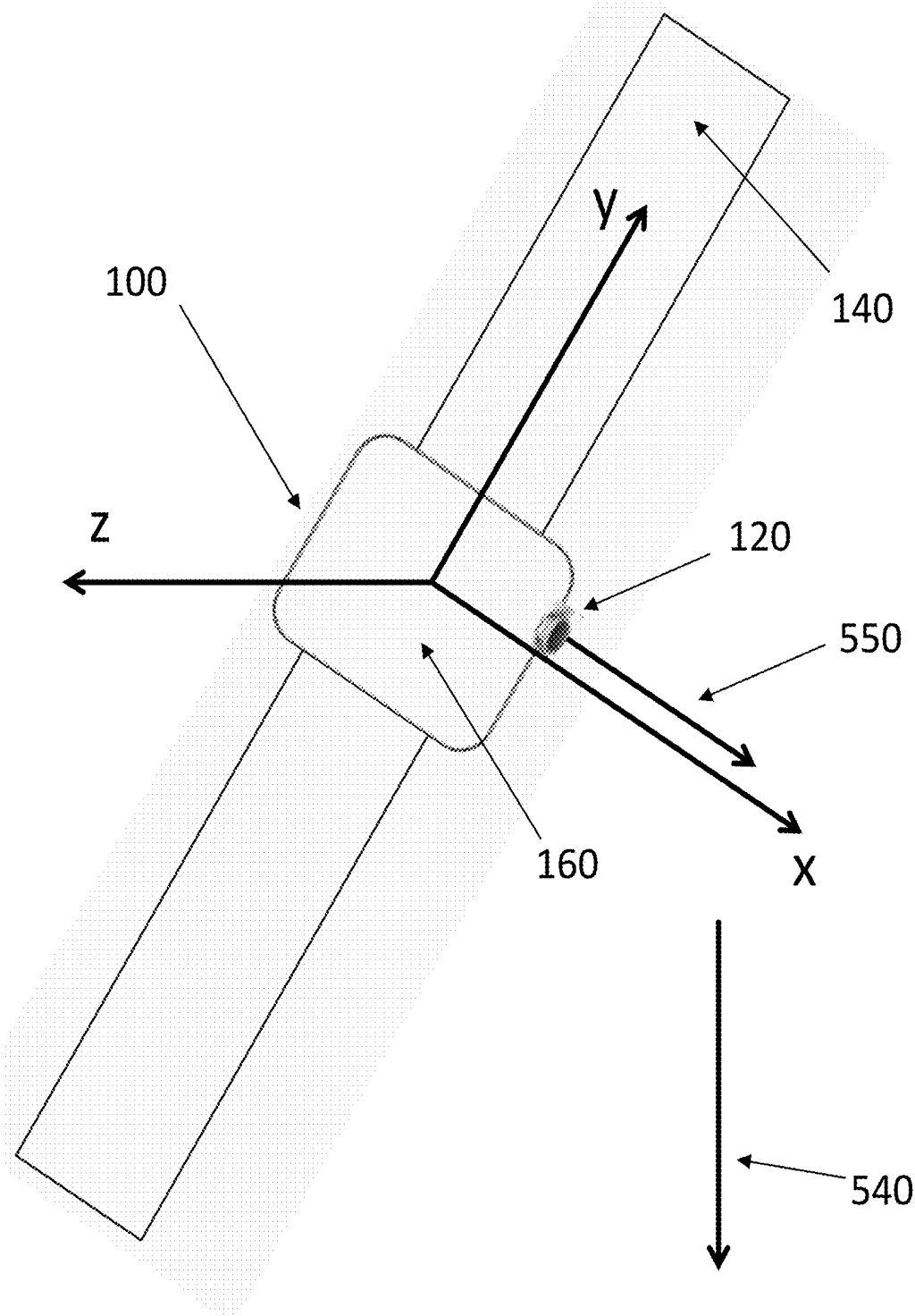


FIG. 5D

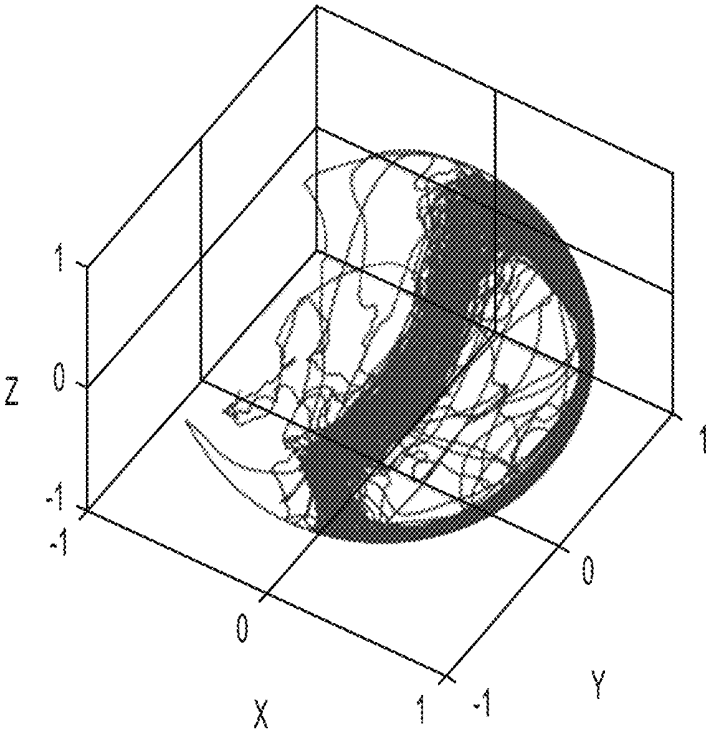


FIG. 6

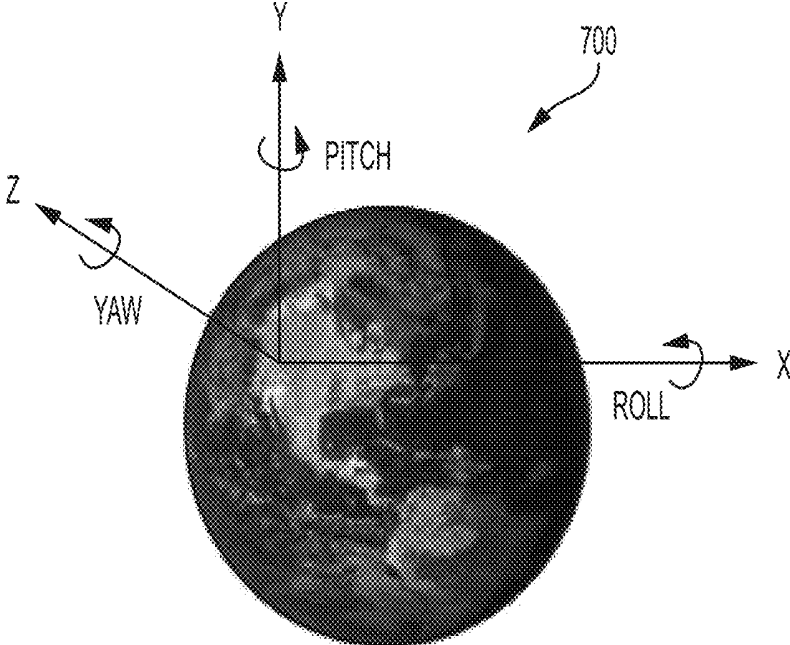


FIG. 7

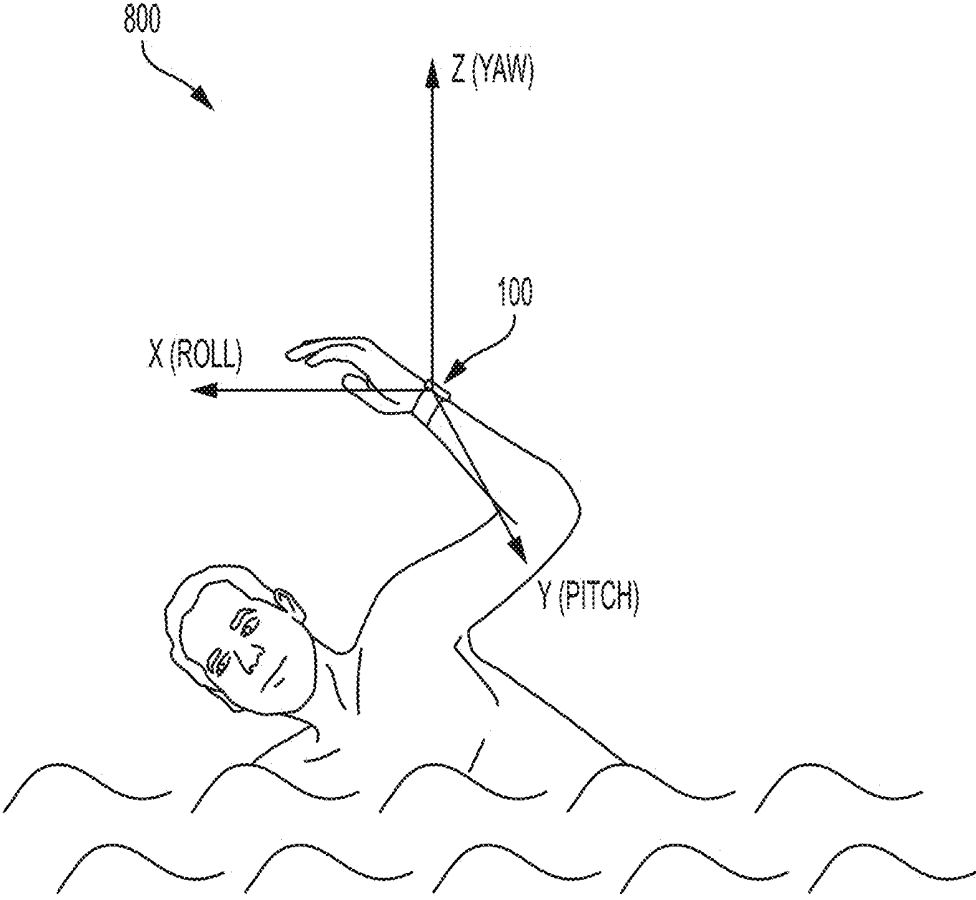


FIG. 8A

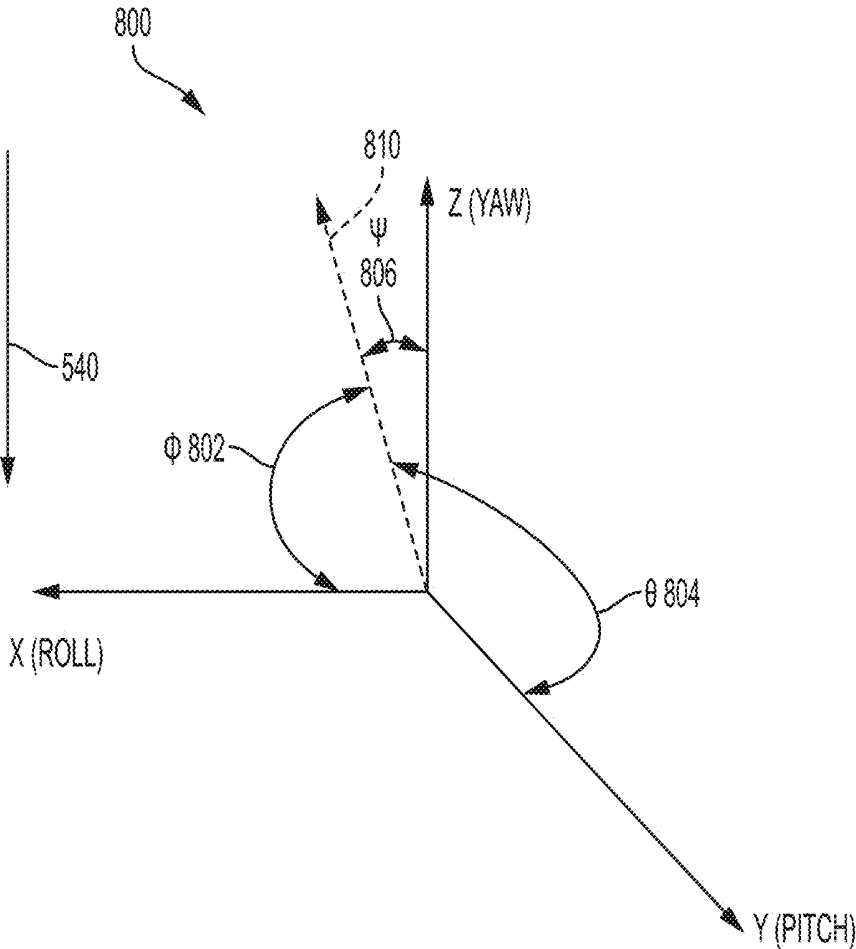


FIG. 8B

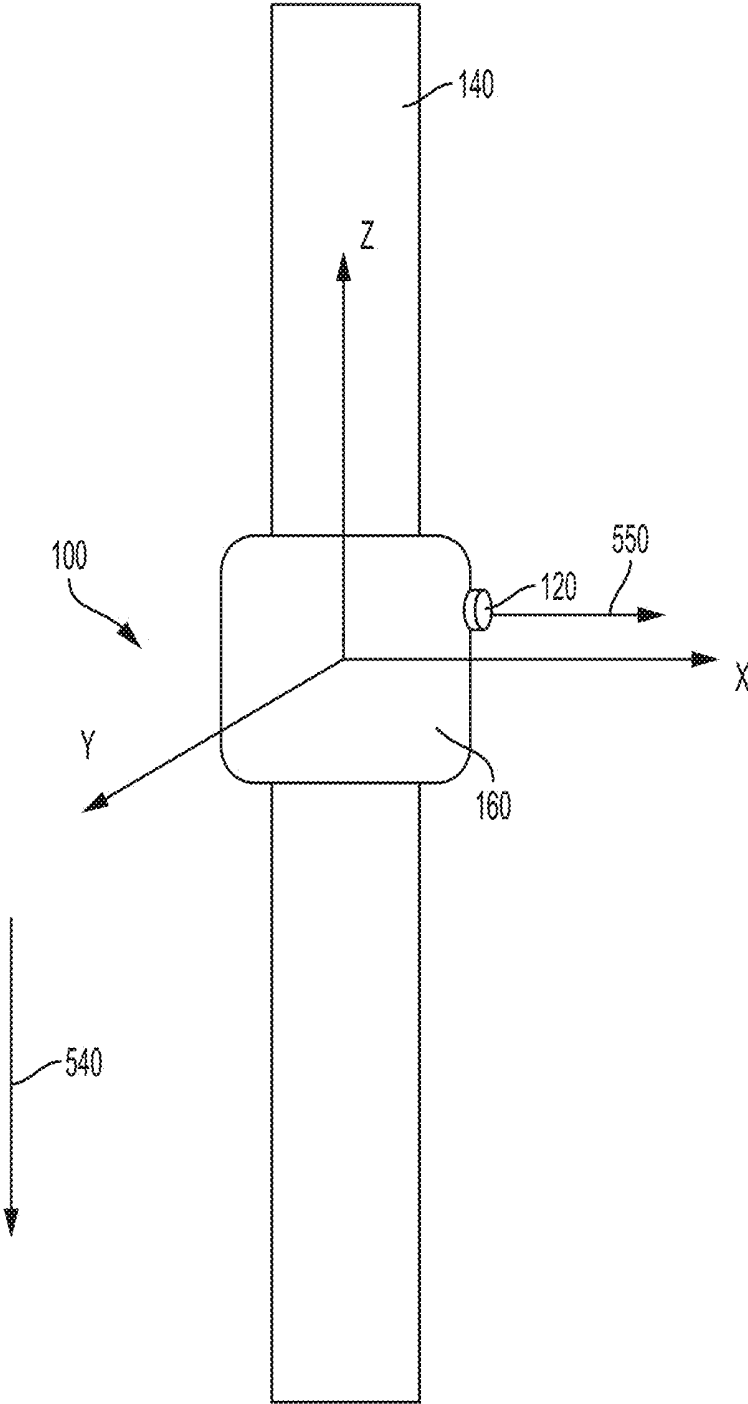


FIG. 8C

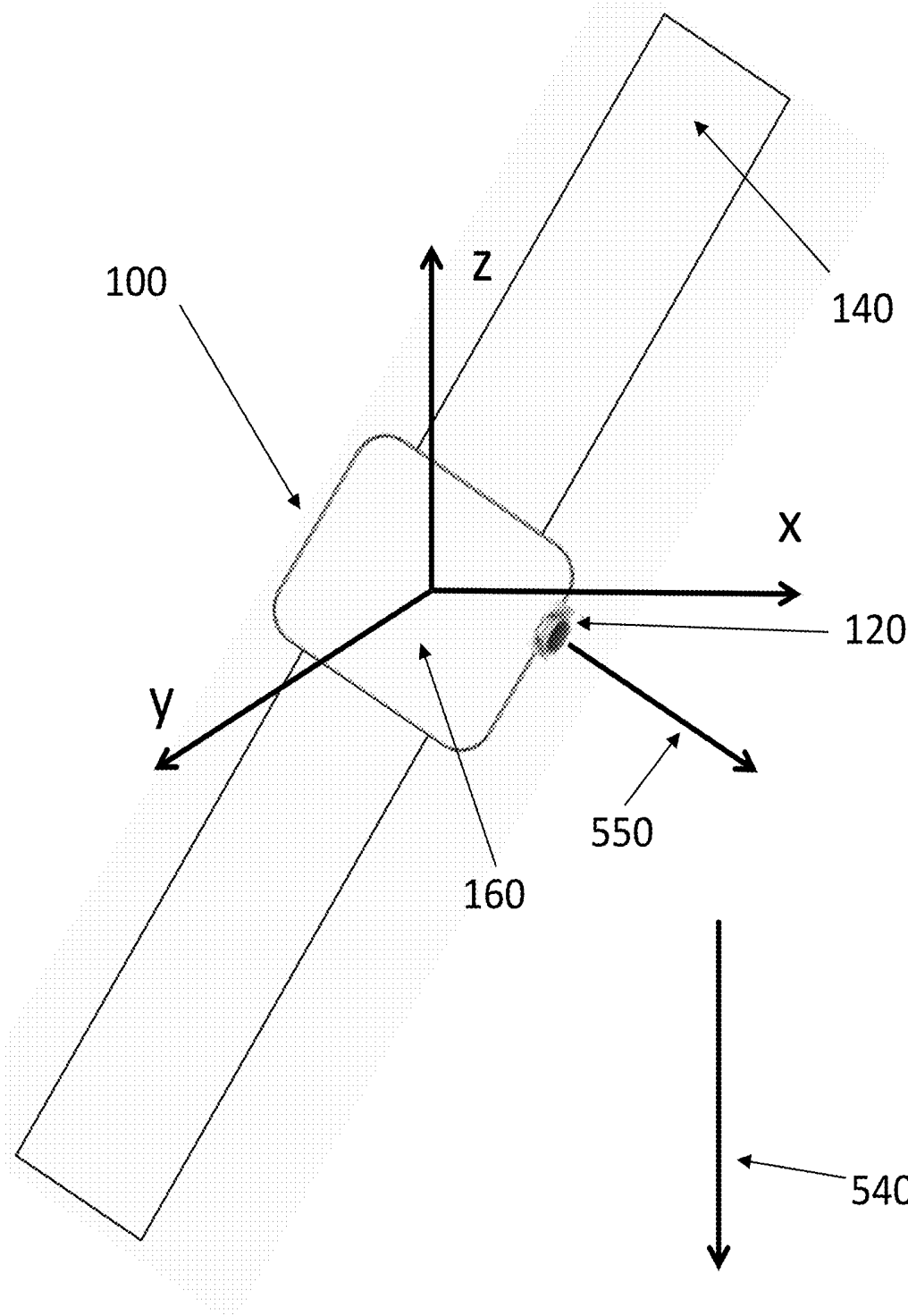


FIG. 8D

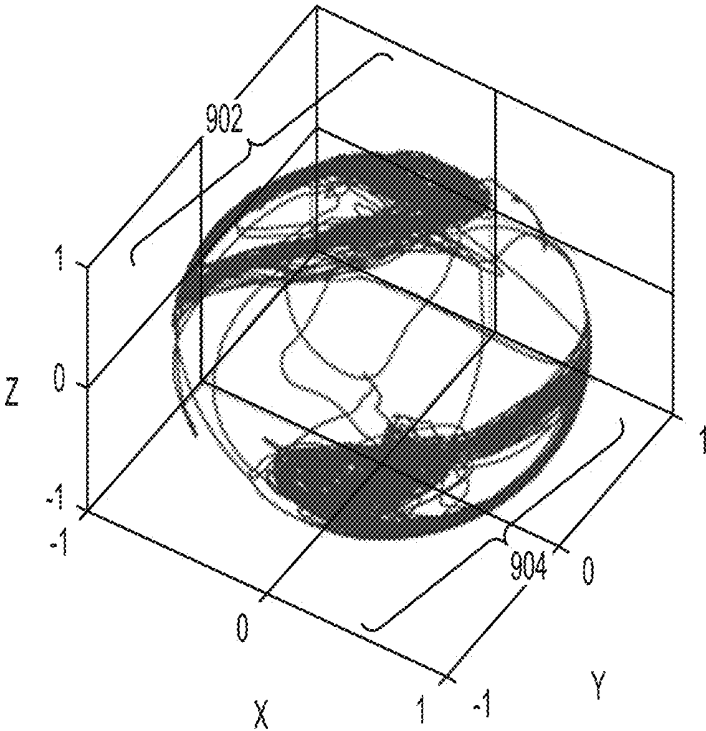


FIG. 9

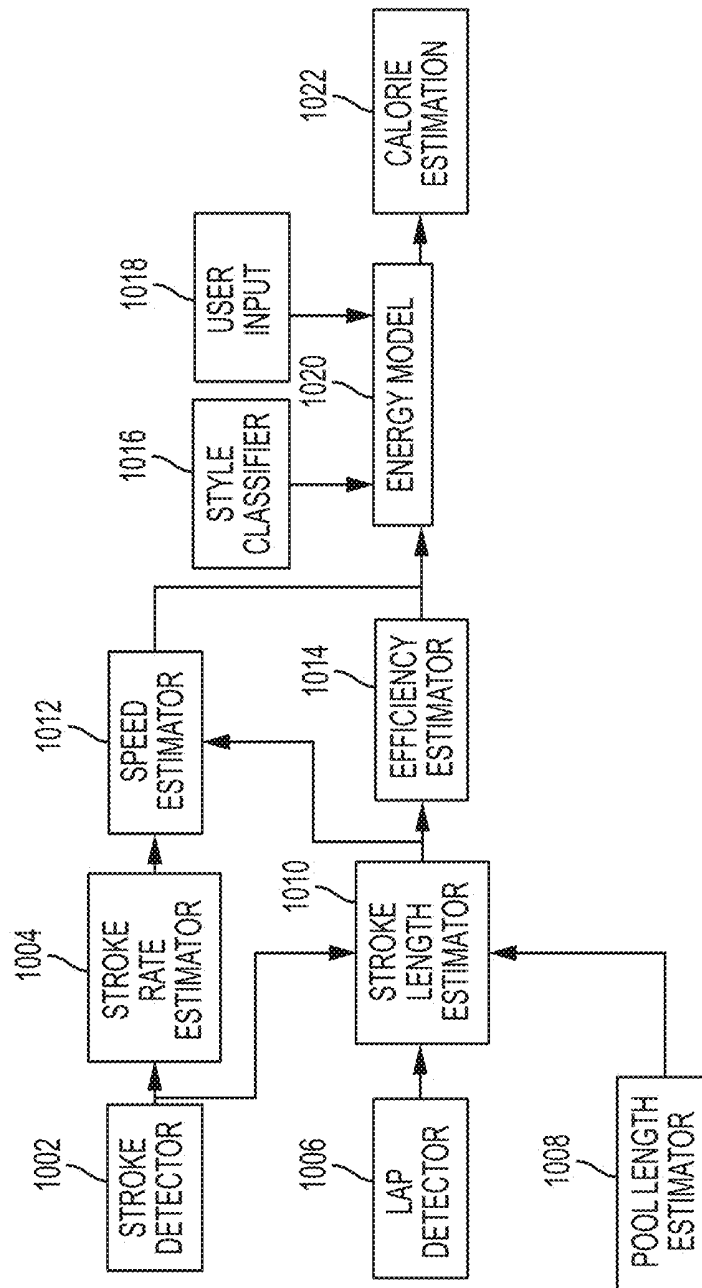


FIG. 10

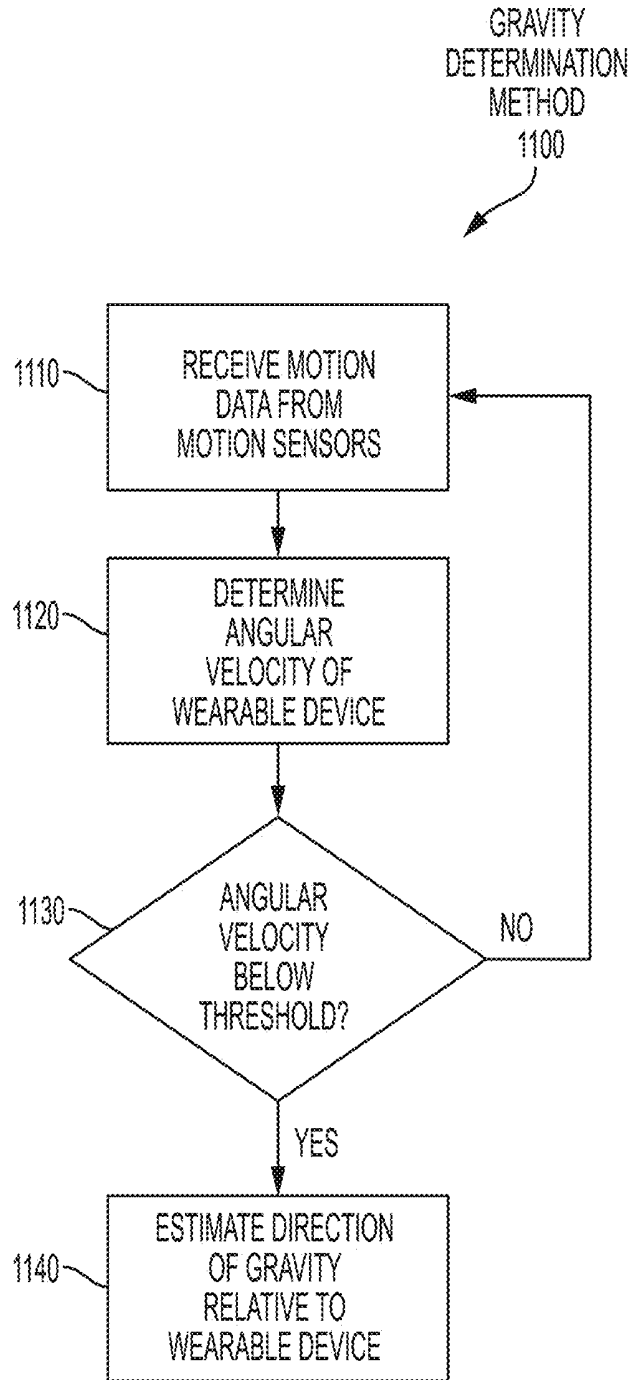


FIG. 11

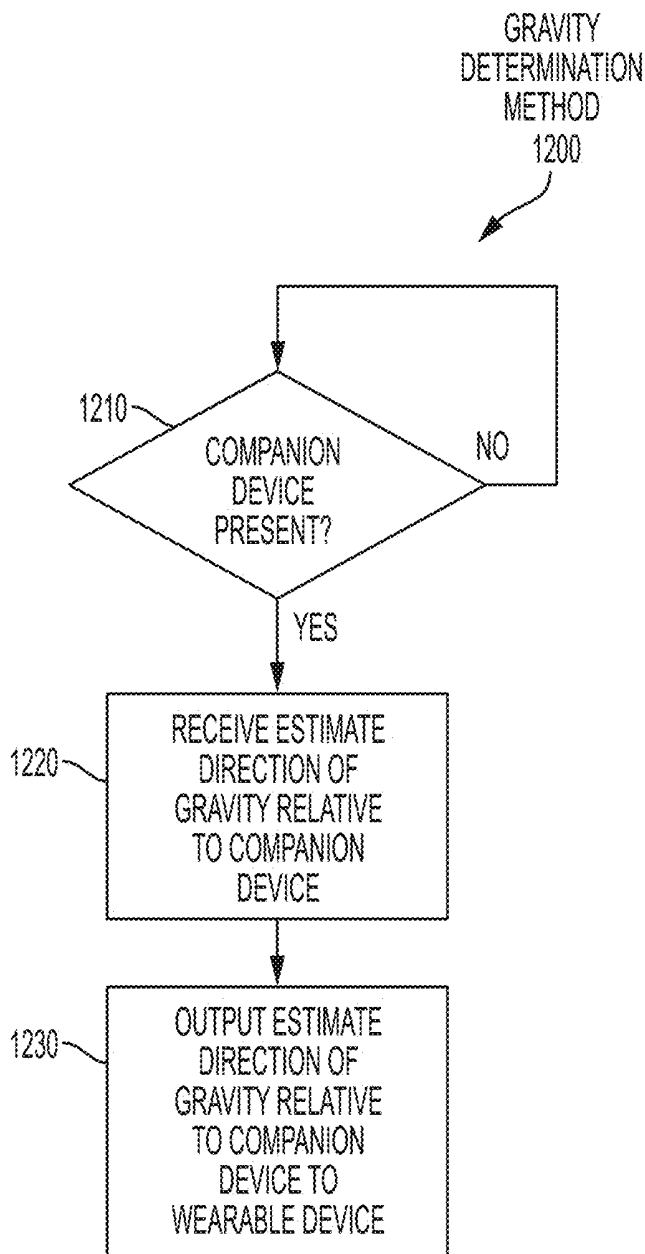


FIG. 12

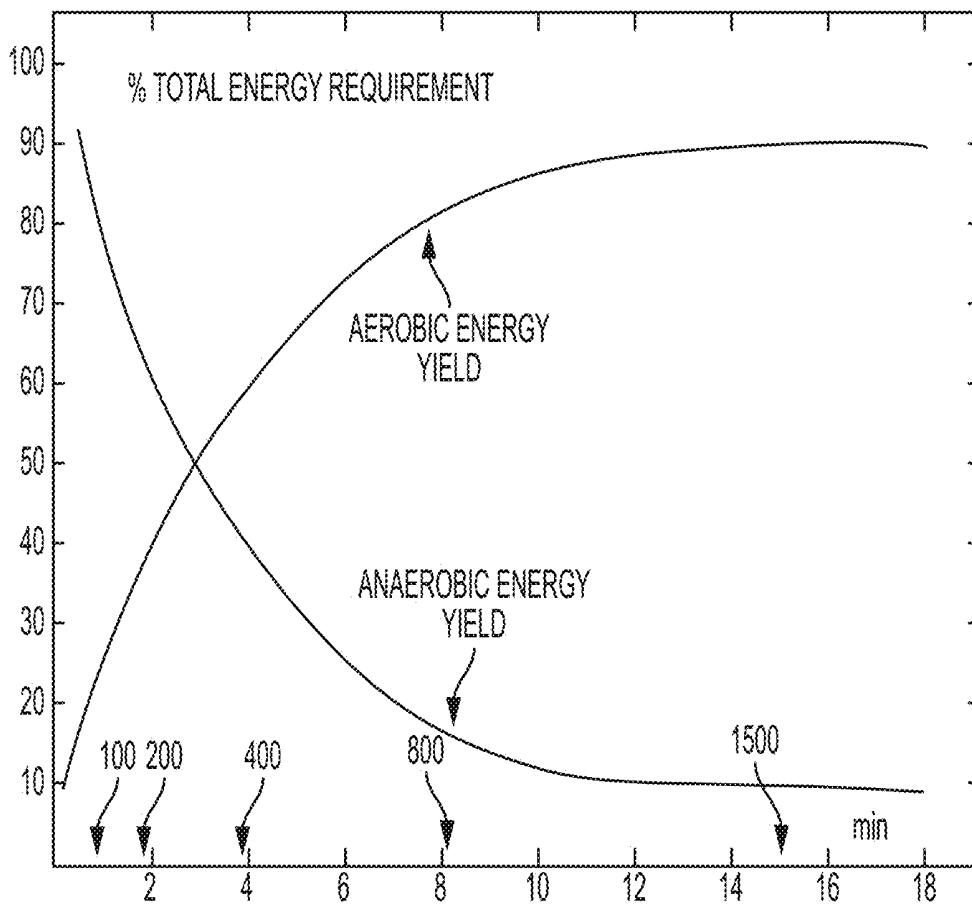


FIG. 13

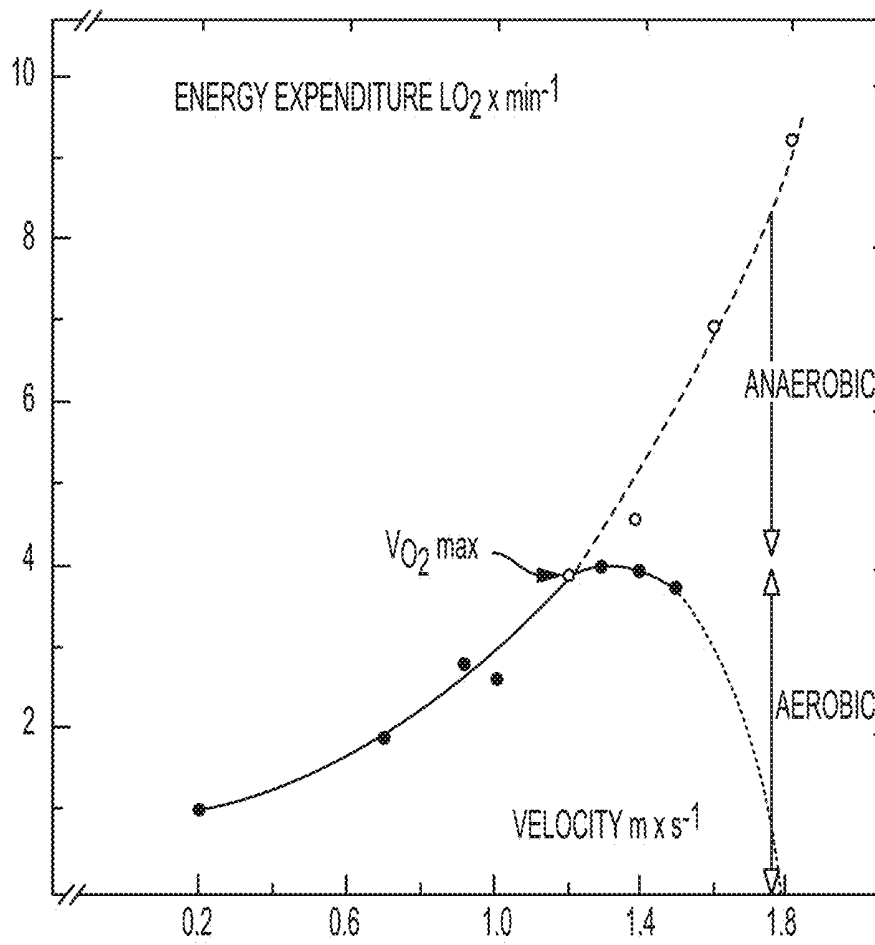


FIG. 14

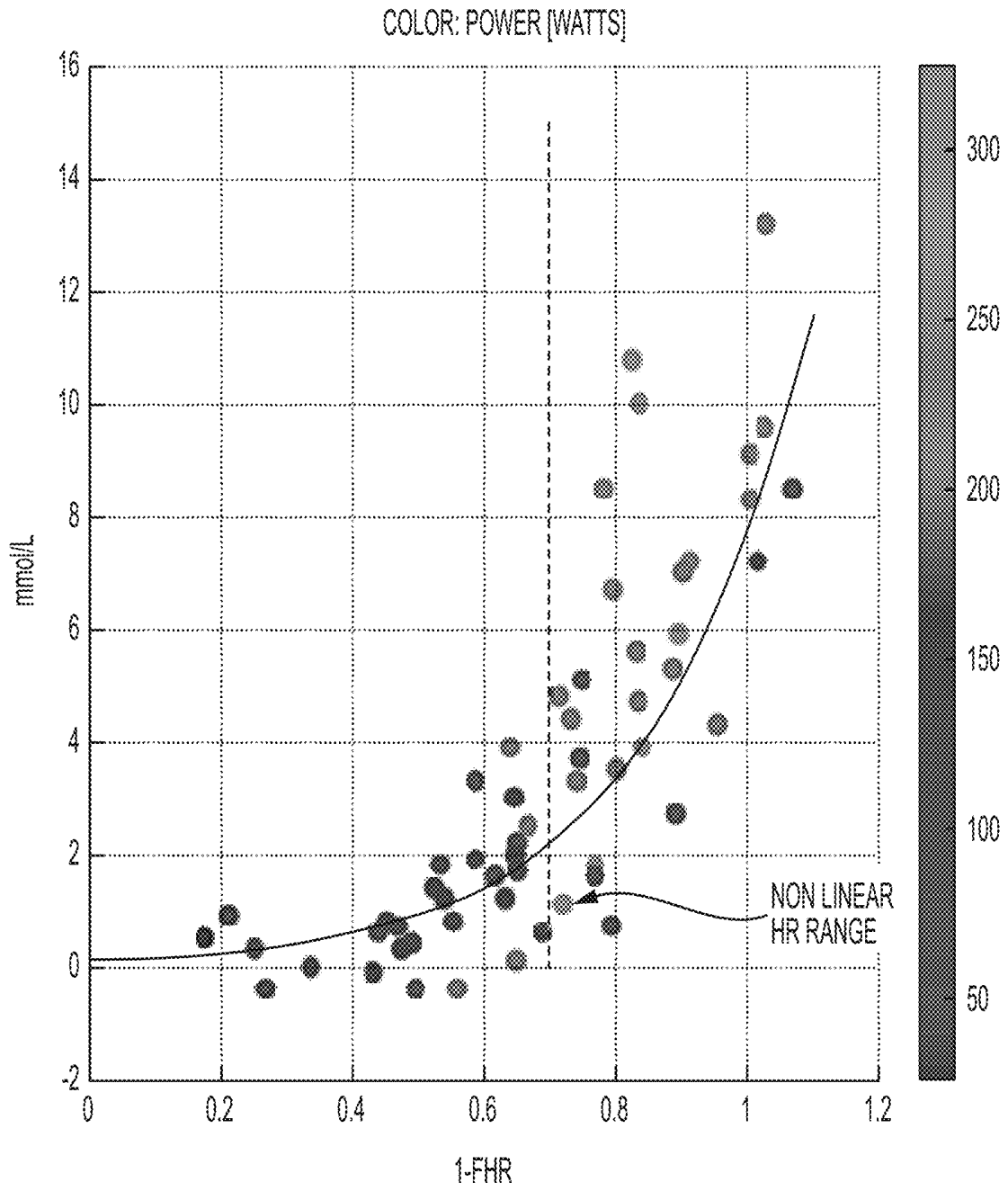


FIG. 15

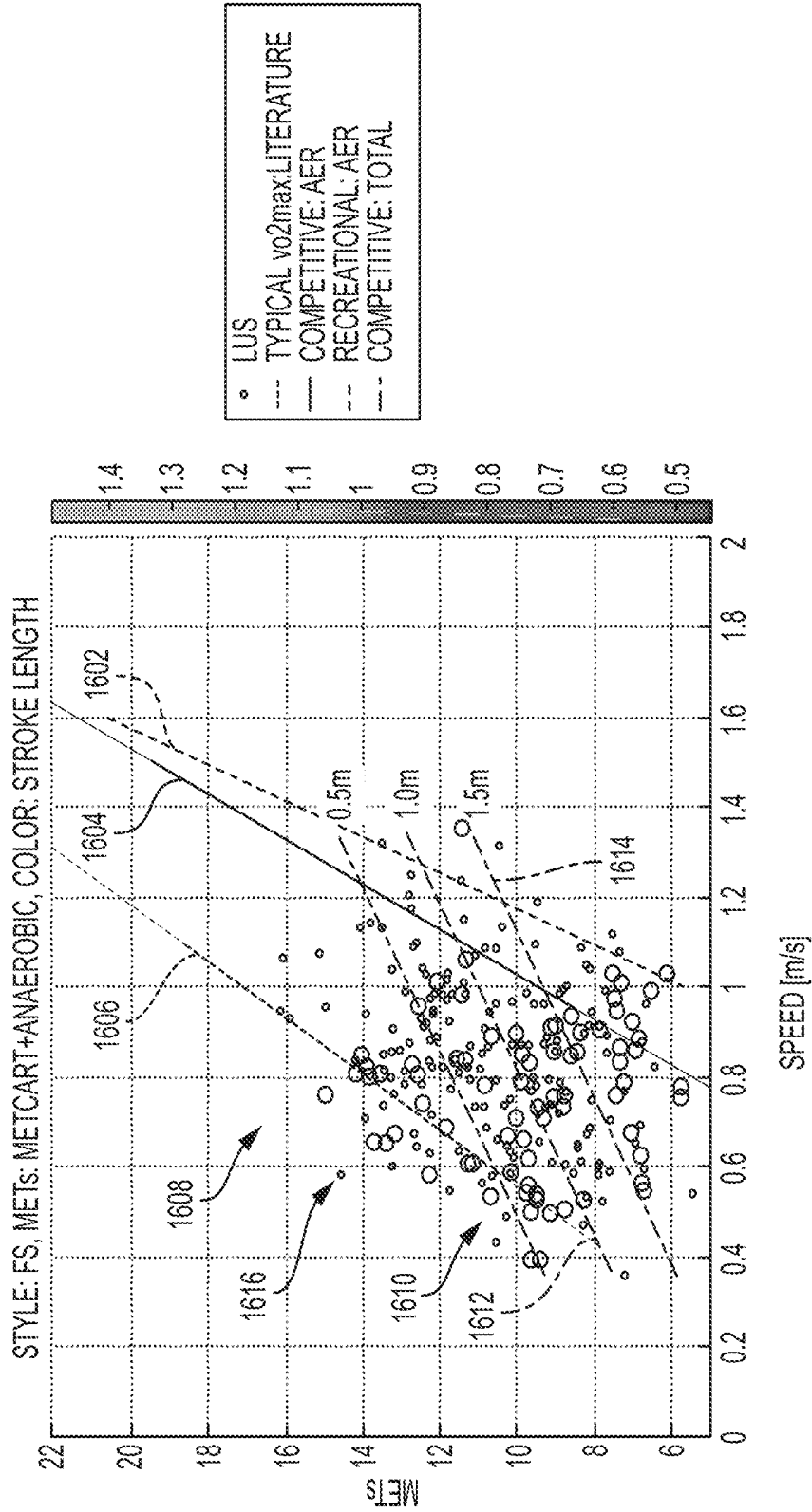


FIG. 16

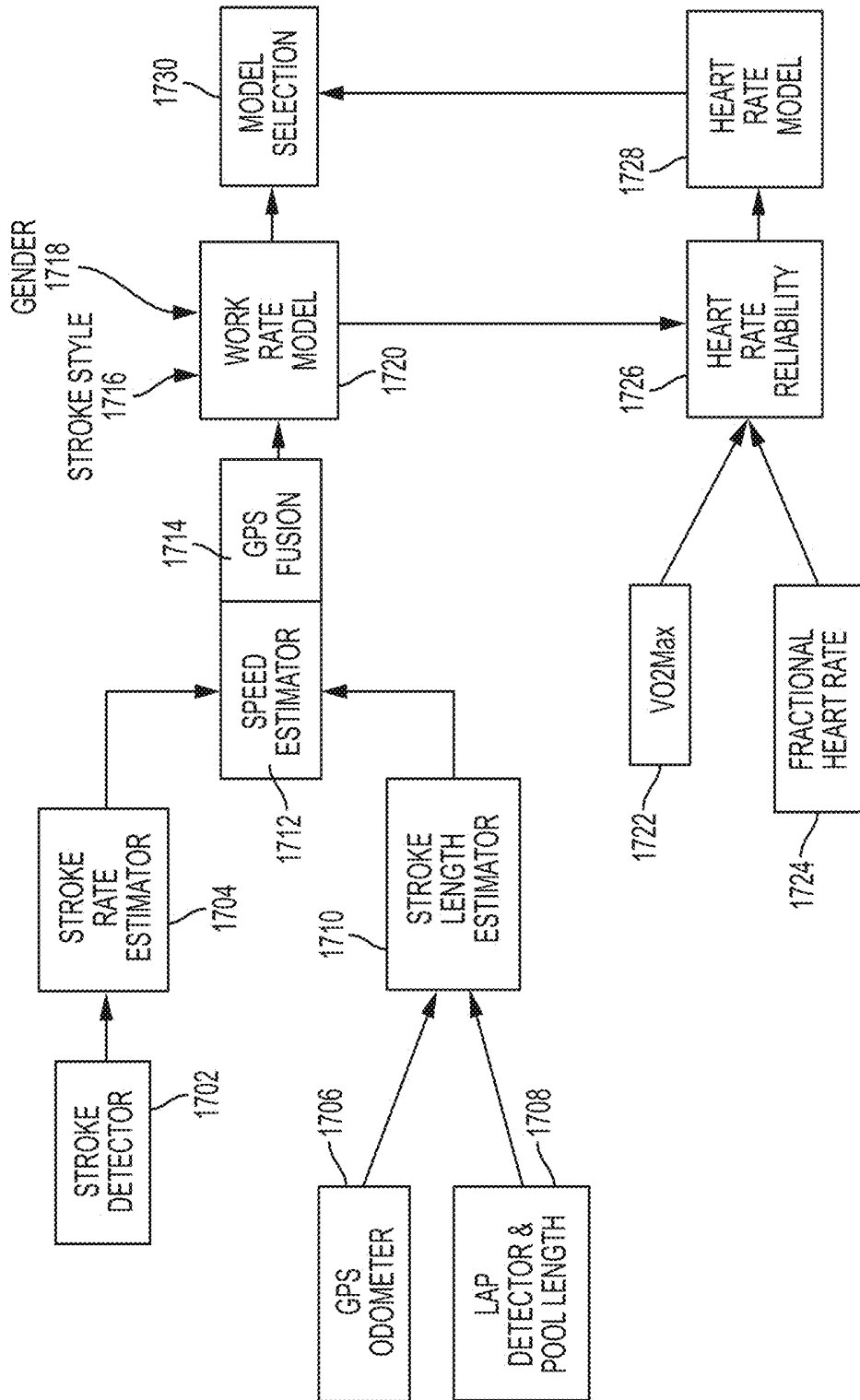


FIG. 17

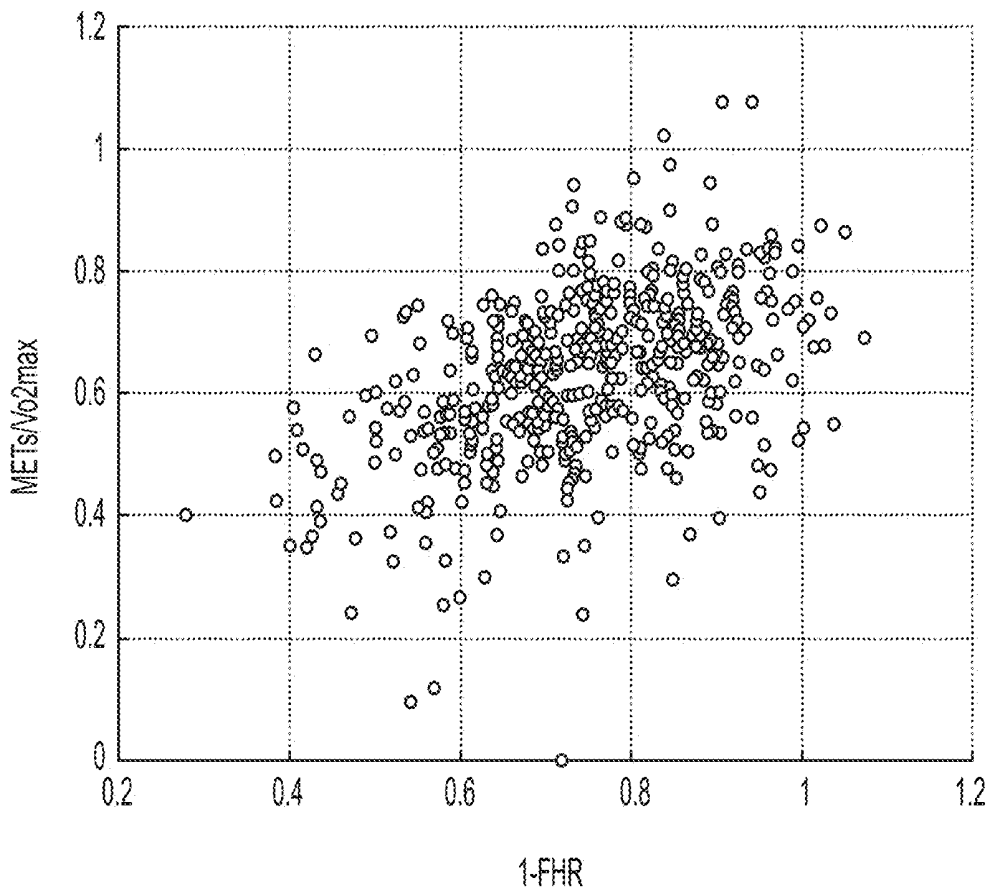


FIG. 18

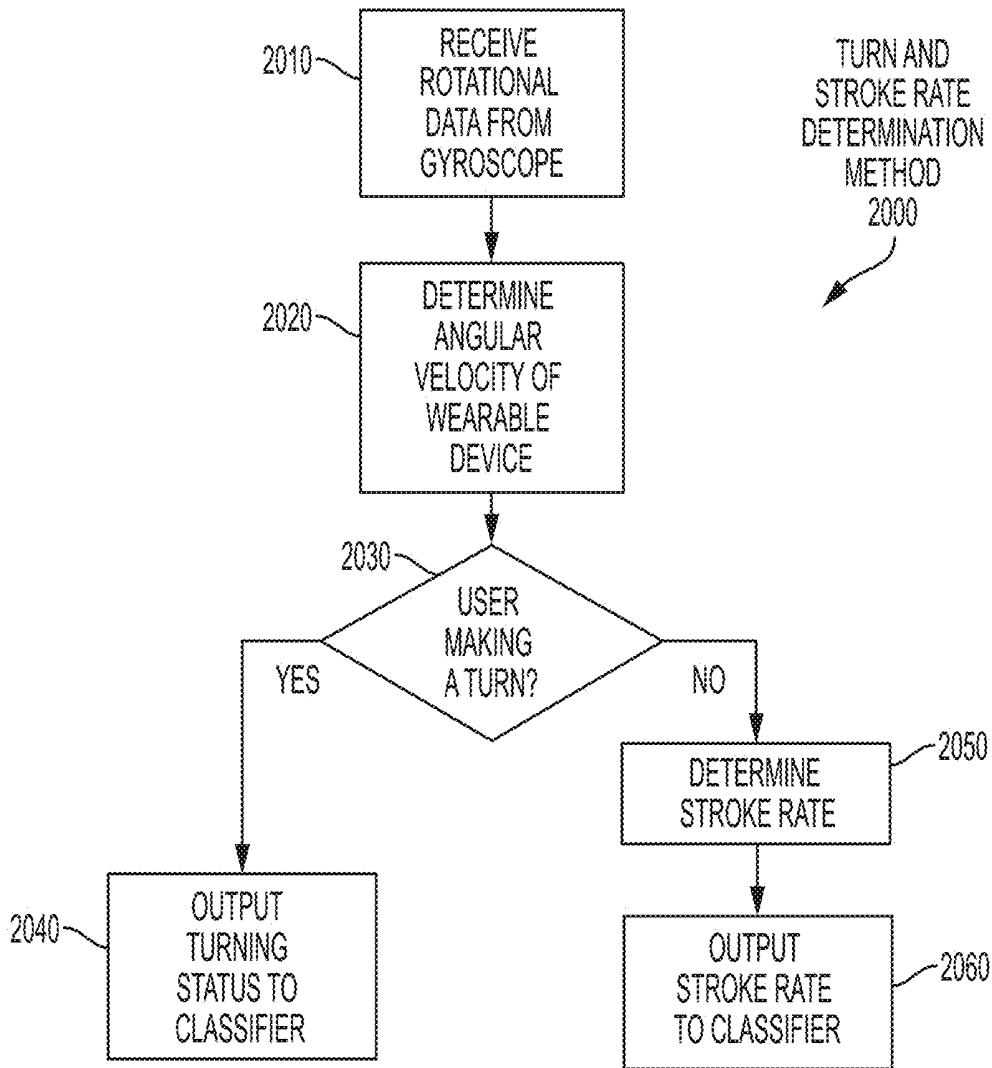


FIG. 20

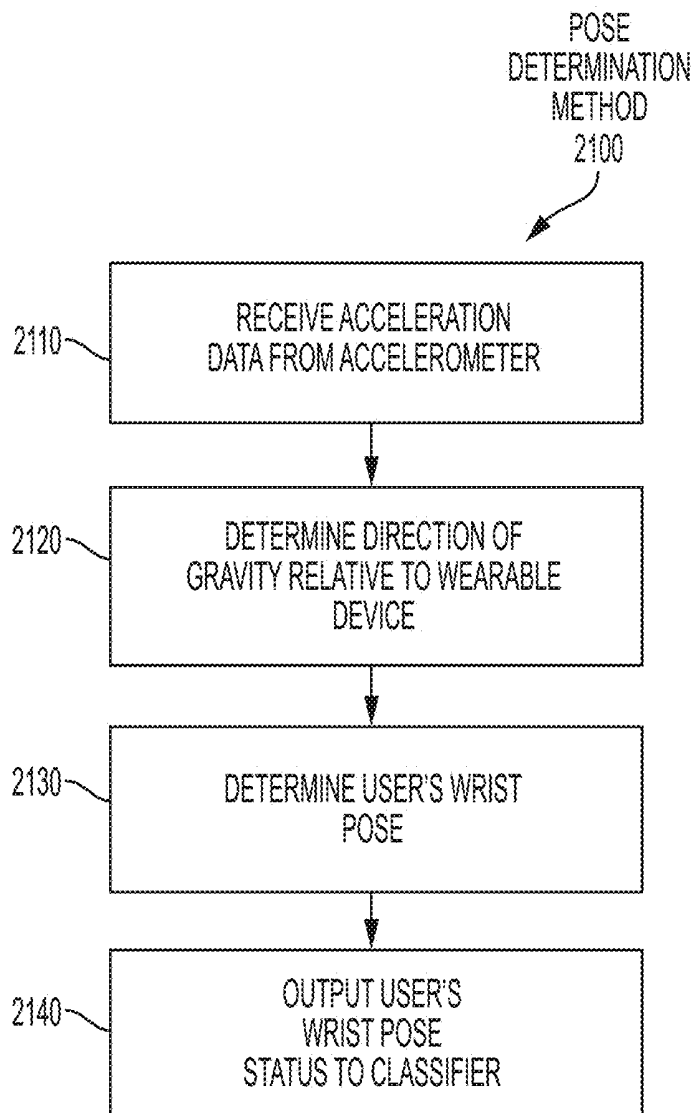


FIG. 21

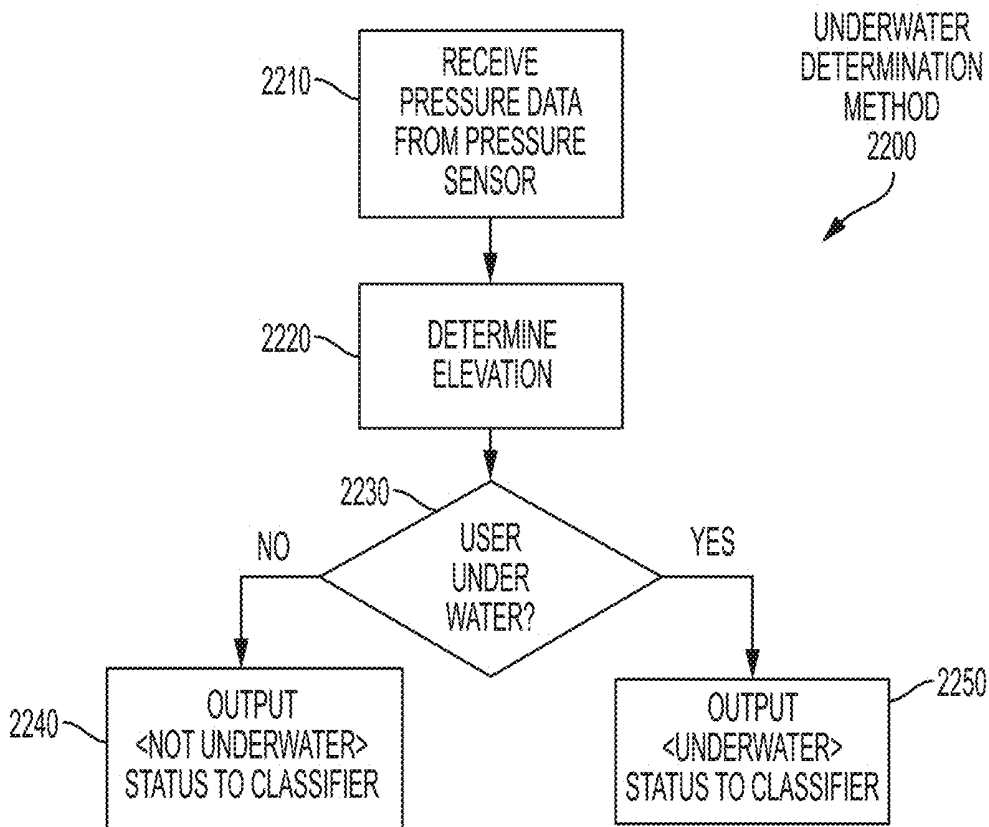


FIG. 22

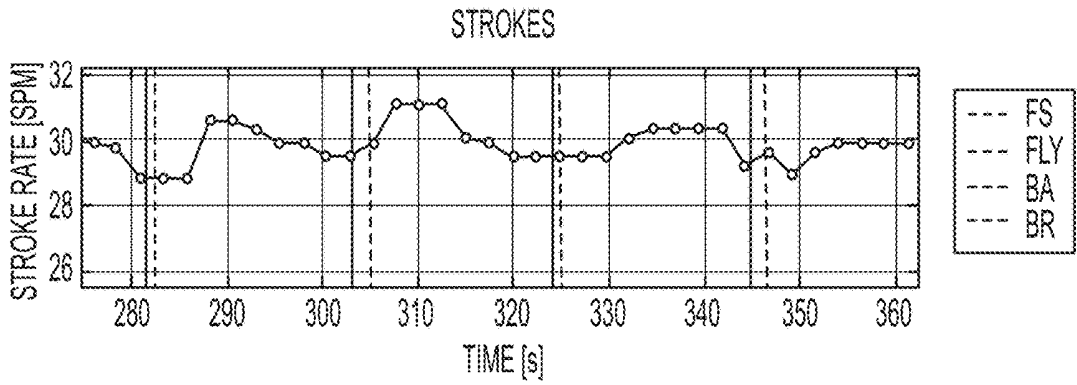


FIG. 23A

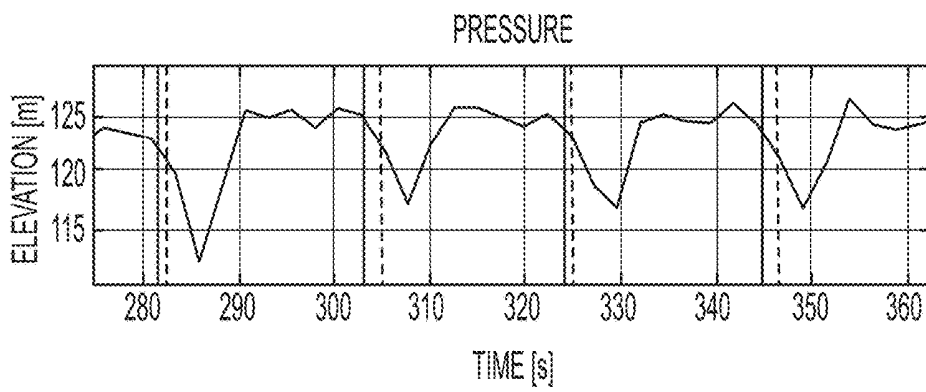


FIG. 23B

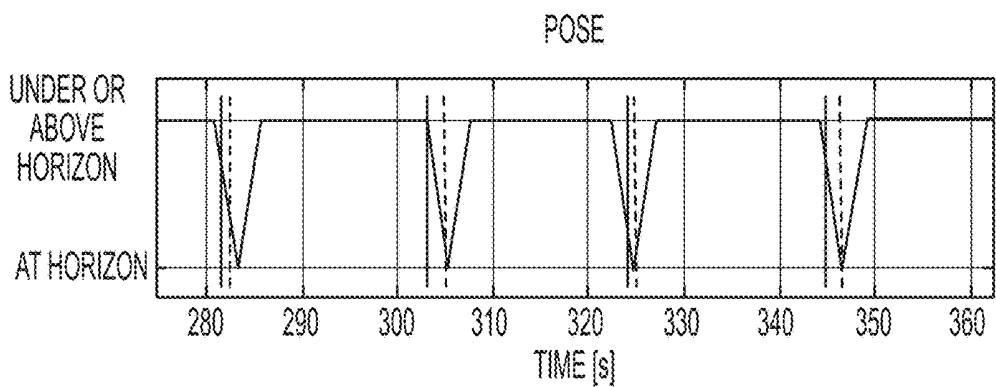


FIG. 23C

SYSTEMS AND METHODS OF SWIMMING CALORIMETRY

PRIORITY CLAIM

This application claims priority to and the benefit of U.S. Provisional Patent Application No. 62/382,060, titled "System and Methods for Swimming Calorimetry," which was filed on Aug. 31, 2016 and is incorporated by reference herein in its entirety.

This application claims priority to and the benefit of U.S. Provisional Patent Application No. 62/478,900, titled "Swimming Glide Detection," which was filed on Mar. 30, 2017 and is incorporated by reference herein in its entirety.

CROSS-REFERENCE TO RELATED APPLICATIONS

This application relates to co-pending U.S. patent application Ser. No. 15/691,245, titled "Systems and Methods for Determining Swimming Metrics," which is filed on Aug. 30, 2017 and is incorporated by reference herein in its entirety.

This application related to co-pending U.S. patent application Ser. No. 15/692,726, titled "Systems and Methods of Swimming Analysis," which is filed on Aug. 31, 2017 and is incorporated by reference herein in its entirety.

FIELD

The present disclosure relates generally to swimming calorimetry.

BACKGROUND

When a user is swimming, there is often a need to know many factors related to the swimming session, such as total distances, number of laps, swimming styles, stroke consistency, and/or energy expenditure. It is, however, generally difficult to estimate how many calories a user burns during a swimming session because energy expenditure depends on many factors such as speed, efficiency, swimming style, etc. Particularly, glides and strokes can correspond to different energy consumption rates, and ignoring glides can cause overestimates in energy expenditure. Accordingly, it is desirable to provide methods and systems for estimating energy expenditure of a user while swimming.

SUMMARY

The present disclosure relates to a method for improving an accuracy of a wearable device while estimating energy expenditure of a user during a swimming session. In some embodiments, the method can include: collecting, by a motion sensing module of a wearable device, motion data of the user; determining, by a processor circuit of the wearable device, rotational data of the user based on the motion data; counting, by the processor circuit, a number of strokes made by the user based on the set of rotational data; estimating, by the processor circuit, a stroke rate of the user based on the number of strokes; counting, by the processor circuit, a number of laps finished by the user based on the set of rotational data; calculating, by the processor circuit, a stroke length based on the number of strokes, the number of laps finished, and a lap length associated with the swimming session; calculating, by the processor circuit, a speed of the user based on the stroke rate and the stroke length; estimating, by the processor circuit, an efficiency of the user based

on at least one of the stroke length or a level of stroke orbit consistency of the user; classifying, by the processor circuit, a swimming style of the user based on the set of rotational data; determining, by the processor circuit, an energy expenditure of the user based on the speed, efficiency, and swimming style of the user; and outputting, by the processor circuit, the determined energy expenditure of the user. In some embodiments, the motion data can be expressed in a first frame of reference and the rotation data can be expressed in a second frame of reference.

In some embodiments, the method can include receiving one or more inputs from the user; adjusting the energy expenditure of the user based on the received one or more inputs; and outputting the adjusted energy expenditure of the user. In some embodiments, the one or more inputs from the user can include at least one of the user's gender, age, height, weight, or body mass index.

In some embodiments, the method can include measuring, by a heart rate sensing module of the wearable device, a heart rate of the user; determining a fraction of heart rate reserve (FHR) of the user based on the measured heart rate; estimating, by the processor circuit, the user's anaerobic energy expenditure based on at least one of the user's fraction of heart rate reserve, stroke length, stroke rate, and or speed; and determining, by the processor circuit, the energy expenditure of the user based on the estimated anaerobic energy expenditure.

In some embodiments, the method can include: measuring, by a heart rate sensing module of the wearable device, a heart rate of the user; determining, by the processor circuit, a fraction of heart rate reserve (FHR) of the user based on the measured heart rate; determining, by the processor circuit, a maximal oxygen uptake of the user; determining, by the processor circuit, a heart rate model based on FHR and the maximal oxygen uptake, wherein determining the energy expenditure of the user based on the heart rate model.

In some embodiments, the method can include: receiving, by a GPS sensor of the wearable device, location data of the user during the swimming session; and calculating, by the processor circuit, a stroke length and a speed of the user based on the received location data. In some embodiments, the motion sensing module can include at least one of a gyroscope or an accelerometer.

In some embodiments, the method can include: detecting, by the processor circuit, one or more glides of the user during the swimming session; and determining, by the processor circuit, the energy expenditure of the user based on the detected one or more glides. In some embodiments, the method can include: determining, by the processor circuit, whether the user is making a turn based on the set of rotational data; detecting, by the processor circuit, a pose angle of the user's wrist based on the set of rotational data; determining, by the processor circuit, whether the user is under water using pressure data received from a pressure sensor of the wearable device; detecting, by the processor circuit, one or more glides of the user based on the stroke rate, the pose angle of the user's wrist, whether the user is making a turn, and whether the user is under water.

In some embodiments, the method can include: determining, by the processor circuit, a direction of gravity relative to the user device based on the motion data; detecting, by the processor circuit, a pose of the user's wrist based on the direction of gravity.

In some embodiments, the method can include: receiving, by the processor circuit, pressure data from a pressure sensor of the wearable device; determining, by the processor circuit, an elevation of the wearable device based on the

pressure data; and determining, by the processor circuit, whether the user is under water based on the determined elevation.

The present disclosure also relates to a system for improving an accuracy of a wearable device while estimating energy expenditure of a user during a swimming session. In some embodiments, the system can include: a motion sensing module configured to collect motion data of the user; a processor circuit in communication with the motion sensing module and configured to execute instructions causing the processor circuit to: determine rotational data of the user base on the motion data; count a number of strokes made by the user based on the set of rotational data; estimate a stroke rate of the user based on the number of strokes; count a number of laps finished by the user based on the set of rotational data; estimate a stroke length based on the number of strokes, the number of laps, and a length associated with the swimming session; estimate a speed of the user based on the stroke rate and the stroke length; estimate efficiency of the user based on at least one of the stroke length or a level of stroke orbit consistency of the user; classify a swimming style of the user based on the set of rotational data; determine an energy expenditure of the user based on the speed, efficiency, and swimming style of the user; and output the determined energy expenditure of the user.

In some embodiments, the system can include a heart rate sensing module configured to measure a heart rate of the user. In some embodiments, the instructions can further cause the processor circuit to: determine, a fraction of heart rate reserve (FHR) of the user based on the measured heart rate; determine, a maximal oxygen uptake of the user; determine, a heart rate model based on the FHR and the maximal oxygen uptake; and determine the energy expenditure of the user based on the heart rate model.

Other features and advantages will become apparent from the following detailed description and drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

Various objects, features, and advantages of the present disclosure can be more fully appreciated with reference to the following detailed description of the present disclosure when considered in connection with the following drawings, in which like reference numerals identify like elements.

FIG. 1 illustrates a wearable device according to some embodiments of the present disclosure.

FIG. 2 illustrates a block diagram of a wearable device according to some embodiments of the present disclosure.

FIG. 3 illustrates a companion device according to some embodiments of the present disclosure.

FIG. 4 illustrates a method of determining rotational data of a user while swimming according to some embodiments of the present disclosure.

FIGS. 5A-5D illustrate an example of a body-fixed frame of reference according to some embodiments of the present disclosure.

FIG. 6 illustrates a set of rotational data of a wearable device in a body-fixed frame of reference according to some embodiments of the present disclosure.

FIG. 7 illustrates an example of an inertial frame of reference according to some embodiments of the present disclosure.

FIGS. 8A-8D illustrate an example of an inertial frame of reference according to some embodiments of the present disclosure.

FIG. 9 illustrates a set of rotational data of a wearable device in an inertial frame of reference according to some embodiments of the present disclosure.

FIG. 10 illustrates a method of estimating energy expenditure of a user while swimming according to some embodiments of the present disclosure.

FIG. 11 illustrates a method of determining a direction of gravity according to some embodiments of the present disclosure.

FIG. 12 illustrates a method of determining a direction of gravity according to some embodiments of the present disclosure.

FIG. 13 illustrates percentage of aerobic and anaerobic contributions to user's total energy expenditure while swimming according to some prior published research.

FIG. 14 illustrates a user's energy expenditure as a function of swimming speed according to some prior published research.

FIG. 15 illustrates the relationship between the user's lactate concentration and the user's FHR according to some embodiments of the present disclosure.

FIG. 16 shows plot of total metabolic equivalent of task (METs) vs. speed, according to some embodiments of the present disclosure.

FIG. 17 illustrates a method of estimating energy expenditure of a user in open water according to some embodiments of the present disclosure.

FIG. 18 is a plot of normalized METs vs. fractional heart rate, according to some embodiments of the present disclosure.

FIG. 19 illustrates a method of detecting glides of a user while the user is swimming according to some embodiments of the present disclosure.

FIG. 20 illustrates a method of determining if a user is making a turn and the user's stroke rate according to some embodiments of the present disclosure.

FIG. 21 illustrates a method of determining a pose of a user's wrist according to some embodiments of the present disclosure.

FIG. 22 illustrates a method of determining if a user is under water according to some embodiments of the present disclosure.

FIGS. 23A-23C show plots of stroke rate, pressure, and pose information of an example user's swimming session according to some embodiments of the present disclosure.

DETAILED DESCRIPTION

In the following description, numerous specific details are set forth regarding the systems, methods and media of the present disclosure and the environment in which such systems, methods and media may operate, etc., in order to provide a thorough understanding of the present disclosure. It will be apparent to one skilled in the art, however, that the present disclosure may be practiced without such specific details, and that certain features, which are well known in the art, are not described in detail in order to avoid complication of the present disclosure. In addition, it will be understood that the examples provided below are exemplary, and that it is contemplated that there are other systems, methods, and media that are within the scope of the present disclosure.

The present disclosure describes a wearable device (or a "user device") that may be configured to determine consistency of a user's stroke orbits while the user is swimming. The wearable device can include one or more motion sensors to collect data about the wearable device's position

and orientation in space and to track changes to the wearable device's position and orientation over time. Because a user can wear the wearable device, the motion information can provide information about the user's movements. For example, when a user is swimming, the user's arms are typically swinging along a particular path and at a particular frequency. If the user wears the wearable device on the user's wrist, the wearable device may be able to infer that the user is swimming in a certain style and/or changing in direction by sensing the way the user's arm moves in a certain path. When the user is swimming, there is a fairly periodic motion of the user's arm/wrist that can be tracked by the wearable device. For example, the user may take a breath every stroke, or every suitable number of strokes (e.g., every two strokes, every three strokes, every four strokes, etc.)

FIG. 1 shows an example of a wearable device (or a "user device") 100 according to some embodiments of the present disclosure. In some embodiments, wearable device 100 may be any suitable wearable device, such as a watch and/or a fitness band configured to be worn around an individual's wrist. In some embodiments, wearable device 100 includes a crown 120, a band 140, and/or a display surface 160.

FIG. 2 depicts a block diagram of exemplary components that may be found within wearable device 100 according to some embodiments of the present disclosure. In some embodiments, wearable device 100 can include a main processor 210 (or "application processor"), a motion co-processor 215, a memory 220, one or more motion sensors 240, a display 270, an interface 280, and a heart rate sensor 290. Wearable device 100 may include additional modules, fewer modules, or any other suitable combination of modules that perform any suitable operation or combination of operations.

In some embodiments, main processor 210 can include one or more cores and can accommodate one or more threads to run various applications and modules. Software can run on main processor 210 capable of executing computer instructions or computer code. Main processor 210 can also be implemented in hardware using an application specific integrated circuit (ASIC), programmable logic array (PLA), field programmable gate array (FPGA), or any other integrated circuit.

In some embodiments, wearable device 100 also includes motion co-processor 215 which may draw less power than the main processor 210. Whereas the main processor 210 may be configured for general purpose computations and communications, the motion co-processor 215 may be configured to perform a relatively limited set of tasks, such as receiving and processing data from motion sensor 240, heart rate sensor 290, and other modules within the wearable device 100. In many embodiments, the main processor 210 may be powered down at certain times to conserve power, while the motion co-processor 215 remains powered on. Thus, the motion co-processor 215 is sometimes referred to as an "always-on" processor (AOP). Motion co-processor 215 may control when the main processor 210 is powered on or off.

Memory 220 can be a non-transitory computer readable medium, flash memory, a magnetic disk drive, an optical drive, a programmable read-only memory (PROM), a read-only memory (ROM), or any other memory or combination of memories. Memory 220 can include one or more modules 230.

Main processor 210 or motion co-processor 215 can be configured to run module 230 stored in memory 220 that is configured to cause main processor 210 or motion co-

processor 215 to perform various steps that are discussed throughout the present disclosure.

In some embodiments, wearable device 100 can include one or more motion sensors 240. For example, motion sensors 240 can include a gyroscope 250 and an accelerometer 260. In some embodiments, accelerometer 260 may be a three-axis accelerometer that measures linear acceleration in up to three-dimensions (for example, x-axis, y-axis, and z-axis). In some embodiments, gyroscope 250 may be a three-axis gyroscope that measures rotational data, such as rotational movement and/or angular velocity, in up to three-dimension (for example, yaw, pitch, and roll). In some embodiments, accelerometer 260 may be a microelectromechanical system (MEMS) accelerometer, and gyroscope 250 may be a MEMS gyroscope. Main processor 210 or motion co-processor 215 of wearable device 100 may receive motion information from one or more motion sensors 240 to track acceleration, rotation, position, or orientation information of wearable device 100 in six degrees of freedom through three-dimensional space.

In some embodiments, wearable device 100 may include other types of sensors in addition to accelerometer 260 and gyroscope 250. For example, wearable device 100 may include an altimeter or barometer, or other types of location sensors, such as a GPS sensor.

Wearable device 100 may also include display 270. Display 270 may be a screen, such as a crystalline (e.g., sapphire) or glass touchscreen, configured to provide output to the user as well as receive input from the user via touch. For example, display 270 may be configured to display a current heart rate or daily average energy expenditure. Display 270 may receive input from the user to select, for example, which information should be displayed, or whether the user is beginning a physical activity (e.g., starting a session) or ending a physical activity (e.g., ending a session), such as a swimming session, a running session, or a cycling session. In some embodiments, wearable device 100 may present output to the user in other ways, such as by producing sound with a speaker (not shown), and wearable device 100 may receive input from the user in other ways, such as by receiving voice commands via a microphone (not shown).

In some embodiments, wearable device 100 may communicate with external devices via interface 280, including a configuration to present output to a user or receive input from a user. Interface 280 may be a wireless interface. The wireless interface may be a standard Bluetooth (IEEE 802.15) interface, such as Bluetooth v4.0, also known as "Bluetooth low energy." In other embodiments, the interface may operate according to a cellphone network protocol such as Long Term Evolution (LTE) or a Wi-Fi (IEEE 802.11) protocol. In other embodiments, interface 280 may include wired interfaces, such as a headphone jack or bus connector (e.g., Lightning, Thunderbolt, USB, etc.).

Wearable device 100 can measure an individual's current heart rate from heart rate sensor 290. Heart rate sensor 290 may also be configured to determine a confidence level indicating a relative likelihood of an accuracy of a given heart rate measurement. In other embodiments, a traditional heart rate monitor may be used and may communicate with wearable device 100 through a near field communication method (e.g., Bluetooth).

Wearable device 100 may be configured to communicate with a companion device 300 (FIG. 3), such as a smartphone, as described in more detail herein. In some embodiments, wearable device 100 may be configured to commu-

nicate with other external devices, such as a notebook or desktop computer, tablet, headphones, Bluetooth headset, etc.

The modules described above are examples, and embodiments of wearable device 100 may include other modules not shown. For example, some embodiments of wearable device 100 may include a rechargeable battery (e.g., a lithium-ion battery), a microphone or a microphone array, one or more cameras, one or more speakers, a watchband, water-resistant casing or coating, etc. In some embodiments, all modules within wearable device 100 can be electrically and/or mechanically coupled together. In some embodiments, main processor 210 can coordinate the communication among each module.

FIG. 3 shows an example of a companion device 300 according to some embodiments of the present disclosure. Wearable device 100 may be configured to communicate with companion device 300 via a wired or wireless communication channel (e.g., Bluetooth, Wi-Fi, etc.). In some embodiments, companion device 300 may be a smartphone, tablet computer, or similar portable computing device. Companion device 300 may be carried by the user, stored in the user's pocket, strapped to the user's arm with an armband or similar device, placed in a mounting device, or otherwise positioned within communicable range of wearable device 100.

In some embodiments, companion device 300 may include a variety of sensors, such as location and motion sensors (not shown). When companion device 300 is available for communication with wearable device 100, wearable device 100 may receive additional data from companion device 300 to improve or supplement its calibration or calorimetry processes. For example, in some embodiments, wearable device 100 may not include a GPS sensor as opposed to an alternative embodiment in which wearable device 100 may include a GPS sensor. In the case where wearable device 100 may not include a GPS sensor, a GPS sensor of companion device 300 may collect GPS location information, and wearable device 100 may receive the GPS location information via interface 280 (FIG. 2) from companion device 300.

In another example, wearable device 100 may not include an altimeter or barometer, as opposed to an alternative embodiment in which wearable device 100 may include an altimeter or barometer. In the case where wearable device 100 may not include an altimeter or barometer, an altimeter or barometer of companion device 300 may collect altitude or relative altitude information, and wearable device 100 may receive the altitude or relative altitude information via interface 280 (FIG. 2) from the companion device 300.

In another example, wearable device 100 may receive motion information from companion device 300. Wearable device 100 may compare the motion information from companion device 300 with motion information from one or more motion sensors 240 of wearable device 100. Motion information such as data from accelerometer 260 and/or gyroscope 250 may be filtered (e.g. by a high-pass, low-pass, band-pass, or band-stop filter) in order to improve the quality of motion information. For example, a low-pass filter may be used to remove some ambient noise.

Wearable device 100 may use sensed and collected motion information to predict a user's activity. Examples of activities may include, but are not limited to, walking, running, cycling, swimming, etc. Wearable device 100 may also be able to predict or otherwise detect when a user is sedentary (e.g., sleeping, sitting, standing still, driving or otherwise controlling a vehicle, etc.) Wearable device 100

may use a variety of motion information, including, in some embodiments, motion information from a companion device.

Wearable device 100 may use a variety of heuristics, algorithms, or other techniques to predict the user's activity. Wearable device 100 may also estimate a confidence level (e.g., percentage likelihood, degree of accuracy, etc.) associated with a particular prediction (e.g., 90% likelihood that the user is running) or predictions (e.g., 60% likelihood that the user is running and 40% likelihood that the user is walking).

FIG. 4 shows a flow chart illustrating a process 400 of determining one or more breaths taken by a user while swimming according to some embodiments of the present disclosure. In some embodiments, the process 400 can be modified by, for example, having steps combined, divided, rearranged, changed, added, and/or removed. As described in more details below, in some embodiments, the process 400 can include three steps. At step 410, wearable device 100 receives motion information from one or more motion sensors 240. At step 420, wearable device 100 determines a first set of rotational data of wearable device 100. At step 430, wearable device 100 converts the first set of rotational data into a second set of rotational data, where the second set of rotational data include pitch rotational data.

At step 410, motion information may be received from one or more motion sensors 240 on wearable device 100. In some embodiments, motion information may include three-dimensional rotational data of wearable device 100 from gyroscope 250. In some embodiments, motion information may include three-dimensional accelerations of wearable device 100 from accelerometer 260.

At step 420, wearable device 100 may determine a first set of rotational data of wearable device 100 based on the motion information received from one or more motion sensors 240. In some embodiments, the rotational data of wearable device 100 include how wearable device 100 rotates, such as angular position, angular velocity, and/or angular acceleration of wearable device 100, with respect to a frame of reference. In some embodiments, if the rotational data of wearable device 100 is angular acceleration, then angular velocity and/or angular position can be obtained by integrating the angular acceleration over time. Likewise, if the rotational data of wearable device 100 is angular velocity, then angular position can be obtained by integrating the angular velocity over time. In some embodiments, the first set of rotational data is received from gyroscope 250 and is expressed in a body-fixed frame of reference with respect to wearable device 100.

FIG. 5A illustrates an example of a body-fixed frame of reference 500 according to some embodiments of the present disclosure. In FIG. 5A, the rotational axes of body-fixed frame of reference 500 are with respect to wearable device 100. For example, the z-axis is perpendicular to the display surface 160 of wearable device 100. The x-axis and the y-axis can be chosen relatively arbitrarily as long as the three axes are perpendicular to each other. In FIG. 5A, the x-axis is parallel with the direction pointed by crown 120 of wearable device 100, and the y-axis is parallel with the direction of band 140 of wearable device 100 (assuming the direction pointed by crown 120 of wearable device 100 is perpendicular to the direction of band 140 of wearable device 100).

FIG. 5B-5D illustrates examples to express one or more orientations in body-fixed frame of reference 500 according to some embodiments of the present disclosure. In FIG. 5B, an orientation/direction 510 has an angle (ϕ) 502 with

respect to the positive x-axis, an angle (θ) **504** with respect to the positive y-axis, and an angle (ψ) **506** with respect to the positive z-axis. The direction **510** can be expressed in body-fixed frame of reference **500** as $[\cos(\phi), \cos(\theta), \cos(\psi)]$, which is a non-limiting example/format of the first set of rotational data. For example, direction **520** in FIG. **5B** is parallel with and pointing toward the positive x-axis, so the angle (ϕ) between direction **520** and the positive x-axis is 0 degree; the angle (θ) between direction **520** and the positive y-axis is 90 degrees; and the angle (ψ) between direction **520** and the positive z-axis is 90 degrees. Therefore, direction **520** can be expressed as $[\cos(0), \cos(90), \cos(90)]$, which is $[1, 0, 0]$. As another example, direction **530** in FIG. **5B** is parallel with and pointing toward the positive z-axis, so the angle (ϕ) between direction **530** and the positive x-axis is 90 degrees; the angle (θ) between direction **530** and the positive y-axis is 90 degrees; and the angle (ψ) between direction **530** and the positive z-axis is 0 degrees. Therefore, direction **530** can be expressed as $[\cos(90), \cos(90), \cos(0)]$, which is $[0, 0, 1]$. As yet another example, direction **540** represents direction of gravity in FIG. **5B** and is parallel with and pointing toward the negative y-axis, so the angle (ϕ) between direction **540** and the positive x-axis is 90-degrees; the angle (θ) between direction **540** and the positive y-axis is 180 degrees; and the angle (ψ) between direction **540** and the positive z-axis is 90 degrees. Therefore, direction **540** can be expressed as $[\cos(90), \cos(180), \cos(90)]$, which is $[0, -1, 0]$.

In FIG. **5C**, wearable device **100** is held vertically. As discussed earlier, the x-axis is parallel with direction pointed by crown **120**, the y-axis is parallel with band **140**, and the z-axis is perpendicular to display surface **160**. Direction **550** in FIG. **5C** represents the direction pointed by crown **120**, so the angle (ϕ) between direction **550** and the positive x-axis is 0 degrees; the angle (θ) between direction **550** and the positive y-axis is 90 degrees; and the angle (ψ) between direction **550** and the positive z-axis is 90 degrees. Therefore, direction **550** can be expressed as $[\cos(0), \cos(90), \cos(90)]$, which is $[1, 0, 0]$. As another example, direction **540** represents direction of gravity in FIG. **5C** and is parallel with and pointing toward the negative y-axis, so the angle (ϕ) between direction **540** and the positive x-axis is 90 degrees; the angle (θ) between direction **540** and the positive y-axis is 180 degrees; and the angle (ψ) between direction **540** and the positive z-axis is 90 degrees. Therefore, direction **540** in FIG. **5C** can be expressed as $[\cos(90), \cos(180), \cos(90)]$, which is $[0, -1, 0]$.

In FIG. **5D**, wearable device **100** is rotated 45 degrees clockwise compared with FIG. **5C**. As discussed earlier, the x-axis is parallel with direction pointed by crown **120**, the y-axis is parallel with band **140**, and the z-axis is perpendicular to display surface **160**. Direction **550** in FIG. **5D** represents the direction pointed by crown **120**, so the angle (ϕ) between direction **550** and the positive x-axis is 0 degrees; the angle (θ) between direction **550** and the positive y-axis is 90 degrees; and the angle (ψ) between direction **550** and the positive z-axis is 90 degrees. Therefore, direction **550** can be expressed as $[\cos(0), \cos(90), \cos(90)]$, which is $[1, 0, 0]$. As another example, direction **540** represents direction of gravity in FIG. **5D**. The angle (ϕ) between direction **540** and the positive x-axis is 45 degrees; the angle (θ) between direction **540** and the positive y-axis is 135 degrees; and the angle (ψ) between direction **540** and the positive z-axis is 90 degrees. Therefore, direction **540** in FIG. **5D** can be expressed as $[\cos(45), \cos(135), \cos(90)]$, which is $[0.707, -0.707, 0]$.

It is noted that the expression of direction **550** is the same in FIG. **5C** and FIG. **5D** even though wearable device **100** has rotated. This is because the body-fixed frame of reference **500** is always fixed with respect to wearable device **100**. As a result, when the position of wearable device **100** changes, the three axes in body-fixed frame of reference **500** and direction **550** change too, and the relative position between direction **550** and the three axes remain the same. On the other hand, although the direction of gravity **540** does not change in an "absolute" sense, it does change its position relative to the wearable device **100**, when the wearable device **100** changes position. Therefore, the expression of gravity direction **540** does not stay fixed in the body-fixed frame of reference **500** when wearable device changes position.

FIG. **6** illustrates a first set of rotational data of wearable device **100** according to some embodiments of the present disclosure. Specifically, FIG. **6** illustrates estimation of the gravity in the body-fixed frame of reference **500**. The x-axis shows $\cos(\phi)$ where ϕ is the angle between gravity and the positive x-axis in the body-fixed frame of reference **500**. The y-axis shows $\cos(\theta)$, where θ is the angle between gravity and the positive y-axis in the body-fixed frame of reference **500**. The z-axis shows $\cos(\psi)$, where ψ is the angle between gravity and the positive z-axis in the body-fixed frame of reference **500**. For example, if the display surface of wearable device **100** faces up toward the sky, parallel with the ground, then the gravity direction can be expressed as $[0, 0, -1]$. As another example, if crown is pointed towards the ground, then the gravity direction can be expressed as $[1, 0, 0]$. Gravity estimation in body-fixed frame of reference can help indicate when wearable device **100** is making a pitch and/or roll movement. For example, as discussed above, when a user's wrist is in a position such that crown is pointed towards the ground, the gravity direction is $[1, 0, 0]$. If the user then pitches his or her wrist up for 90 degrees, then display surface of wearable device **100** faces up toward the sky, parallel with the ground, and the gravity direction is expressed as $[0, 0, -1]$. If the user then rolls his or her wrist up for 90 degrees, then crown of wearable device **100** faces up toward the sky, and the gravity direction is expressed as $[-1, 0, 0]$. These examples illustrate that gravity direction in the body-fixed frame of reference **500** can change in response to pitch and/or roll movement. In some embodiments, the gravity estimation in body-fixed frame of reference **500** can be used together with accelerometer **260** to estimate gravity. However, the gravity direction in the body-fixed frame of reference **500** does not change in response to yaw movement. For example, if the display surface of wearable device **100** is facing up toward the sky, parallel with the ground, then the gravity direction is expressed as $[0, 0, -1]$. If the user then makes a yaw movement along the horizontal plane, the gravity direction remains $[0, 0, -1]$.

Also, as discussed above, because wearable device **100** is rotating with the body-fixed frame of reference **500**, the directions of wearable device **100** and components thereof are fixed. For example, no matter whether the crown is pointing up, straight, or down, the crown direction is always expressed in a body-fixed frame of reference **500** as $[1, 0, 0]$. Therefore, in some embodiments, it is more suitable to express the positions of wearable device **100** in a frame of reference that is not body-fixed in order to more readily indicate the movements of wearable device **100** with respect to external references.

At step **430**, wearable device **100** converts the first set of rotational data into a second set of rotational data. As

described above, rotational data in the body-fixed frame of reference cannot readily indicate whether or not wearable device 100 undergoes movements with respect to external references. To address this issue, wearable device 100 converts the rotational data in the body-fixed frame of reference into rotational data in an inertial frame of reference using techniques appreciated by people skilled in the art such as the one discussed in “Kalman-filter-based orientation determination using inertial/magnetic sensors: observability analysis and performance evaluation,” Angelo Maria Sabatini, published Sep. 27, 2011, *Sensors* 2011, 11, 9182-9206.

FIG. 7 illustrates an inertial frame of reference 700 according to some embodiments of the present disclosure. In FIG. 7, the z-axis is based on the direction of gravity. The x-axis and the y-axis can be chosen relatively arbitrarily as long as the three axes are perpendicular to each other. The z-axis is also referred to as yaw axis because any yaw movement rotates around the z-axis. In some embodiments, the x-axis can indicate the direction of movements, and the x-axis can be referred to as roll axis because any roll movement rotates around the x-axis. And the y-axis can be referred to as pitch axis because any pitch movement rotates around the y-axis.

FIGS. 8A-8D illustrate an example of an inertial frame of reference 800 according to some embodiments of the present disclosure. FIG. 8A depicts inertial frame of reference 800 in a context where a user is swimming. In FIG. 8A, the user wears wearable device 100. But the z-axis (or the yaw axis) in the inertial frame of reference is based on the direction of gravity rather than the wearable device itself. Additionally, assuming the user is swimming laps, the x-axis (or the roll axis) is substantially parallel to the direction of the laps, and the y-axis (or the pitch axis) is perpendicular to the other two axes. In some embodiments, the x-axis (or the roll axis) and the y-axis (or the pitch axis) can be chosen relatively arbitrarily as long as the three axes are perpendicular to each other. In FIG. 8A, the z-axis is also referred to as yaw axis because any yaw movement rotates around the z-axis. Similarly, the x-axis is also referred to as roll axis because any roll movement rotates around the x-axis. And the y-axis is also referred to as pitch axis because any pitch movement rotates around the y-axis. By knowing the difference between the three-axes in the fixed-body frame of reference 500 and the three-axis in the inertial frame of reference 800, the rotational data expressed in the fixed-body frame of reference 500 can be converted into the rotational data expressed in the inertial frame of reference 800 using techniques appreciated by people skilled in the art such as the one discussed in Sabatini.

FIG. 8B illustrates that wearable device 100 can make rotational movement with respect to inertial frame of reference 800. In FIG. 8B, an orientation/direction 810 has an angle (ϕ) 802 with respect to the positive x-axis, an angle (θ) 804 with respect to the positive y-axis, and an angle (ψ) 806 with respect to the positive z-axis. The direction 810 can be expressed in inertial frame of reference 800 as $[\cos(\phi), \cos(\theta), \cos(\psi)]$, which is a non-limiting example/format of the second set of rotational data.

FIGS. 8C and 8D illustrate how same orientations in FIGS. 5C and 5D can be expressed differently in inertial frame of reference 800. In FIG. 8C, wearable device 100 is held vertically, which is the same as FIG. 5C. As discussed earlier, the z-axis is based on the gravity in inertial frame of reference 800. In FIG. 8C, the positive z-axis is chosen as the direct opposite position of gravity, the x-axis is perpendicular to the z-axis and pointing right horizontally, and the y-axis is perpendicular to both x-axis and y-axis and point-

ing “out” of FIG. 8C. Direction 550 in FIG. 8C represents the direction pointed by crown 120, so the angle (ϕ) between direction 550 and the positive x-axis is 0 degree; the angle (θ) between direction 550 and the positive y-axis is 90 degrees; and the angle (ψ) between direction 550 and the positive z-axis is 90 degrees. Therefore, direction 550 can be expressed as $[\cos(0), \cos(90), \cos(90)]$, which is $[1, 0, 0]$. As another example, direction 540 represents direction of gravity in FIG. 8C and is parallel with and pointing toward the negative z-axis, so the angle (ϕ) between direction 540 and the positive x-axis is 90 degrees; the angle (θ) between direction 540 and the positive y-axis is 90 degrees; and the angle (ψ) between direction 540 and the positive z-axis is 180 degrees. Therefore, direction 540 in FIG. 8C can be expressed as $[\cos(90), \cos(90), \cos(180)]$, which is $[0, 0, -1]$.

In FIG. 8D, wearable device 100 is rotated 45 degrees clockwise compared with FIG. 8C. Because the three axes are based on gravity, they can remain the same as FIG. 8C. Direction 550 in FIG. 8D represents the direction pointed by crown 120, and the angle (ϕ) between direction 550 and the positive x-axis is 45 degrees; the angle (θ) between direction 550 and the positive y-axis is 90 degree; and the angle (ψ) between direction 550 and the positive z-axis is 135 degree. Therefore, direction 550 can be expressed as $[\cos(45), \cos(90), \cos(135)]$, which is $[0.707, 0, -0.707]$. As another example, direction 540 represents direction of gravity in FIG. 8D. The angle (ϕ) between direction 540 and the positive x-axis is 90 degree; the angle (θ) between direction 540 and the positive y-axis is 90 degrees; and the angle (ψ) between direction 540 and the positive z-axis is 180 degrees. Therefore, direction 540 in FIG. 8D can be expressed as $[\cos(90), \cos(90), \cos(180)]$, which is $[0, 0, -1]$.

It is noted that the expression of gravity direction 540 is the same in FIG. 8C and FIG. 8D even though wearable device 100 has rotated. This is because the inertial frame of reference 800 is always fixed with respect to gravity. As a result, when position of wearable device 100 changes, the three axes in the inertial frame of reference 800 do not move. On the other hand, the direction 550 does move with respect to the three axes, so the expression of direction 550 can change in the inertial frame of reference 500 even though it is fixed in body-fixed frame of reference 500.

FIG. 9 illustrates a first set of rotational data of wearable device 100 according to some embodiments of the present disclosure. Specifically, FIG. 9 illustrates estimation of crown direction in the inertial frame of reference 800 while a user is swimming laps. The x-axis shows $\cos(\phi)$ where ϕ is the angle between crown direction and the positive x-axis in the inertial frame of reference 800. The y-axis shows $\cos(\theta)$, where θ is the angle between crown direction and the positive y-axis in the inertial frame of reference 800. The z-axis shows $\cos(\psi)$, where ψ is the angle between crown direction and the positive z-axis in the inertial frame of reference 800. For example, if the display surface of the wearable device 100 is facing up towards the sky, parallel with the ground, and the crown is pointed towards the positive x-axis, then the crown direction can be expressed as $[1, 0, 0]$. Further, if wearable device 100 is making yaw movements, and the crown changes direction to point towards the negative x-axis, then the crown direction can be expressed as $[-1, 0, 0]$. As another example, if the crown is pointed towards the ground, then the new crown direction can be expressed as $[0, 0, 1]$. The rotational data in FIG. 9 are largely divided into two clusters, 902 and 904, because every time the user makes a turn, the angle ϕ between crown direction and the positive x-axis in the inertial frame of

reference **800** changes substantially around 180 degrees. Therefore, the rotational data expressed in FIG. 9 (i.e., the data switching from cluster **902** to cluster **904**, or vice versa) can indicate that wearable device **200** is undergoing a steady-state change in the direction that the user is heading.

The present disclosure describes ways to estimate energy expenditure of a user while swimming. Generally, a user's energy expenditure while swimming can depend on one or more of the following factors: swimming style, skill level, stroke rate, stroke length, gender, body surface area, and/or body composition and distribution. In some embodiments, other relevant factors can also affect the user's energy expenditure.

FIG. 10 illustrates a flow chart illustrating a computerized process **1000** of determining a user's energy expenditure while swimming according to certain embodiments of the present disclosure. In some embodiments, the computerized process **1000** can be modified by, for example, having steps combined, divided, rearranged, changed, added, and/or removed.

At step **1002**, wearable device **100** may detect each time the user makes a stroke. In some embodiments, wearable device **100** can only detect the strokes made by the arm wearing the wearable device **100**. In these embodiments, for every stroke detected, the user may make two strokes, and the metrics related to strokes can sometimes be adjusted accordingly.

At step **1004**, wearable device **100** may estimate stroke rate of the user. In some embodiments, the stroke rate is determined as the number of strokes per unit period, such as a minute. For example, if wearable device **100** detects 120 strokes in four minutes, then the stroke rate can be determined to be $120 \text{ strokes}/4 \text{ minutes}=30 \text{ stroke}/\text{min}$.

At step **1006**, wearable device **100** may detect each time the user finishes a lap.

At step **1008**, wearable device **100** may determine the length of the pool where the user swims, as described in co-pending U.S. patent application Ser. No. 15/691,245, titled "Systems and methods for determining swimming metrics", which is incorporated by reference herein by its entirety.

At step **1010**, wearable device **100** may estimate stroke length of the user. In some embodiments, the stroke length is determined as the length per stroke. For example, if wearable device **100** detects that the user finishes four laps with each lap 50 meters, and wearable device **100** detects the user makes 100 strokes in the four laps, then wearable device **100** can determine the stroke length as $50 \text{ meters}/\text{lap} * 4 \text{ laps}/100 \text{ strokes}=2 \text{ meter}/\text{stroke}$.

At step **1012**, wearable device **100** may estimate the speed of the user. In some embodiments, wearable device **100** estimates the speed of the user based on the user's stroke rate and stroke length. The user's speed can be determined as $\text{stroke rate} * \text{stroke length}$. For example, if wearable device **100** detects that the user finishes four laps with each lap 50 meters in five minutes, and wearable device **100** detects that the user makes 100 strokes in the four laps, then as described above, wearable device **100** can determine the stroke length as $50 \text{ meters}/\text{lap} * 4 \text{ laps}/100 \text{ strokes}=2 \text{ meter}/\text{stroke}$ and the stroke rate as $100 \text{ strokes}/4 \text{ minutes}=25 \text{ stroke}/\text{min}$. Then the speed can be determined as $\text{stroke length} * \text{stroke rate}=2 \text{ meter}/\text{stroke} * 25 \text{ strokes}/\text{min}=50 \text{ meter}/\text{min}$. In some embodiments, the speed of the user can also be determined by one or more sensors of wearable device **100**.

At step **1014**, wearable device **100** may estimate the user's efficiency. In some embodiments, wearable device **100** estimates the user's efficiency based on two factors. One

factor is the user's stroke length. In general, the longer the user's stroke length, the higher the user's efficiency. Another factor is the user's stroke orbit consistency. In general, high stroke orbit consistency indicates high efficiency. Systems and methods for determining stroke orbit consistency are described in co-pending U.S. patent application Ser. No. 15/692,726 titled "Systems and methods of swimming analysis", which is incorporated by reference herein in its entirety.

At step **1016**, wearable device **100** may classify the user's swimming style. In some embodiments, wearable device **100** can classify the user's swimming style as one of the following styles: breaststroke, backstroke, freestyle, butterfly, or unknown. Systems and methods for classifying swimming strokes are also described in co-pending U.S. patent application Ser. No. 15/692,726 titled "Systems and methods of swimming analysis", which is incorporated by reference herein in its entirety.

At step **1018**, wearable device **100** may receive one or more inputs from the user. In some embodiments, wearable device **100** can receive user's gender. In some cases, female users can have more body fat than male users. Users with more body fat are more buoyant and as a result expend less energy. In some embodiments, wearable device **100** can receive other information regarding the user, such as the user's height and weight. In some embodiments, wearable device **100** can calculate the user's body mass index based on the user's height and weight, which measures a user's body fat and can be used to calculate a swimmer's buoyancy and energy expenditure.

At step **1020**, wearable device **100** may select an energy expenditure model based on information provided in step **1016** and/or step **1018**. For example, if wearable device **100** determines the user is swimming in freestyle, it will choose a model corresponding to freestyle. In some embodiments, once wearable device **100** selects an energy expenditure model based on the user's swimming style, it can further modify the model based on the gender.

At step **1022**, wearable device **100** may estimate the user's energy expenditure based on the user's speed, efficiency, and the selected model. In some embodiments, the user's energy expenditure can be expressed as the metabolic equivalent of task (MET). MET has unit of $\text{kcal}/(\text{kg} * \text{h})$, and 1 MET indicates the rate of energy spent per unit surface of a person during sitting.

FIG. 11 shows a method **1100** for determining a direction of gravity according to some embodiments of the present disclosure. The determined direction of gravity may be used to determine a frame of reference for motion information, such as rotational data, of wearable device **100**. In some embodiments, method **1100** can be modified by, for example, having steps combined, divided, rearranged, changed, added, and/or removed. Gravity determination method **1100** may begin at step **1110**.

At step **1110**, wearable device **100** may receive motion information from the one or more motion sensors **240** on a wearable device (e.g., wearable device **100**) of a user. In some embodiments, motion information may include three-dimensional rotational information from one or more sensors **240** such as gyroscope **250** and three-dimensional acceleration information from one or more sensors **240** such as accelerometer **260**. In some embodiments, motion information may be filtered such as by a low-pass filter to remove unwanted noise from the ambient.

At step **1120**, wearable device **100** may determine the angular velocity of wearable device **100** with respect to a

frame of reference such as a body-fixed frame of reference or an inertial frame of reference.

At step 1130, wearable device 100 may determine whether the angular velocity of wearable device 100 determined at step 1120 is below a threshold. For example, the threshold may be approximately 0.05 radians per second, 0.2 radians per second, or 0.5 radians per second, etc. If the angular velocity exceeds the threshold (e.g., when the user is doing exercise), wearable device 100 may return to step 510. In some embodiments, wearable device 100 may pause or wait for a period of time (e.g., 1 second, 5 seconds, 1 minute, etc.) before proceeding at step 1110.

If the angular velocity is below the threshold (e.g., when the user is relatively still), wearable device 100 may proceed to step 1140. In some embodiments, at step 1130 wearable device 100 may determine if the magnitude of forces acting on wearable device 100 are approximately equal to the normal force of gravity (1G) before proceeding to step 1140. If the magnitude is not approximately the normal magnitude, wearable device 100 may also return to block 1110. Wearable device 100 may estimate the direction of gravity when the angular velocity is below the threshold (e.g., when the user is relatively still) to avoid or reduce interference of confusion from acceleration due to other movements. Hypothetically, if wearable device 100 is having a 1 g acceleration along x-axis, then wearable device 100 may incorrectly determine the direction of gravity.

At step 1140, wearable device 100 may estimate the direction of gravity relative to wearable device 100. For example, in some embodiments, when wearable device 100 is held relatively still, accelerometer 260 within wearable device 100 may provide data about the direction of forces acting on wearable device 100, which may be attributable primarily to gravity. In some embodiments, wearable device 100 may determine whether the user wearing wearable device 100 is accelerating (e.g., speeding up or slowing down) or traveling at an approximately constant velocity so as to further improve the estimate of the direction of gravity.

In some embodiments, wearable device 100 may end gravity determination method 1100 after outputting the estimated direction of gravity. In other embodiments, wearable device 100 may return to step 1110 to refine or otherwise repeat the method of estimating the direction of gravity relative to the wearable device.

FIG. 12 shows a method 1200 for determining a direction of gravity according to some embodiments of the present disclosure. In some embodiments, the method 1200 can be modified by, for example, having steps combined, divided, rearranged, changed, added, and/or removed. Gravity determination method 1200 can be used when the user has companion device 300 and may begin at step 1210.

At step 1210, wearable device 100 may periodically or continuously check for the presence of a companion device (e.g., companion device 300). For example, in some embodiments, wearable device 100 may determine whether a connection (e.g., Bluetooth, IEEE 802.11 Wi-Fi, or other wireless or wired communication channel) has been established or may be established with companion device 300. If the companion device 300 is present, wearable device 100 and/or companion device 300 may proceed to step 1220.

At step 1220, wearable device 100 and/or companion device 300 may estimate the direction of gravity relative to companion device 300. In some embodiments, in contrast to the gravity determination method 1100, it may not be necessary to check whether the angular velocity of companion device 300 is below a threshold because most or all of

rotation of the angular velocity of companion device 300 may be orthogonal to the direction of gravity.

At step 1230, wearable device 100 and/or companion device 300 may output the direction of gravity relative to companion device 300. In some embodiments, the direction of gravity relative to companion device 300 may be combined or otherwise compared with the direction of gravity relative to wearable device 100. In some embodiments, companion device 300 may further determine a rotation rate around the direction of gravity relative to the companion device and output the rotation rate instead of or in addition to the direction of gravity relative to companion device 300.

In some embodiments, wearable device 100 and/or companion device 300 may end gravity determination method 1200 after outputting the estimated direction of gravity. In other embodiments, wearable device 100 and/or companion device 300 may return to step 1210 to refine or otherwise repeat the method of estimating the direction of gravity relative to the wearable device.

In some embodiment, the process 1000 also considers anaerobic contribution when estimating the user's overall energy expenditure. During high intensity workouts such as swimming, the anaerobic component plays an important role in the total energy expenditure.

For example, FIG. 13 illustrates percentage of aerobic and anaerobic contributions to user's total energy expenditure while swimming according to some prior published research. FIG. 13 is adapted from data by Hermansen and Karlsson (1967) and Houston (1978). In FIG. 13, the x-axis shows the duration of the swimming workout expressed in minutes, and the y-axis shows the percentage of total energy expenditure. FIG. 13 shows that when the user swims for a short time (e.g., less than four minutes), the anaerobic contribution to energy expenditure is more dominant. And when the user swims for a longer time, the aerobic component becomes more dominant.

As another example, FIG. 14 illustrates a user's energy expenditure as a function of swimming speed according to some prior published research. FIG. 14 is adapted from Pendergast et al. (1978b). In FIG. 14, the x-axis shows swimming speed, and the y-axis shows energy expenditure. The solid line and solid dots show the aerobic contribution to energy expenditure, and the dashed line and open dots show the anaerobic contribution to energy expenditure. FIG. 14 shows that when the user swims at a lower speed (e.g., less than 1.2 m/s), the aerobic component is more dominant. And when the user swims at a higher speed, the anaerobic component is more dominant.

Both FIG. 13 and FIG. 14 show that, in some cases, ignoring the anaerobic component could lead to inconsistent user experience and incorrect/underestimated calorie values.

There are several ways to modify the model shown in FIG. 10 to consider the anaerobic component of the user's energy expenditure. In some embodiments, the user's anaerobic energy expenditure can be estimated based on the user's fraction of heart rate reserve (FHR). FHR may be defined as the ratio of how close an individual's current heart rate is to his or her maximum heart rate (e.g., HRmax-HR) to the individual's heart rate range (e.g., HRmax-HRmin):

$$FHR = \frac{HR - HR_{min}}{HR_{max} - HR_{min}} \quad (\text{Eq. 1})$$

FHR may range from 0 to 1 for any individual. When an individual's FHR is close to 0, it indicates that the user's heart rate is close to the individual's maximum heart rate. Similarly, when an individual's FHR is close to 1, it indicates that the individual's heart rate is close to the individual's minimum heart rate.

For example, FIG. 15 illustrates the relationship between the user's lactate concentration and the user's FHR according to some embodiments of the present disclosure. The x-axis shows the value of 1-FHR, and the y-axis shows the user's lactate concentration. FIG. 15 shows when the value of 1-FHR is greater than 0.7, the user's lactate concentration increases much faster. Because one's lactate concentration is positively related to one's anaerobic energy expenditure, when the value of 1-FHR is greater than 0.7, the user's anaerobic energy expenditure is more pronounced. When 1-FHR is greater than 0.7, FHR is less than 0.3, which means the user's heart rate is relatively close to his or her maximum heart rate. Therefore, in some embodiments, wearable device 100 can monitor the user's heart rate, and increase the estimation of energy expenditure in process 1000 to take the anaerobic contribution to energy expenditure into consideration based on the user's heart rate.

In some embodiments, wearable device 100 can estimate the user's anaerobic energy expenditure based one or more of the following factors about the user: stroke length, stroke rate, and/or speed.

FIG. 16 shows plot of total METs versus speed, according to some embodiments of the present disclosure. In FIG. 16, the x-axis is the user's swimming speed in freestyle, and the y-axis is the user's METs estimated by the model shown in FIG. 10. In FIG. 16, each circle represents a sample. For example, circle 1616 represents a user with speed at around 0.6 m/s with stroke length around 1 m, and the estimated MET is around 14.8. FIG. 16 also plots some previously published research by others. For example, curve 1602 shows total METs versus speed for competitive swimmers, curve 1604 shows aerobic METs versus speed for competitive swimmers, curve 1606 shows total METs versus speed for recreational swimmers. FIG. 16 also shows regression models based on stroke length for all samples. For example, curve 1610 shows total METs versus speed estimated for a swimmer with stroke length of 0.5 m, curve 1610 shows total METs versus speed estimated for a swimmer with stroke length of 1.0 m, and curve 1610 shows total METs versus speed estimated for a swimmer with stroke length of 1.5 m. FIG. 16 shows that, in some embodiments, based on the user's speed, stroke length, and swimming style, wearable device 100 can estimate the user's energy expenditure such as METs.

While many swimmers swim in pools, swimmers competing in open water events or in triathlons often swim in open waters, for example, lakes, oceans and rivers. In these open environments, calculating energy expenditure for a particular swimming workout can be challenging. For example, because laps are not being counted in a set distance pool, distance estimates may be difficult. Even with the assistance of a global positioning system (GPS) it may be difficult to obtain an accurate GPS fix. Further, open water conditions result in unknown resistance to the swimmer, for example water currents, waves, and even varying water densities.

FIG. 17 illustrates a method of estimating energy expenditure of a user in open water according to some embodiments of the present disclosure. FIG. 17 is substantially similar to FIG. 10 above. However, FIG. 17 has the additional components/steps related to heart rate measurements and calculations: GPS odometer 1706, GPS sensor fusion 1714, VO₂max 1722, fractional heart rate 1724, heart rate reliability 1726 and heart rate model 1728.

For example, in some embodiments, a GPS sensor can be used to improve the stroke length estimates from 1710 and

also the speed calculations from 1712. Accordingly, a more accurate work rate model for the swimming session can be created.

In some embodiments, data from a PPG heart rate sensor can also be used to provide a more accurate calorie determination. For example, as discussed in the co-pending U.S. patent application Ser. No. 15/466,397, titled "Techniques for Jointly Calibrating Load and Aerobic Capacity," the user's VO₂max 1722 and fractional heart rate 1724 can be determined. Based on the user's VO₂max 1722 and fractional heart rate 1724 and the work rate model 1720, a heart rate reliability 1726 and then a heart rate can be determined. In some embodiments, heart rate measurements can be more reliable in segments with small motion artifacts, for example, during glides or at the end of a lap. Based on this information, a heart rate model can be created.

Once both the work rate model 1720 and the heart rate model 1728 have been determined, and accordingly, a reliability of each of the models is determined, the appropriate model can be selected at model selection 1730. Model selection may depend upon errors in the stroke length, stroke rate, distance, and heart rate to determine which model is more accurate. Further, the models can be fused together to create a more accurate total of model of calorimetry.

Once the appropriate model for the swimming session has been determined, then the METs for that session also can be calculated.

FIG. 18 is a plot of normalized METs vs. fractional heart rate, according to some embodiments of the present disclosure. The y axis shows METs/VO₂max from 0.0 to 1.2 and the x axis is 1-Fractional Heart rate from 0.2 to 1.2. This plot shows a linear relationship between METs, normalized to VO₂max, and fractional heart rate.

One difficulty in estimating energy expenditure of a user while swimming is how to distinguish glides and strokes. Glide detection can help to achieve more accurate calorimetry. For example, glides can cover up to 25% of a lap distance for some swimmers, in particular, efficient, experienced swimmers. Therefore, ignoring glides could lead to overestimates in energy expenditure, because glides may correspond to lower energy expenditure rate (i.e., lower MET) compared to strokes.

Glide detection can also help with the classifications of swimming styles. Based on information related to glide times, stroke rates, stroke patterns, and times for turns, the user's movement can be assigned to different styles (e.g., freestyle stroke, breaststroke, backstroke, butterfly stroke, etc.)

Glide detection can also help to provide more accurate lap times to the user. If the wearable device 100 or the companion device 300 can determine if the user is gliding, or stroking, or turning, the lap time can then be broken up into different parts, e.g., turn time, glide time, and stroke time. In this way, the user can review the data and assess his or her performances in further detail.

FIG. 19 shows a method 1900 of detecting glides during swimming. In some embodiments, the detection method 1900 can use measurements data from a gyroscope 250 in the wearable device 100 (not shown). The gyroscope 250 may be a three-axis gyroscope that measures rotational data, such as rotational movement and/or angular velocity, in up to three-dimension (e.g., yaw, pitch, and roll). In some embodiments, the method 1900 can use measurements data from an accelerometer 260 in the wearable device 100. The accelerometer 260 may be a three-axis accelerometer that measures linear acceleration in up to three dimensions (e.g., x-axis, y-axis, and z-axis). In some embodiments, the

method **1900** can use measurements data from a pressure sensor **1930** (e.g., an altimeter or barometer) in the wearable device **100**. In some embodiments, wearable device **100** can include a classifier module **1940** (e.g., of the processor **210**) which may determine whether the user is gliding based on the measurements data.

In some embodiments, the gyroscope **250** can measure rotational data and can provide information related to a user's stroke rate **1911**. For example, during glides, a user usually does not stroke. Thus the angular velocity value measured by the gyroscope **250** may be smaller compared to angular velocity values measured during strokes. In some embodiments, the gyroscope **250** can provide information related to turns **1912**. For example, a small or close to zero angular velocity value can indicate the user is not making a turn. The information related to stroke rate **1911** and turns **1912** may be sent to the classifier **1940**.

In some embodiments, the accelerometer **260** can measure acceleration data and can provide information related to a pose **1913** of a user's wrist. For example, during gliding, the user usually keeps his or her wrists relatively still. Thus the direction of gravity remains relatively constant in the body-fixed frame of reference of the wearable device **100**. The pose of the user's wrist can be determined based on the gravity direction. The information related to pose **1913** may be sent to the classifier **1940**.

In some embodiments, the pressure sensor **1930** can measure pressure data and can provide information related to under water detection **1914**. For example, during gliding, the user usually keeps his or her hands and/or arms under water. Thus, the pressure sensor **1930** may sense higher pressure due to the pressure from the water, which generally will be greater than pressure from the air. If the pressure sensor **1930** includes an altimeter, it may show a drop in elevation. The information related to under water detection **1914** may be sent to the classifier **1940**. The under water detection **1914** can help to pick up spurious strokes while the user is not under water. For example, the user may walk around the pool or wipe hair, and the wearable device **100** may obtain rotational and acceleration data. However, the measurements by the pressure sensor **1930** may indicate the user may not be under water. Therefore, these strokes may not be regarded as swimming strokes.

In some embodiments, other methods can be used to detect if the user is under water. For example, wearable device **100** can have a pressure sensitive screen which can detect a pressure imposed on it. Based on the detected pressure, wearable device **100** and/or companion device **300** can determine if the user is under water. In some embodiments, wearable device **100** and/or companion device **300** can estimate a underwater depth based on the detected pressure.

In some embodiments, the classifier **1940** can determine whether or not the user is gliding based on the measurements data from one sensor or multiple sensors. The classifier **1940** can be a computer program executed by the processor in the wearable device **100** and/or the companion device **300** (not shown). The classifier **1940** can implement algorithms to classify the user's movements during a swimming session into different categories, e.g., glide **1941**, or not glide **1942**.

FIG. **20** shows a method **2000** for determining whether a user is making a turn and the user's stroke rate according to some embodiments of the present disclosure. The user's turning status and stroke rate may be determined and used to detect if the user is gliding. In some embodiments, method **2000** can be modified by, for example, having steps combined, divided, rearranged, changed, added, and/or removed.

In the example described herein, method **2000** is performed by processor **210** of wearable device **100**. However, in some embodiments, some or all steps may be performed by other elements (e.g., by a processor of a mobile device in communication with wearable device **100**). The method **2000** may begin at step **2010**.

At step **2010**, three-dimensional rotational information may be received at the main processor **210** or motion co-processor **215** from the gyroscope **250** on a wearable device (e.g., wearable device **100**) of a user. In some embodiments, rotational information may be filtered, such as by a low-pass filter, to remove unwanted noise from the ambient.

At step **2020**, main processor **210** may determine angular velocity of wearable device **100** with respect to a frame of reference such as a body-fixed frame of reference or an inertial frame of reference.

At step **2030**, main processor **210** may determine whether the user is making a turn from the angular velocity. If it is determined that the user is making a turn, the turn and stroke rate determination method **2000** may proceed to step **2040**. At step **2040**, the user's turning status may be outputted to the classifier of the processor **200** for further processing. The user's turning status may be one of the parameters the classifier uses to detect gliding.

If main processor **210** determines that the user is not making a turn, it may proceed to step **2050**. At step **2050**, the user's stroke rate can be determined based on the angular velocity collected from the gyroscope **250**. Then at step **2060**, the user's stroke rate may be outputted to the classifier for further processing. The user's stroke rate may be one of the parameters the classifier uses to detect gliding.

FIG. **21** shows a method **2100** for determining a pose of a user's wrist according to some embodiments of the present disclosure. The determined pose of the user's wrist may be used to detect gliding during swimming. In some embodiments, method **2100** can be modified by, for example, having steps combined, divided, rearranged, changed, added, and/or removed. In the example described herein, method **2100** is performed by main processor **210** of wearable device **100**. However, in some embodiments, some or all steps may be performed by other elements (e.g., by a processor of a mobile device in communication with wearable device **100**). Pose determination method **2100** may begin at step **2110**.

At step **2110**, three-dimensional acceleration information may be received at main processor **210** or motion co-processor **215** from the accelerometer **260** on a wearable device (e.g., wearable device **100**) of a user. In some embodiments, acceleration information may be filtered, such as by a low-pass filter, to remove unwanted noise from the ambient.

At step **2120**, main processor **210** or motion co-processor **215** may determine a direction of gravity relative to the wearable device **100** with respect to a frame of reference such as a body-fixed frame of reference or an inertial frame of reference.

At step **2130**, main processor **210** may determine the pose of the user's wrist from the acceleration information and the gravity direction. For example, the user's wrist may be in a position such that display surface of the wearable device **100** may faces up toward the sky, parallel with the ground.

At step **2140**, the pose information of the user's wrist may be outputted to the classifier of main processor **210** for further processing. The pose information may be one of the parameters the classifier uses to detect gliding.

FIG. 22 shows a method 2200 for determining if a user is under water according to some embodiments of the present disclosure. The determined under water status may be used to detect gliding during swimming. In some embodiments, method 2200 can be modified by, for example, having steps combined, divided, rearranged, changed, added, and/or removed. In the example described herein, method 2200 is performed by processor 210 of wearable device 100. However, in some embodiments, some or all steps may be performed by other elements (e.g., by a processor of a mobile device in communication with wearable device 100). Underwater determination method 2200 may begin at step 2210.

At step 2210, pressure information may be received at main processor 210 or motion co-processor 215 from a pressure sensor on a wearable device (e.g., wearable device 100) of a user. In some embodiments, pressure information may be filtered, such as by a low-pass filter, to remove unwanted noise.

At step 2220, main processor 210 may determine an elevation of the wearable device 100 based on the received pressure data.

At step 2230, main processor 210 may determine if the user is under water. For example, if the elevation of the wearable device 100 has a sudden decrease, possibly due to additional pressure from water, main processor 210 may determine the user is under water. If it is determined that the user is not under water, the status may be outputted to the classifier for further processing at step 2240. If it is determined that the user is under water, the status may be outputted to the classifier for further processing at step 2250. The status may be one of the parameters the classifier uses to detect gliding.

FIGS. 23A-23C show examples of measured data during a user's swimming session in a pool. The horizontal time axes in the three figures are synchronized. The dashed vertical lines mark the time when the user started from one end of the pool and the solid vertical lines mark the time when the user reached the other end of the pool. FIG. 23A shows the stroke rates as a function of time. The decrease in the stroke rate may be attributed to glides because most of the user's motions may be full body undulations during glides. FIG. 23B shows the measured elevation from the pressure sensor as a function of time. The elevation dips may correspond to glides because the user is under water during glides and the pressure increase leads to an observable decrease of elevation. As the user's hands exit the water, the pressure decreases and the elevation increases. FIG. 23C shows the pose information as a function of time. The pose of the user's wrist during the glide undulations is mostly in line with the horizon and under or above horizon during the strokes.

It is to be understood that the present disclosure is not limited in its application to the details of construction and to the arrangements of the components set forth in the description or illustrated in the drawings. The present disclosure is capable of other embodiments and of being practiced and carried out in various ways. In addition, it is to be understood that the phraseology and terminology employed herein are for the purpose of description and should not be regarded as limiting.

As such, those skilled in the art will appreciate that the conception, upon which this disclosure is based, may readily be utilized as a basis for the designing of other structures, systems, methods and media for carrying out the several purposes of the present disclosure. It is important, therefore, that the claims be regarded as including such equivalent

constructions insofar as they do not depart from the spirit and scope of the present disclosure.

Although the present disclosure has been described and illustrated in the foregoing exemplary embodiments, it is understood that the present disclosure has been made only by way of example, and that numerous changes in the details of implementation of the present disclosure may be made without departing from the spirit and scope of the present disclosure, which is limited only by the claims which follow.

What is claimed is:

1. A method for improving an accuracy of a wearable device while estimating energy expenditure of a user during a swimming session, the method comprising:

collecting, by a motion sensing module of a wearable device, motion data of the user;

determining, by a processor circuit of the wearable device, rotational data of the user based on the motion data;

counting, by the processor circuit, a number of strokes made by the user based on the set of rotational data;

estimating, by the processor circuit, a stroke rate of the user based on the number of strokes;

counting, by the processor circuit, a number of laps finished by the user based on the set of rotational data;

calculating, by the processor circuit, a stroke length based on the number of strokes, the number of laps finished, and a lap length associated with the swimming session;

calculating, by the processor circuit, a speed of the user based on the stroke rate and the stroke length;

estimating, by the processor circuit, an efficiency of the user based on at least one of the stroke length or a level of stroke orbit consistency of the user;

classifying, by the processor circuit, a swimming style of the user based on the set of rotational data;

determining, by the processor circuit, an energy expenditure of the user based on the speed, efficiency, and swimming style of the user; and

outputting, by the processor circuit, the determined energy expenditure of the user.

2. The method of claim 1, wherein the motion data is expressed in a first frame of reference and the rotation data is expressed in a second frame of reference.

3. The method of claim 1, comprising:

receiving, by the processor circuit, one or more inputs from the user, wherein the one or more inputs from the user comprise at least one of the user's gender, age, height, weight, or body mass index;

adjusting, by the processor circuit, the energy expenditure of the user based on the received one or more inputs; and

outputting, by the processor circuit, the adjusted energy expenditure of the user.

4. The method of claim 1, comprising:

measuring, by a heart rate sensing module of the user wearable device, a heart rate of the user;

determining, by the processor circuit, a fraction of heart rate reserve (FHR) of the user based on the measured heart rate;

estimating, by the processor circuit, the user's anaerobic energy expenditure based on at least one of the FHR, the stroke length, the stroke rate, or the speed; and

determining, by the processor circuit, the energy expenditure of the user based on the estimated anaerobic energy expenditure.

5. The method of claim 1, comprising:

measuring, by a heart rate sensing module of the wearable device, a heart rate of the user;

determining, by the processor circuit, a fraction of heart rate reserve (FHR) of the user based on the measured heart rate;

determining, by the processor circuit, a maximal oxygen uptake of the user; and

determining, by the processor circuit, a heart rate model based on FHR and the maximal oxygen uptake, wherein determining the energy expenditure of the user based on the heart rate model.

6. The method of claim 1, wherein calculating the speed of the user comprises:

receiving, by a GPS sensor of the wearable device, location data of the user during the swimming session; and

calculating, by the processor circuit, a stroke length and a speed of the user based on the received location data.

7. The method of claim 1, wherein the motion sensing module comprises at least one of a gyroscope or an accelerometer.

8. The method of claim 1, comprising:

detecting, by the processor circuit, one or more glides of the user during the swimming session; and

determining, by the processor circuit, the energy expenditure of the user based on the detected one or more glides.

9. The method of claim 8, wherein detecting the one or more glides of the user comprises:

determining, by the processor circuit, whether the user is making a turn based on the set of rotational data;

detecting, by the processor circuit, a pose angle of the user's wrist based on the set of rotational data;

determining, by the processor circuit, whether the user is under water using pressure data received from a pressure sensor of the wearable device; and

detecting, by the processor circuit, one or more glides of the user based on the stroke rate, the pose of the user's wrist, whether the user is making a turn, and whether the user is under water.

10. The method of claim 9, wherein detecting a pose angle of the user's wrist comprises:

determining, by the processor circuit, a direction of gravity relative to the user device based on the motion data;

detecting, by the processor circuit, a pose angle of the user's wrist based on the direction of gravity.

11. The method of claim 9, wherein determining whether the user is under water comprises:

determining, by the processor circuit, an elevation of the wearable device based on the pressure data; and

determining, by the processor circuit, whether the user is under water based on the determined elevation.

12. A system for improving an accuracy of a wearable device while estimating energy expenditure of a user during a swimming session, the system comprising:

a motion sensing module configured to collect motion data of the user;

a processor circuit in communication with the motion sensing module and configured to execute instructions causing the processor circuit to:

determine rotational data of the user base on the motion data;

count a number of strokes made by the user based on the set of rotational data;

estimate a stroke rate of the user based on the number of strokes;

count a number of laps finished by the user based on the set of rotational data;

estimate a stroke length based on the number of strokes, the number of laps finished, and a lap length associated with the swimming session;

estimate a speed of the user based on the stroke rate and the stroke length;

estimate efficiency of the user based on at least one of the stroke length or a level of stroke orbit consistency of the user;

classify a swimming style of the user based on the set of rotational data;

determine an energy expenditure of the user based on the speed, efficiency, and swimming style of the user; and

output the determined energy expenditure of the user.

13. The system of claim 12, wherein the instructions further cause the processor circuit to:

receive one or more inputs from the user, wherein the one or more inputs from the user comprise at least one of the user's gender, age, height, weight, or body mass index;

adjust the determined energy expenditure of the user based on the received one or more inputs; and

output the adjusted energy expenditure of the user.

14. The system of claim 12, further comprising a heart rate sensing module configured to measure a heart rate of the user.

15. The system of claim 14, wherein the instructions further cause the processor circuit to:

determine, a fraction of heart rate reserve (FHR) of the user based on the measured heart rate; determine, a maximal oxygen uptake of the user;

determine, a heart rate model based on the FHR and the maximal oxygen uptake; and

determine, the energy expenditure of the user based on the heart rate model.

16. The system of claim 12, further comprising a GPS sensor configured to receive location data of the user.

17. The system of claim 16, wherein the instructions further cause the processor circuit to:

estimate a stroke length and a speed of the user based on the received location data of the user.

18. The system of claim 12, wherein the motion sensing module comprises at least one of a gyroscope or an accelerometer.

19. The system of claim 12, wherein the instructions further cause the processor circuit to:

determine whether the user is making a turn based on the set of rotational data;

detect a pose of the user's wrist based on the set of rotational data;

determine whether the user is under water based on pressure data received from a pressure sensor of the wearable device;

determine whether the user is gliding while swimming based on the stroke rate, the pose of the user's wrist, whether the user is making a turn, and whether the user is under water;

adjust the energy expenditure of the user based on the determined glide; and

output the adjusted energy expenditure of the user.

专利名称(译)	游泳量热系统和方法		
公开(公告)号	US10617912	公开(公告)日	2020-04-14
申请号	US15/692237	申请日	2017-08-31
[标]申请(专利权)人(译)	苹果公司		
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当前申请(专利权)人(译)	苹果公司.		
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IPC分类号	A63B24/00 A61B5/11 A61B5/00 A61B5/0205 A61B5/024		
CPC分类号	A63B24/0006 A61B5/1114 A63B24/0062 A61B5/1121 A61B5/1112 A61B5/7278 A61B5/7221 A61B5/0205 A61B5/7475 A61B5/681 A61B5/1123 A61B5/4866 A61B5/02438 A61B5/7264 A63B2220/30 A63B2220/03 A63B2220/803 A63B2220/12 A63B2220/73 A63B2230/06 A63B2230/75 A63B2220/56 A61B2562/0219 A63B2024/0071 A63B2220/74 A63B2225/50 A63B2220/17 A63B2220/836 A61B5/1118 G06K9/00342 G06K9/00355 G16H50/20		
优先权	62/382060 2016-08-31 US 62/478900 2017-03-30 US		
其他公开文献	US20180056129A1		
外部链接	Espacenet		

摘要(译)

本公开涉及估计使用者游泳时的能量消耗的系统和方法。用户设备的处理器电路可以基于笔划速率和笔划长度来估计用户的速度。处理器电路可以估计用户的效率。处理器电路可以对用户的游泳方式进行分类。处理器电路可以基于速度，效率和样式来确定用户的能量消耗。处理器电路还可以检测用户的滑行并调节能量消耗。

