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(54) **Title**: NON-INVASIVE CONTINUOUS BLOOD PRESSURE MONITORING WITH REDUCED MOTION ARTIFACTS

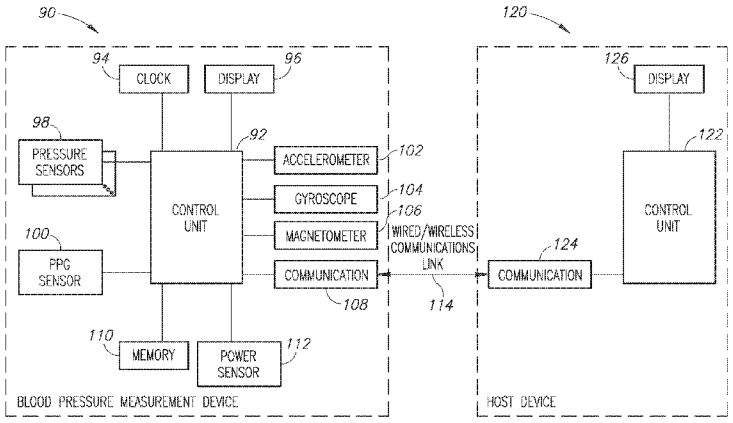

FIG. 5

(57) **Abstract**: A novel and useful system and method of non-invasively and continuously sensing and measuring blood pressure based on direct pressure sensing of one or more of the hand arteries including the radial, ulnar and/or brachial arteries. Accuracy is greatly enhanced by countering natural motion artifacts obtained with direct measurement by using one or more motion artifact mechanisms. Several mechanisms are disclosed including an avoidance mechanism wherein blood pressure readings are ignored during active periods; a calibration mechanism wherein pressure sensor data from the user's brachial artery is used to improve the accuracy of the data from sensors on the user's ulnar and/or radial arteries; and a cancellation mechanism wherein motion sensor data is processed and subtracted from pressure sensor data. All three of the above, alone or in combination yield a blood pressure waveform with reduced motion artifacts.

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NON-INVASIVE CONTINUOUS BLOOD PRESSURE MONITORING WITH REDUCED MOTION ARTIFACTS

FIELD OF THE DISCLOSURE

[0001] The subject matter disclosed herein relates to the field of biological sensing and more particularly relates to a mechanism for non-invasive continuous blood pressure measurement with reduced motion artifacts, the monitoring of other physiological parameters and to a wearable device incorporating blood pressure monitoring.

BACKGROUND OF THE INVENTION

[0002] The following discussion of the background to the invention is intended to facilitate an understanding of the present invention. However, it should be appreciated that the discussion is not an acknowledgment or admission that any of the material referred to was published, known or part of the common general knowledge in any jurisdiction as of the priority date of the application.

[0003] The use of wearable devices for monitoring body physiological parameters (e.g. blood pressure (blood pressure), heart rate (HR) pulse, body temperature, blood glucose level, movement patterns, etc.) non-invasively, continuously and/or intermittently for extended periods of time are becoming popular as a way to monitor and improve health.

[0004] Traditional blood pressure measurements require inflatable cuffs, which are gradually deflated from a state of full vessel occlusion to a lower pressure while listening using a mechanical sensor (e.g., stethoscope) to the sounds generated by the blood eddies in the vessel. The advantage of this method is its relative robustness to movements, while the major disadvantage is its large form factor and the need for either user manual inflation or an automatic

pump, which requires large quantities of energy. Since energy efficiency and small form factor are major requirements in wearable devices, inflatable cuff blood pressure sensing is not a useful paradigm in this space.

[0005] There is thus a need for a mechanism of continuously measuring and monitoring blood pressure that overcomes the disadvantages of traditional prior art method. For example, it is advantageous to have a mechanism of measuring blood pressure that does not require the use of a cuff with its associated high energy requirements. In addition, the mechanism should be able to sense the blood pressure waveform on one or more of the arteries in the arm (i.e. the radial and ulnar arteries) while significantly reducing or eliminating motion artifacts from the waveform.

SUMMARY OF THE INVENTION

[0006] The present invention is a system for and method of non-invasive continuous blood pressure measurement with reduced motion artifacts, the monitoring of other physiological parameters and to a wearable device incorporating blood pressure monitoring. The present invention relies on direct pressure sensing of one or more of the radial, ulnar or brachial arteries on the wrist or hand. Pressure sensing data is obtained by locating at least one sensitive pressure sensor upon the radial, ulnar and/or brachial artery. The pressure sensed is related to the blood pressure in the arteries and generally referred to as a blood pressure waveform.

[0007] Blood pressure measurement accuracy is greatly enhanced by countering natural motion artifacts obtained with direct measurement by using one or more motion artifact mechanisms. Several mechanisms are disclosed including an avoidance mechanism wherein blood pressure readings are ignored during active periods; a calibration mechanism wherein pressure sensor data from the user's brachial artery is used to improve the accuracy of the data from sensors on the user's ulnar and/or radial arteries; and a cancellation mechanism wherein motion sensor data is processed and subtracted from pressure sensor data. All three of the above, alone or in combination yield a blood pressure waveform with reduced motion artifacts

[0008] Blood pressure sensing is based on direct pressure sensing of one or more of the hand arteries. An advantage of the present invention is that it counters natural notion artifacts obtained with such direct measurement using either an avoidance method and/or a cancellation method. Furthermore, in one embodiment, calibration of the blood pressure waveform obtained from the radial and/or ulnar arteries is calibrated with pressure sensed from the brachial artery by either direct pressure sensing or cuff based measurements.

[0009] In one embodiment of the present invention, the blood pressure waveform derived from direct pressure sensing on a hand artery is either discarded or sent for further processing (e.g.,

display, storage or analysis) using motion sensing data received from a motion detection sensor and activity detection subsequently generated therefrom.

[0010] In another embodiment, an accelerometer, gyroscope or magnetometer is used to detect motion by computing a variation index or interquartile range of acceleration measurements collected during a period of time, and comparing it to a predetermined threshold. When no motion is detected for a period of time, e.g., variation index or interquartile range are below the predefined threshold, rest is declared. All non-rest periods are considered undesirable for blood pressure waveform measurement.

[0011] In another embodiment, direct pressure sensing is applied to a hand artery yielding blood pressure waveform data. Concurrently, movement correlated data is collected from a device such as an accelerometer, gyroscope or magnetometer. Movement correlated data is filtered and subtracted from the blood pressure waveform yielding a clean or motion compensated blood pressure waveform, which is then further processed (e.g., display, storage or analysis).

[0012] In another embodiment of the present invention, the blood pressure waveform coming from direct pressure sensing on the radial and/or ulnar arteries is first calibrated against pressure sensed from the brachial artery. Concurrently, motion correlated data is collected from a motion measurement device (e.g., accelerometer, gyroscope and magnetometer) and activity detection processing is performed on movement correlated data. The calibrated blood pressure waveform is then either discarded or sent for further processing (e.g., display, storage or analysis) depending on the extent of activity detected.

[0013] In a further embodiment, the blood pressure waveform signal from direct pressure sensing on the radial and/or ulnar arteries is first calibrated against pressure sensed from the brachial artery. Concurrently, motion correlated data is collected from a device such as an

accelerometer, gyroscope or magnetometer. The motion correlated data is filtered and subtracted from the calibrated blood pressure waveform yielding a clean, calibrated blood pressure waveform, which is sent for further processing (e.g., display, storage or analysis).

[0014] In one embodiment, an apparatus is provided that comprises a wearable incorporating a blood pressure waveform measurement module. The wearable can directly detect pressure from a hand artery, process the pressure data and provide blood pressure waveform data over a communication link. Optionally, the wearable also incorporates a photo plethysmograph (PPG) device for detecting a user's heart rate.

[0015] In another embodiment, the blood pressure waveform measurement module or a wearable containing it can communicate with a host unit and transmit blood pressure waveform samples, blood pressure measurements, telemetry data and/or any other desired data (e.g., battery status, heart rate, etc.) over a wired or wireless or a wired communications link.

[0016] In another embodiment, systolic and/or diastolic blood pressure measurements are obtained for sensed blood pressure waveform data by extracting a feature set (e.g., rise/fall times, amplitude, variance, inter-event durations, etc.) and filtering and/or combining the feature set with a set of coefficients. In one embodiment, the coefficients are trained using any suitable method such as linear or nonlinear estimation, machine learning, etc.

[0017] In one embodiment, the blood pressure measurement mechanism of the present invention is incorporated in a wearable device such as a health monitoring device, fitness band, media player, communication device, smartwatch, or other portable electronic device.

[0018] There is thus provided in accordance with the invention, a method of reducing motion artifacts in a blood pressure measurement device, the method comprising sensing pressure from at least one of a user's radial, ulnar and brachial arteries utilizing at least one pressure sensor to

yield a blood pressure waveform therefrom, measuring the user's motion utilizing at least one motion sensor to yield movement correlated data therefrom, detecting activity from the movement correlated data and generating an activity indication signal thereby, and discarding the blood pressure waveform when the activity indication signal exceeds a predetermined threshold.

[0019] There is also provided in accordance with the invention, a method of reducing motion artifacts in a blood pressure measurement device, the method comprising sensing pressure from at least one of a user's radial, ulnar and brachial arteries utilizing at least one pressure sensor to yield a blood pressure waveform therefrom, measuring the user's motion utilizing at least one motion sensor to yield motion correlated data therefrom, filtering the motion correlated data to yield filtered motion correlated data therefrom, and subtracting the filtered motion correlated data from the blood pressure waveform to yield clean blood pressure waveform data thereby.

[0020] There is further provided in accordance with the invention, a method of reducing motion artifacts in a blood pressure measurement device, the method comprising first sensing pressure from at least one of a user's radial and ulnar arteries utilizing a first at least one pressure sensor to yield a first blood pressure waveform therefrom, second sensing pressure from the user's brachial artery utilizing a second at least one pressure sensor to yield a second blood pressure waveform therefrom, measuring the user's motion utilizing at least one motion sensor to yield movement correlated data therefrom, calibrating the first blood pressure waveform using the second blood pressure waveform to yield a calibrated blood pressure waveform therefrom, detecting activity from the movement correlated data and generating an activity indication signal thereby, and discarding the calibrated blood pressure waveform when the activity indication signal exceeds a predetermined threshold.

[0021] There is also provided in accordance with the invention, a method of reducing motion artifacts in a blood pressure measurement device, the method comprising first sensing pressure from at least one of a user's radial and ulnar arteries utilizing a first at least one pressure sensor to yield a first blood pressure waveform therefrom, second sensing pressure from the user's brachial artery utilizing a second at least one pressure sensor to yield a second blood pressure waveform therefrom, measuring the user's motion utilizing at least one motion sensor to yield movement correlated data therefrom, calibrating the first blood pressure waveform using the second blood pressure waveform to yield a calibrated blood pressure waveform therefrom, filtering the motion correlated data to yield filtered motion correlated data therefrom, and subtracting the filtered motion correlated data from the correlated blood pressure waveform to yield clean, calibrated blood pressure waveform data thereby.

[0022] There is further provided in accordance with the invention, a wearable device, comprising a housing, a circuit disposed within the housing, the circuit, comprising a processor, a memory coupled to the processor, a communication module coupled to the processor, a blood pressure measurement mechanism coupled to the processor, the blood pressure measurement mechanism comprising at least one pressure sensor operative to sense pressure from one or more of a user's brachial, radial and ulnar arteries, at least one motion sensor operative to detect periods of user activity and rest, and wherein the processor is configured to implement one or more of an avoidance mechanism, cancellation mechanism and a calibration mechanism utilizing the blood pressure measurement mechanism.

BRIEF DESCRIPTION OF THE DRAWINGS

[0023] The invention is herein described, by way of example only, with reference to the accompanying drawings, wherein:

[0024] Fig. 1 is a diagram illustrating an example wearable device incorporating the blood pressure measurement mechanism of the present invention mounted on a user's wrist;

[0025] Fig. 2 is a diagram illustrating pressure sensors incorporated within a wearable device and configured to sense pressure from the radial and/or the ulnar artery;

[0026] Fig. 3 is a diagram illustrating a side view of an example wearable device incorporating the blood pressure measurement mechanism of the present invention;

[0027] Fig. 4 is a high level block diagram illustrating an example wearable electronic device incorporating the blood pressure measurement mechanism of the present invention;

[0028] Fig. 5 is a high level block diagram illustrating an example blood pressure measurement device such as a wearable in communication with an optional host device;

[0029] Fig. 6 is a graph illustrating an example motion sensing signal generated by a user during active and rest periods;

[0030] Fig. 7 is a diagram illustrating an example mechanism for rejecting motion artifact ridden blood pressure waveform samples utilizing motion measurements;

[0031] Fig. 8 is a flow diagram illustrating an example method of identifying time slots suitable for blood pressure waveform measurements that do not have motion artifacts;

[0032] Fig. 9 is a diagram illustrating an example mechanism that utilizes motion sensing measurements to cancel out artifacts in pressure sensor derived blood pressure waveform data;

[0033] Fig. 10 is a diagram illustrating an example mechanism that utilizes pressure sensor data from the brachial artery to calibrate blood pressure waveform readings and also uses motion measurements to reject motion artifact ridden blood pressure waveform samples; and

[0034] Fig. 11 is a diagram illustrating an example mechanism that calibrates blood pressure waveform readings utilizing pressure sensor data from the brachial artery and also cancels out artifacts from blood pressure waveform data using motion measurements.

DETAILED DESCRIPTION

[0035] In the following detailed description, numerous specific details are set forth in order to provide a thorough understanding of the invention. It will be understood by those skilled in the art, however, that the present invention may be practiced without these specific details. In other instances, well-known methods, procedures, and components have not been described in detail so as not to obscure the present invention.

[0036] The subject matter regarded as the invention is particularly pointed out and distinctly claimed in the concluding portion of the specification. The invention, however, both as to organization and method of operation, together with objects, features, and advantages thereof, may best be understood by reference to the following detailed description when read with the accompanying drawings.

[0037] It will be appreciated that for simplicity and clarity of illustration, elements shown in the figures have not necessarily been drawn to scale. For example, the dimensions of some of the elements may be exaggerated relative to other elements for clarity. Further, where considered appropriate, reference numerals may be repeated among the figures to indicate corresponding or analogous elements.

[0038] Because the illustrated embodiments of the present invention may for the most part, be implemented using electronic components and circuits known to those skilled in the art, details will not be explained in any greater extent than that considered necessary, for the understanding and appreciation of the underlying concepts of the present invention and in order not to obfuscate or distract from the teachings of the present invention.

[0039] Any reference in the specification to a method should be applied mutatis mutandis to a system capable of executing the method. Any reference in the specification to a system should be applied mutatis mutandis to a method that may be executed by the system.

[0040] The description that follows includes sample devices, components, modules, systems, methods, and apparatuses that embody various elements of the present invention. It should be understood, however, that various elements of the invention may be combined and/or practiced in a variety of forms in addition to those described herein. In particular, the modules and components are described in a particular combination with respect to some examples provided below. Other combinations are possible, however, which may be achieved by adding, removing, and/or rearranging modules to obtain a device or system having the desired characteristics.

[0041] As will be appreciated by one skilled in the art, the algorithm portion of the present invention may be embodied as a system, method, computer program product or any combination thereof. Accordingly, the present invention may take the form of an entirely hardware embodiment, an entirely software embodiment (including firmware, resident software, micro-code, etc.) or an embodiment combining software and hardware aspects that may all generally be referred to herein as a "circuit," "module" or "system." Furthermore, the present invention may take the form of a computer program product embodied in any tangible medium of expression having computer usable program code embodied in the medium.

[0042] The algorithms may be described in the general context of computer-executable instructions, such as program modules, being executed by a computer. Generally, program modules include routines, programs, objects, components, data structures, etc. that perform particular tasks or implement particular abstract data types. The algorithms may also be practiced in distributed computing environments where tasks are performed by remote

processing devices that are linked through a communications network. In a distributed computing environment, program modules may be located in both local and remote computer storage media including memory storage devices.

[0043] Any combination of one or more computer usable or computer readable medium(s) may be utilized. The computer-usable or computer-readable medium may be, for example but not limited to, an electronic, magnetic, optical, electromagnetic, infrared, or semiconductor system, apparatus, device, or propagation medium. More specific examples (a non-exhaustive list) of the computer-readable medium would include the following: an electrical connection having one or more wires, a portable computer diskette, a hard disk, a random access memory (RAM), a read-only memory (ROM), an erasable programmable read-only memory (EPROM or flash memory), an optical fiber, a portable compact disc read-only memory (CDROM), an optical storage device, a transmission media such as those supporting the Internet or an intranet, or a magnetic storage device. Note that the computer-usable or computer-readable medium could even be paper or another suitable medium upon which the program is printed, as the program can be electronically captured, via, for instance, optical scanning of the paper or other medium, then compiled, interpreted, or otherwise processed in a suitable manner, if necessary, and then stored in a computer memory. In the context of this document, a computer-usable or computer-readable medium may be any medium that can contain or store the program for use by or in connection with the instruction execution system, apparatus, or device.

[0044] Computer program code for carrying out operations of the present invention may be written in any combination of one or more programming languages, including an object oriented programming language such as Java, Smalltalk, C++, C# or the like, conventional procedural programming languages, such as the “C” programming language, and functional programming

languages such as Prolog and Lisp, machine code, assembler or any other suitable programming languages. The program code may execute entirely on the user's computer, partly on the user's computer, as a stand-alone software package, partly on the user's computer and partly on a remote computer or entirely on the remote computer or server. In the latter scenario, the remote computer may be connected to the user's computer through any type of network using any type of network protocol, including for example a local area network (LAN) or a wide area network (WAN), or the connection may be made to an external computer (for example, through the Internet using an Internet Service Provider).

[0045] The present invention is described below with reference to flowchart illustrations and/or block diagrams of methods, apparatus (systems) and computer program products according to embodiments of the invention. It will be understood that each block of the flowchart illustrations and/or block diagrams, and combinations of blocks in the flowchart illustrations and/or block diagrams, can be implemented or supported by computer program instructions. These computer program instructions may be provided to a processor of a general purpose computer, special purpose computer, or other programmable data processing apparatus to produce a machine, such that the instructions, which execute via the processor of the computer or other programmable data processing apparatus, create means for implementing the functions/acts specified in the flowchart and/or block diagram block or blocks.

[0046] These computer program instructions may also be stored in a computer-readable medium that can direct a computer or other programmable data processing apparatus to function in a particular manner, such that the instructions stored in the computer-readable medium produce an article of manufacture including instruction means which implement the function/act specified in the flowchart and/or block diagram block or blocks.

[0047] The computer program instructions may also be loaded onto a computer or other programmable data processing apparatus to cause a series of operational steps to be performed on the computer or other programmable apparatus to produce a computer implemented process such that the instructions which execute on the computer or other programmable apparatus provide processes for implementing the functions/acts specified in the flowchart and/or block diagram block or blocks.

[0048] The invention is operational with numerous general purpose or special purpose computing system environments or configurations. Examples of well-known computing systems, environments, and/or configurations that may be suitable for use with the invention include, but are not limited to, wearable computing devices such as smartwatches or fitness bands, personal computers, server computers, cloud computing, hand-held or laptop devices, multiprocessor systems, microprocessor, microcontroller or microcomputer based systems, set top boxes, programmable consumer electronics, ASIC or FPGA core, DSP core, network PCs, minicomputers, mainframe computers, distributed computing environments that include any of the above systems or devices, and the like.

[0049] In addition, the invention is operational in systems incorporating sensors such as found in automated factories, in wearable devices such as fitness bands or smartwatches, in mobile devices such as tablets and smartphones, smart meters installed in the power grid and control systems for robot networks. In general, any computation device that can host an agent can be used to implement the present invention.

[0050] The flowchart and block diagrams in the Figures illustrate the architecture, functionality, and operation of possible implementations of systems, methods and computer program products according to various embodiments of the present invention. In this regard, each block in the

flowchart or block diagrams may represent a module, segment, or portion of code, which comprises one or more executable instructions for implementing the specified logical function(s). It should also be noted that, in some alternative implementations, the functions noted in the block may occur out of the order noted in the figures. For example, two blocks shown in succession may, in fact, be executed substantially concurrently, or the blocks may sometimes be executed in the reverse order, depending upon the functionality involved. It will also be noted that each block of the block diagrams and/or flowchart illustration, and combinations of blocks in the block diagrams and/or flowchart illustration, can be implemented by special purpose hardware-based systems that perform the specified functions or acts, or by combinations of special purpose hardware and computer instructions.

Wearable Device Incorporating the Blood Pressure Measurement Mechanism

[0051] A diagram illustrating an example wearable device incorporating the blood pressure measurement mechanism of the present invention mounted on a user's wrist is shown in Figure 1. The wearable consumer product device, generally referenced 16. In one example, the device 16 is a wearable multifunctional electronic device including multiple functionalities such as time keeping, health monitoring, sports monitoring, medical monitoring, communications to a host device and/or a cloud server, navigation, computing operations, and/or the like. The functionalities may include but are not limited to: keeping time; monitoring a user's physiological signals (e.g., heart rate, blood pressure, etc.) and providing health-related information based on those signals; communicating (in a wired or wireless fashion) with other electronic devices or services, which may be different types of devices having different functionalities; providing alerts to a user, which may include audio, haptic, visual and/or other sensory output, any or all of which may be synchronized with one another; visually depicting

data on a display; gathering data form one or more sensors that may be used to initiate, control, or modify operations of the device; determining a location of a touch on a surface of the device and/or an amount of force exerted on the device, and using either or both as input; accepting voice input to control one or more functions; accepting tactile input to control one or more functions; capturing and transmitting images; and so on.

[0052] The device 16 can take a variety of forms. In one example, the device is a wrist worn electronic device. The device may include a variety of types of form factors including, wristbands, armbands, bracelets, jewelry, and/or the like.

[0053] A wearable consumer product is one that can be worn by or otherwise secured to a user. Note that a wearable consumer product can be worn by a user in a variety of ways such as around the wrist. In this case, the device includes a band or wrist strap that can be wrapped around a user's wrist to secure the device to the user's body. The device may include one or more other types of attachments including, for example, an armband, lanyard, waistband, chest strap, etc.

[0054] In one embodiment, the device 16 comprises a device body 18. The device body may include a housing that carries, encloses and supports both externally and internally various components (including, for example. integrated circuit chips and other circuitry) to provide computing and functional operations for the device 16. The components may be disposed on the outside of the housing, partially within the housing, through the housing, completely inside the housing, and the like. The housing may, for example, include a cavity for retaining components internally, holes or windows for providing access to internal components, and various features for attaching other components. The housing may also be configured to form a water resistant or waterproof enclosure for the body 18. For example, the housing may be formed from as a single

unitary body and the openings in the unitary body may be configured to cooperate with other components to form a water-resistant or waterproof barrier. In another embodiment, the housing may not comprise a cavity but rather is constructed from plastic where the device electronics are molded into the plastic.

[0055] Examples of components that may be contained in the device body 18 include processing units, memory, display, sensors, biosensors, speakers, microphones, haptic actuators, batteries, and so on. In some cases, the device body 18 may take on a small form factor. In cases such as these, the components may be packaged and/or in order to provide the most functionality in the smallest space. The components may also be configured to take up a minimal amount of space, which may facilitate the device body 18 having a small form factor. Additionally, the integration and assembly of the various components may be configured to enhance the reliability of the device 16.

[0056] The construction of the housing of the device body 18 may be widely varied. For example, housing may be formed from a variety of materials including plastic, rubber, wood, silicone, glass, ceramics, fiber composites, metal or metal alloys, (e.g., stainless steel, aluminum), precious metals (e.g., gold, silver), or other suitable materials, or a combination of these materials.

[0057] Also in the illustrated embodiment, the wearable electronic device includes a band 14 or strap or other means for attaching to a user's arm 10. The band may, for example, be configured to attach to the body and provide a loop for securing to the wrist of the user. The band may be integral with the housing or it may be a separate part. If integral, the band can be a continuation of the housing. In some cases, the integral band may be formed from the same material as the housing. If the band is separate, the band may be fixed or releasably coupled to the housing. In

both cases, the band may be formed from similar or different materials as the housing. In most cases, the band is formed from a flexible material such that it can conform to a user's body. Furthermore, the band itself may be a single integral part or it may include attachment ends that provide an open and closed configuration. The attachment ends may, for example, be manifested as a clasp or other similar attachment mechanism or device. This particular configuration allows a user to open the band for placement on the arm and close the band in order to secure the band and body to the arm. The band may be widely varied. By way of example, they may be formed from rubber, silicone, leather, metal, mesh, links and/or the like.

[0058] A diagram illustrating pressure sensors incorporated within a wearable device and configured to sense pressure from the radial and/or the ulnar artery is shown in Figure 2. The wearable device 14 is shown fastened to a user's wrist portion of their arm 10. In accordance with the present invention, the wearable incorporates a blood pressure measurement mechanism, described in more detail infra. In the example embodiment shown, one or more of the wrist straps 14 of the device 16 includes one or more pressure sensors 24, 26 adapted to sense pressure of the radial 28 and/or ulnar 30 arteries.

[0059] A diagram illustrating a side view of an example wearable device incorporating the blood pressure measurement mechanism of the present invention is shown in Figure 3. The wearable device 16, comprises a housing 18, one or more buttons, switches or dials 44, wrist band 14, clasp or fastening mechanism 43 and pressure sensors 24, 26 adapted to sense pressure of the radial 28 and/or ulnar 30 arteries.

[0060] A high level block diagram illustrating an example wearable electronic device incorporating the blood pressure measurement mechanism of the present invention is shown in Figure 4. By way of example, device 50 may correspond to the consumer product 16 shown in

Figures 1, 2 and 3. To the extent that multiple functionalities, operations, and structures are disclosed as being part of, incorporated into, or performed by device 50, it should be understood that various embodiments may omit any or all such described functionalities, operations, and structures. Thus, different embodiments of the device 50 may have some, none, or all of the various capabilities, apparatuses, physical features, modes, and operating parameters discussed herein.

[0061] The device 50 comprises one or more processing units 52 that are configured to access a memory 56 having instructions stored thereon. The instructions or computer programs may be configured to perform one or more of the operations or functions described with respect to the device 50. For example, the instructions may be configured to control or coordinate the operation of a display 64, one or more input/output components such as the touch sensor 60, etc., one or more communication channels 70, one or more sensors such as biological sensors 74 and non-biological sensors 78, a speaker 66, a microphone 62 and/or one or more haptic feedback devices 68.

[0062] The processing units 52 may be implemented as any electronic device capable of processing, receiving, or transmitting data or instructions. For example, the processing units may include one or more of: a microprocessor, a central processing unit (CPU), an application-specific integrated circuit (ASIC), a digital signal processor (DSP), or combinations of such devices. As described herein, the term “processor” is meant to encompass a single processor or processing unit, multiple processors, multiple processing units, or other suitably configured computing element or elements.

[0063] For example, the processor may comprise one or more general purpose CPU cores and optionally one or more special purpose cores 16 (e.g., DSP core, floating point, etc.). The one or

more general purpose cores execute general purpose opcodes while the special purpose cores execute functions specific to their purpose.

[0064] The memory 56 comprises dynamic random access memory (DRAM) or extended data out (EDO) memory, or other types of memory such as ROM, static RAM, flash, and non-volatile static random access memory (NVSRAM), removable memory, bubble memory, etc., or combinations of any of the above The memory stores electronic data that can be used by the device. For example, a memory can store electrical data or content such as, for example, audio and video files, documents and applications, device settings and user preferences, timing and control signals or data for the various modules, data structures or databases, and so on. The memory can be configured as any type of memory.

[0065] The display 64 functions to present visual or graphical output to a user. In some embodiments, the display includes a graphical user interface produced using an operating system or software application executed on one or more processing units of the device. In one example, the display includes a graphical depiction that resembles a watch face or other timekeeping device. In other examples, the display includes a graphical interface for an e-mail, text messaging, or other communication-oriented program. The display may also present visual information that corresponds to one of the other functional aspects of the device 50. For example, the display may include information that corresponds to the input of the biosensor 74, non-biosensor 78, force sensor 59, touch sensor 60, and others.

[0066] Input components 72 may include buttons, switches, dials, and crowns for accepting user input, and so on. Generally, the input components are configured to translate a user provided input into a signal or instructions that may be accessed using instructions executed on the processor. In the present example, the input components may include the hardware configured to

receive the user input (e.g., button, switch, crown, and encoder) which is operatively coupled to circuitry and firmware used to generate signals or data that are able to be accessed using processor instructions. Each input component may include specialized circuitry for generating signals or data and, additionally or alternatively, circuitry and firmware for generating signals or data may be shared between multiple input components. In some cases, the input components produce user provided feedback for application specific input that corresponds to a prompt or user interface object presented on display 64. For example, a crown may be used to receive rotational input from the user, which may be translated into an instruction to scroll a list or object presented on the display. The input components may also produce user input for system level operations. For example, the input components may be configured to interact directly with hardware or firmware being executed on the device for system level operations, including, without limitation, power on, power off, sleep, awake, and do-not-disturb operations.

[0067] The device 50 may also comprise one or more acoustic elements, including audio outputs 66 (e.g., speaker, headphone jack, etc.) and a microphone 62. The audio output 66 may include drive electronics or circuitry and may be configured to produce an audible sound or acoustic signal in response to a command or input. Similarly, the microphone may also include drive electronics or circuitry and is configured to receive an audible sound or acoustic signal in response to a command or input. The speaker and the microphone may be acoustically coupled to respective ports or openings in the housing that allow acoustic energy to pass, but may prevent the ingress of liquid and other debris.

[0068] The speaker and microphone are also operatively coupled to the processor, which may control the operation of the speaker and microphone. In some cases, the processor is configured to operate the speaker to produce an acoustic output that corresponds to an application or system-

level operation being performed on the device 50. In some cases, the speaker is operatively coupled to other modules, including, for example, input components 72, such as a crown or button. In some implementations, the device is configured to produce an audible output that corresponds to the operation of the crown or buttons using the speaker. The microphone may be configured to produce an output or signal in response to an acoustic stimulus. For example, the microphone may be operatively coupled to the memory 56 and may be configured to record audio input, including human speech, music, or other sounds. In some cases, the microphone may be configured to receive voice signals, which may be interpreted as voice commands by the processor.

[0069] The one or more communication channels 70 may include one or more wired and/or wireless interface(s) that are adapted to provide communication between the processor 52 and an external device such as a host device 120 (Figure 5). In general, the one or more communication channels may be configured to transmit and receive data and/or signals that may be interpreted by instructions executed on the processor. In some cases, the external device is part of an external communication network that is configured to exchange data with wireless devices. Generally, the wireless interface may include, without limitation, radio frequency, optical, acoustic, and/or magnetic signals and may be configured to operate over a wireless interface or protocol. Example wireless interfaces include radio frequency cellular interfaces, fiber optic interfaces, acoustic interfaces, Bluetooth interfaces (e.g., Bluetooth, Bluetooth Low Energy, etc.), infrared interfaces, USB interfaces, Wi-Fi interfaces, TCP/IP interfaces, network communications interfaces, or any conventional communication interfaces.

[0070] In some implementations, the one or more communications channels may include a dedicated wireless communication channel between the device and another user device, such as a

mobile phone, tablet, computer, host device, or the like. In some cases, output, including audio sounds or visual display elements, are transmitted directly to the other user device for output to the user. For example, an audible alert or visual warning may be transmitted to a user's mobile phone for output on that device. Similarly, the one or more communications channels may be configured to receive user input provided on another user device. In one example, the user may control one or more operations on the device using a user interface on an external mobile phone, table, computer, or the like.

[0071] Additionally, the communications channels 70 may include a near field communication (NFC) interface. The NFC interface may be used to identify the device and initiate a secure data connection, which may be used to authorize transactions, purchases, or conduct other forms of e-commerce.

[0072] The device 50 also comprises one or more biological 74 and non-biological 78 sensors. Non biological sensors 78 may include one or more different sensors, including devices and components that are configured to detect environmental conditions and/or other aspects of the operating environment. Examples include an ambient light sensor (ALS), proximity sensor, temperature sensor, barometric pressure sensor, moisture sensor, and the like. Thus, the non-biological 78 sensors may also be used to compute an ambient temperature, air pressure, and/or water ingress into the device. In some embodiments, non-biological 78 sensors may include one or more motion sensors for detecting movement and acceleration of the device. The one or more motion sensors may include one or more of the following: a tile sensor 76, accelerometer 80, gyroscope 84, magnetometer 86 or other type of inertial measurement device.

Motion sensor data can be used to monitor and detect changes in motion of the device. Changes in linear and angular motion may be used to determine or estimate an orientation of the device

relative to a known location or fixed datum. The sensor input produced from the one or more motion sensors may also be used to track the movement of the user. The movement of the user may be used to facilitate navigation or map-guided functionality of the device. Additionally, input related to the gross movement of the user can be used as a pedometer or activity meter, which may be stored and tracked over time to determine health metrics or other health related information. Additionally, in some embodiments, sensor input from the one or more motion sensors may be used to identify motion gestures. For example, the motion sensors can be used to detect an arm raise or the position of a user's body (within a predetermined confidence level of certainty).

[0073] The device 50 also comprises one or more biological sensors (biosensors) 74 that may include optical and/or electronic biometric sensors that may be used to compute one or more health metrics. One or more of the biosensors may include one or more pressure sensors 86 for measuring blood pressure, a light source and a photodetector to form a photoplethysmography (PPG) sensor 88. The optical (e.g., PPG) sensor or sensors may be used to compute various health metrics including, without limitation, heart rate, a respiration rate, blood oxygenation level, blood volume estimate, blood pressure, or a combination thereof. One or more of the biosensors may also be configured to perform an electrical measurement using one or more electrodes in contact with the user's body. The electrical sensor(s) may be used to measure electrocardiographic (ECG) characteristics, galvanic skin resistance, and other electrical properties of the user's body. Additionally or alternatively, one or more of the biosensors may be configured to measure body temperature, exposure to UV radiation, and other health related information.

[0074] The device 50 may also comprise one or more haptic devices 68. The haptic device may include one or more of a variety of haptic technologies such as, but not necessarily limited to, rotational haptic devices, linear actuators, piezoelectric devices, vibration elements, and so on. In general, the haptic device may be configured to provide punctuated and distinct feedback to a user of the device. More particularly, the haptic device may be adapted to produce a knock or tap sensation and/or a vibration sensation. The haptic device may be operatively coupled to the processor 52 and memory 56. In some embodiments, the haptic device may be directly controlled by the processor. In some embodiments, the haptic device may be controlled, at least in part, by the operation of an input component 72, including, for example, a button, dial, crown, or the like. The operation of the haptic device may also be paired or linked to the operation of one or more other output devices, including, for example, the display 64 or audio output device 66, e.g., a speaker. In one embodiment, haptic output may be produced using one or more electromechanical subassemblies that are configured to induce motion or vibration in the device, which may be perceived or sensed by the user.

[0075] The device 50 may comprise a battery or other suitable power source 54 that is used to store and provide power to the other components of the device. The battery may be a rechargeable power supply that is configured to provide power to the device while it is being worn by the user. The device may also be configured to recharge the battery using a wireless charging system. Accordingly, in some cases, the device may include a wireless power module 55 that may be configured to receive power from an external device or dock. The wireless power module may be configured to deliver power to components of the device, including the battery.

[0076] In some implementations, the device includes one or more receiving inductive coils that are configured to cooperate with one or more transmitting inductive coils that are located in a

charging dock or other external device. The wireless charging system allows the transfer of power and/or wireless communications with the device without the use of an external port or terminal connection.

[0077] The wireless power module and an external charging station or dock may also be configured to transmit data between the device and a base or host device. In some cases, the wireless power module may interface with the wireless charging station or dock to provide an authentication routine that is able to identify specific hardware, firmware, or software on the device in order to facilitate device maintenance or product updates.

[0078] The device 50 may also comprise a variety of other components, including for example, a camera or camera modules 58. The camera may be configured to capture an image of a scene or subject located within a field of view of the camera. The image may be stored in a digital file in accordance with any one of a number of digital formats. In some embodiments, the device includes a camera, which includes an image sensor formed from a charge-coupled device (CCD) and/or a complementary metal-oxide-semiconductor (CMOS) device. The camera may also include one or more optical components disposed relative to the image sensor, including, for example, a lens, a filter, a shutter, and so on.

[0079] The device 50 may comprise a force sensor 59 configured to detect and measure the magnitude of a force of a touch on a surface of the device. The output of the force sensor can be used to control various aspects of the device. For example, the force sensor may be used to control an aspect, such as a cursor or item selection on a user interface presented on the display of the device. The force sensor may also be used to control the audio output, haptic output, and other functionality of the device. The force sensor may also be used to distinguish between different types of input from the user. For example, a light touch from the user may be

interpreted as a scroll command and used to index or scroll through a list of items on the display. A harder touch from the user may be interpreted as a selection or confirmation of an item on the display.

[0080] The device 50 also may comprise a touch sensor 60 configured to detect and measure the location of a touch on a surface of the device. In some implementations, the touch sensor is a capacitive based touch sensor that is disposed relative to the display or display stack of the device. The touch sensor may be a separate nonintegrated sensor relative to the force sensor. In alternative embodiments, the touch sensor may also be physically and/or logically integrated with the force sensor to produce a combined output. The touch sensor may be used to control various aspects of the device, e.g., to control an aspect of the user interface presented on the display of the device, the audio output, haptic output, and other functionality of the device.

[0081] In some cases, the logical integration of the force sensor 59 and touch sensor 60 enhances the versatility or adaptability of device 50 by enabling a sophisticated user interface. For example, they may be combined to interpret a wider range of gestures and input commands than may be possible using, for example, only a touch input. For example, the force sensor may provide a magnitude of a force of a touch, which may be used to distinguish between two touch input commands that have a similar location or gesture path. An improved touch interface using both force sensor and touch sensor may be particularly advantageous when interpreting touch commands on a relatively small area surface, such as a display screen or cover glass of a wearable electronic device.

[0082] A high level block diagram illustrating an example blood pressure measurement device such as a wearable in communication with an optional host device is shown in Figure 5. The blood pressure measurement device, generally referenced 90, comprises a control unit or

processor 92, clock source 94 such as a crystal oscillator, display 96, communications module 108, memory 110, power source 112, one or more pressure sensors 98, PPG sensor 100, and one or more motions sensors such as 3D Microelectromechanical system (MEMS) accelerometer 102, gyroscope 104 and/or magnetometer 106. The host device, generally referenced 120, comprises a control unit or processor 122, display 126 and communications module 124. Note that the device 90 may be incorporated into a wearable device such as shown in Figure 4 described in detail supra.

[0083] Note that the one or more pressure sensors may comprise (1) a microelectromechanical system (MEMS) capacitive pressure sensor; (2) a patch sensor applied to the brachial artery; (3) an array of pressure sensors simultaneously collecting pressure data; (4) a pressure sensor array operative to generate a single pressure measurement; (5) a pressure sensor array operative to generate a plurality of pressure measurements; and (6) a pressure sensor array time domain multiplexed based on each sensor's respective signal quality.

[0084] In operation, the control unit is configured to receive data from multiple sources, process it and output waveforms, measurements and telematics. The one or more pressures sensors are adapted to sense pressure when pressed against a hand artery such as the radial, ulnar or brachial artery. The display is adapted to display waveforms, measurements (e.g., blood pressure, heart rate, temperature, etc.) and telematics such as battery status. The power source is adapted to provide energy for the various circuits and may comprise a battery (e.g., lithium ion or lithium ion polymer rechargeable battery). The memory function to store program and data. The device 90 may also comprise a photoplethysmography (PPG) sensor for independent measurement and synchronization of heart rate. The communication module functions to send data over a communication link 114 which may comprise a wired or wireless link. In one embodiment, the

device transmits data when the link is available either continuously or intermittently, while in other times the device stores the data in volatile or non-volatile (NV) memory.

[0085] In one embodiment, the blood pressure measurement device 90 may be connected to the host unit 120. The host device is configured to communicate with the blood pressure measurement device over the link 114 using communication module 124. The control unit 122 is programmed to display information from or relating to measurements obtained (and optionally processed) by blood pressure measurement device 90.

Blood Pressure Measurement and
Reduction of Motion Artifacts

[0086] One method of estimating blood pressure is by directly measuring the mechanical pressure applied by the blood volume fluctuations in arteries under the tissue using sensitive pressure sensors and small signal converters attached to the skin sensing the mechanical movements of the tissue. The pressure sensor converts the pressure into electrical voltage that is proportional to it. The measured voltage waveform is related to the blood pressure in the artery and is therefore referred to as the blood pressure waveform.

[0087] A problem of the direct pressure sensing method, however, is its high sensitivity to physical motion. Any measurement that involves measurement of blood flow features within living bodies, particularly by a wearable device, is prone to large movement artifacts. The motion by the body manifests are a pressure wave that is subsequently measured as an undesirable artifact in the pressure waveform signal. The motion artifact, can in fact, be much more significant than typical blood pressure sensing fluctuations, making the latter undetectable and yielding missing or erroneous measurements.

[0088] A graph illustrating an example motion sensing signal generated by a user during active and rest periods is shown in Figure 6. In this graph, signal amplitude from a motion sensor is

shown as a function of time. Five time periods are shown, namely when a user is sitting 136, walking fast 138, standing 140, walking slow 142 and sitting 144. The motion signal 132 is obtained from a MEMS accelerometer as a function of time. Signal 132 represents the acceleration magnitude and dashed signal 130 represents the variation index, computed as the standard deviation of the averaged acceleration signal divided by the amplitude of the averaged acceleration signal. Solid horizontal line 134 represents a threshold to which the variation index is compared in order to determine whether the user is active or resting.

[0089] The graph reveals that the acceleration magnitude signal 132 is highly correlated with the movement of the user and shows a significantly higher amplitude during periods of movement (i.e. periods 138, 142) than during rest (i.e. periods 136, 140, 144). The variation index 130 is an averaged signal showing a slower behavior. When comparing the latter to the threshold, the mechanism is able to determine when the user is at rest and when the user is moving.

[0090] In another embodiment of the invention, an interquartile range of acceleration measurements is collected during a period of time and compared to a predetermined threshold. When no motion is detected for a period of time, e.g., the interquartile range is below the predefined threshold, rest is declared. All non-rest periods are considered undesirable for blood pressure waveform measurements.

[0091] In addition to the problem of motion artifacts, blood pressure waveform and blood pressure measurements stemming from direct pressure measurements can suffer from calibration issues where the pressure sensed has a certain bias and/or scaling factor to the actual blood pressure waveform or measurement.

[0092] In one embodiment, the blood pressure measurement mechanism overcomes these problems by detecting the motion artifacts and avoiding using sensor data acquired during the

motion artifact. The mechanism also consumes low energy and eliminates the need for a cuff. The mechanism of sensing the blood pressure waveform on one or more of the arteries and deriving motion artifact free blood pressure waveform and blood pressure measurement readings will now be described in more detail.

[0093] The blood pressure measurement mechanism estimates blood pressure by measuring the mechanical pressure applied by fluctuations in blood volume in arteries under the tissue. Sensitive pressure sensors and small signals converters attached to the skin sense the mechanical movements of the tissue. The mechanical changes reflected from the skin are coupled with the blood density in the artery and is affected by the mechanical characteristics thereof.

[0094] The mechanism of the invention, which in one embodiment is incorporated in a wearable vital sign measurement device, exploits sensitive pressure measurement of hand arteries as well as motion sensing in order to obtain a blood pressure waveform that is calibrated and free from motion artifacts.

[0095] In one embodiment, the mechanism utilizes an avoidance method based on identification of a time period where the user does not significantly move the body part the device is attached to, e.g., the wrist. This determination is based on measurements of the dynamic motion of the user's body part to which the device is attached. In operation, the mechanism identifies appropriate time slots in between detected motion during which blood pressure sensing is enabled.

[0096] The signal from the motion sensor is processed and a variance index is calculated. In particular, for example, the coefficient of variance of the motion sensor signal within a time frame is computed. If it is below a threshold (e.g., 1%, 3%, 10%, etc.) that this is an indication

that the device and the user's body are not moving. In one embodiment, the time frame referred above is in the order of seconds.

[0097] A diagram illustrating an example mechanism for rejecting motion artifact ridden blood pressure waveform samples utilizing motion measurements is shown in Figure 7. In the avoidance mechanism, generally referenced 150, the pressure sensor on the hand artery generates a signal that is processed (via block 152) resulting in a blood pressure waveform 154. Note that pressure can be sensed on a hand artery such as the radial, ulnar or brachial artery yielding a blood pressure waveform. The blood pressure waveform, however, might suffer from motion artifacts resulting from either the relative movement of the sensor with respect to the artery or the movement of tissues and blood within the artery due to the hand movement.

[0098] A motion sensor measures body motion of the user (via block 162) in parallel with the pressure sensor. Motion measurement can be achieved, for example, using a MEMS based accelerometer, a MEMS based gyroscope, Hall effect magnetometer, etc. This measurement yields movement correlated data such as acceleration, angular velocity, etc.

[0099] The sensor signal is processed and movement correlated data 164 is input to an activity detection algorithm (block 166) which computes an activity indicator, e.g., the variance coefficient, which is then compared to a threshold. The activity signal indicates whether the user is at relative rest or not. If activity is detected (detection signal 168), the blood pressure waveform corresponding to the time period during which user activity is detected is discarded. In one embodiment, the variance coefficient (i.e. variation index) is computed using threshold crossing counting per given duration.

[00100] In another embodiment, interquartile range is calculated and used to detect if the user was active during the blood pressure waveform measurement period.

[00101] In one embodiment, a data multiplexer is 156 controlled by the activity signal 168 either (1) forwards the blood pressure waveform data for display, storage, analysis and/or further processing (via block 160) when the activity signal indicates no motion detected; or (2) discards the blood pressure waveform data when the activity signal indicates motion was detected. Note that while the blood pressure waveform samples can be used even at times of movement by other processes in the system, they are not used for blood pressure waveform analysis, display, etc. when the avoidance mechanism is active.

[00102] A flow diagram illustrating an example method of identifying time slots suitable for blood pressure waveform measurements that do not have motion artifacts is shown in Figure 8. The motion (i.e. activity) detection method starts by zeroing the time counters Time and RestCount (step 170). New acquisition samples are then received from the motion sensing device, e.g., a MEMS accelerometer (step 172) and the Time counter is incremented (step 174). The Time counter is then compared to an initial Tproc_ACCL threshold (step 176). If the Time counter is not greater or equal to the threshold, the method steps 170, 172, 174, acquiring new acceleration samples and incrementing the time counter again. If the Time counter has reached or exceeded the threshold (step 176), the Time counter is zeroed (step 178) and a new Variation Index (VI) is computed for the entire period preceding the computation (step 180). The variation index can be calculated by various well-known averaging techniques such as (1) FIR or IIR filters over absolute value or squared samples, or (2) by computing the coefficient of variation by computing the standard deviation divided by the average. Interquartile range can be calculated and used in the same manner the variation index is used.

[00103] The variation index (VI) is then compared against a threshold (step 182). If the VI is smaller than the threshold, then the user is active and the method goes back to step 170.

Otherwise, the RestCount counter is incremented (step 184), i.e. the VI is greater than or equal to the threshold. The RestCounter is compared against a threshold representing the desired rest time (step 186). If the RestCounter is smaller than the threshold, the method goes to step 170 again, ensuring that only when the desired rest time of consecutive inactivity is detected will rest be declared. Finally, if RestCounter is greater than or equal to the threshold (step 186), the user is declared to be at rest during the relevant time period (step 188). Note that interquartile range can be calculated and used in the same way variation index is used.

[00104] A diagram illustrating an example mechanism that utilizes motion sensing measurements to cancel out artifacts in pressure sensor derived blood pressure waveform data is shown in Figure 9. The cancellation mechanism, generally referenced 200, generates blood pressure measurements, either continuous or intermittently, regardless of whether a user is at rest or active. During the time a user is active, the mechanism generates artifact correlated data during the active time period. An adaptive filtering technique such as an FIR predictor trained/adapted by Least Means Square (LMS), Recursive Least Squares (RLS) or direct solution of the Wiener Hopf (WH) equations is applied to the blood pressure readings with the artifact correlated data, and an adjusted blood pressure waveform signal is computed. An accuracy scoring is applied to the adjusted blood pressure waveform on the basis of any remaining noise correlated components and a reading of systolic and diastolic blood pressure values are produced if a critical threshold of minimum accuracy is met by the particular adjusted blood pressure waveform.

[00105] In operation, the cancellation mechanism treats the inertial dynamic measurements from the inertial sensors (i.e. motion sensors) as noise/artifact correlated data, i.e. the data has similar statistical characteristics compared to the noise/artifact since both are derived from the physical movement of the hand. This data is filtered by an adaptive filter 210 operative to compensate for

the different transformations that the user movement went through. Note that the filtering process can be applied to the blood pressure waveform 202 and/or to motion data 208. The filtered data is then subtracted from blood pressure waveform 202 to yield clean samples.

[00106] Thus, the motion sensor data is combined with the raw blood pressure waveform in an adaptive filter that estimates the noisy component of the raw blood pressure. It is appreciated that alternative filtering schemes can be used to extract the noisy component from the raw blood pressure waveform.

[00107] The cancellation mechanism then uses correlated movement data to cancel the motion artifacts from the sensed pressure blood pressure waveform yielding a clean waveform for storage, display or analysis. Pressure is sensed on a hand artery such as the radial, ulnar or brachial artery (block 201) yielding a blood pressure waveform 202. This blood pressure waveform, however, might suffer from motion artifacts resulting from the relative movement of the sensor with respect to the artery or the movement of tissues and blood within the artery due to the hand or body movement of the user. In parallel (i.e. concurrently), movement correlated data is measured (block 204) yielding movement data 208. This data may be collected from one or more inertial sensors such as MEMS accelerometers, piezo rod and weight accelerometer, MEMS gyroscope or Hall effect magnetometer. A filter 210 is operative to filter the movement data 208 yielding artifact correlated data 212. Note that the filter can be either adaptive or static of various types such as Finite Impulse Response (FIR) or Infinite Impulse Response (IIR) and may be adapted to correlate with the blood pressure waveform during periods of activity.

[00108] The blood pressure artifact correlated data 212 is then subtracted (i.e. cancelled) via summer 206 from the blood pressure waveform 202 yielding a clean blood pressure waveform signal 208. The clean signal is then either displayed, stored, and/or analyzed (block 214).

[00109] A diagram illustrating an example mechanism that utilizes pressure sensor data from the brachial artery to calibrate blood pressure waveform readings and also uses motion measurements to reject motion artifact ridden blood pressure waveform samples is shown in Figure 10. In a best mode of operation, calibration of the blood pressure measurement is performed to optimize the signal to noise values from the one or more pressure sensors. Additional sensors can be located on the ulnar artery to increase the precision that can be extracted from the pressure sensors.

[00110] To achieve highly accurate measurements, a blood pressure patch or armband, referred to as a brachial patch, that contains a pressure sensor, a control unit and communications, is placed on the brachial artery at the level of the heart. The measurement extracted from the brachial patch is used to calibrate coefficients of the measurements that are applied to the wristband sensors that are on the radial and, optionally, the ulnar arteries.

[00111] In one embodiment, the calibration mechanism uses pressure sensed on the brachial artery in order to calibrate the pressure being sensed on the radial and/or the ulnar arteries in conjunction with motion measurement from a third sensor to rule out (i.e. avoid) the artifacts during periods of activity.

[00112] Pressure is sensed on a hand artery such as the radial or ulnar artery (via block 301) yielding blood pressure waveform #1 305. The blood pressure waveform #1 305, however, may suffer from motion artifacts resulting from either the relative movement of the sensor with respect to the artery or the movement of tissues and blood within the artery due to hand movement. As described supra, pressure data can be generated using, for example, highly sensitive capacitive MEMS pressure sensors.

[00113] In parallel, (i.e. concurrently), pressure sensing is performed on the brachial artery (block 302) yielding blood pressure waveform #2 303. Waveform 303 can be obtained using either capacitive MEMS pressure sensors or intermittent standard cuff measurements.

[00114] Calibration is then performed on blood pressure waveform #1 305 utilizing blood pressure waveform #2 303 (via block 304). In one embodiment, the calibration process is operative to remove biases, compute scaling factors, etc. In addition, the calibration can be performed at the start of the measurement or periodically using cuff measurements. Alternatively, the calibration can be performed periodically or on the fly of pressure sensing of the brachial artery is performed using a MEMS pressure sensor continuously. The calibration process, may optionally take into account the activity signal 312 being generated from activity detector 310 and perform calibration only when the patient is at relative rest. The calibration process 304 generates calibrated blood pressure waveform 31 314, which might still suffer from motion artifacts.

[00115] In parallel (i.e. concurrently), motion measurement is performed in block 306. In one embodiment, the motion measurement is performed using MEMS accelerometers, MEMS gyroscopes, Hall effect magnetometers, etc. This measurement yields movement correlated data 308 such as acceleration, angular velocity, etc.

[00116] The activity detector 310 determines whether the user is active or at relative rest. This can be achieved, for example, by averaging the absolute value of the movement correlated data 308 over a period of time and comparing it with a threshold. Alternatively, activity can be detected by dividing the standard deviation of the data 308 with its average and comparing the result to a threshold.

[00117] The output of the activity detector 310 is a logical activity signal 312, which indicates whether the user is at relative rest or not and whether the calibrated blood pressure waveform 314 is valid. Optionally, the activity signal can also be used by the calibration process 304 to enable or inhibit the calibration process.

[00118] The data multiplexer 31 is operative to receive calibrated blood pressure waveform #1 314 and in accordance with the activity signal 312 either (1) discard it (block 322); or (2) send it for further display, store, and/or analysis (block 324). If the user is active, then calibrated blood pressure waveform #1 314 is discarded. Conversely, if relative rest is detected, the waveform is valid and can be used in further processing via block 324.

[00119] Note that the calibration process may be performed periodically or once at the start of a measurement session.

[00120] A diagram illustrating an example mechanism that calibrates blood pressure waveform readings utilizing pressure sensor data from the brachial artery and also cancels out artifacts from blood pressure waveform data using motion measurements is shown in Figure 11. The calibration/cancellation mechanism, generally referenced 400, uses pressure sensed on the brachial artery in order to calibrate the pressure being sensed on the radial and/or the ulnar arteries in conjunction with motion measurement from a third sensor used to cancel out motion artifacts from the calibrated blood pressure waveform.

[00121] Pressure is sensed on a hand artery such as the radial, ulnar artery (via block 401) yielding a blood pressure waveform #1 402. Blood pressure waveform 402, however, may suffer from motion artifacts resulting from either the relative movement of the sensor with respect to the artery or the movement of tissues and blood within the artery due to the hand movement. The

pressure sensing can be achieved using, for example, highly sensitive capacitive MEMS pressure sensors.

[00122] In parallel (i.e. concurrently), pressure sensing is performed on the brachial artery (via block 404) yielding blood pressure waveform #2 408. This can be achieved using a brachial patch described supra, capacitive MEMS pressure sensors or intermittent standard cuff measurements.

[00123] Calibration is performed on blood pressure waveform #1 402 utilizing blood pressure waveform #2 408. The calibration can be performed, for example, to remove biases, compute scaling factors, etc. Furthermore, this calibration can be done at the start of the measurement or periodically using cuff measurement. Alternatively, calibration can be performed periodically or on the fly if pressure sensing (via block 404) is performed using a MEMS pressure sensor continuously.

[00124] The calibration process yields calibrated blood pressure waveform #1 412 which may still, however, suffer from motion artifacts. A filter 416 functions to filter movement data 414 yielding artifact correlated data 418. It is appreciated that the filter can be implemented as adaptive or static of various types such as Finite Impulse Response (FIR) or Infinite Impulse Response (IIR) and may be adapted to correlate with the blood pressure waveform during periods of movement or pre-provisioned during production. Adaptive filter 416 is operative to remove the motion artifacts from signal 412 using as an example an FIR trained/adapted using Least Means Square (LMS), Recursive Least Squares (RLS) or a direct solution of the Wiener Hopf (WH) equations.

[00125] Summer 411 functions to subtract blood pressure artifact correlated data 418 from calibrated blood pressure waveform #1 412 yielding a clean and calibrated blood pressure waveform signal 420. The resultant signal is passed for display, storage, and/or analysis.

[00126] Those skilled in the art will recognize that the boundaries between logic and circuit blocks are merely illustrative and that alternative embodiments may merge logic blocks or circuit elements or impose an alternate decomposition of functionality upon various logic blocks or circuit elements. Thus, it is to be understood that the architectures depicted herein are merely exemplary, and that in fact many other architectures may be implemented which achieve the same functionality.

[00127] Any arrangement of components to achieve the same functionality is effectively "associated" such that the desired functionality is achieved. Hence, any two components herein combined to achieve a particular functionality may be seen as "associated with" each other such that the desired functionality is achieved, irrespective of architectures or intermediary components. Likewise, any two components so associated can also be viewed as being "operably connected," or "operably coupled," to each other to achieve the desired functionality.

[00128] Furthermore, those skilled in the art will recognize that boundaries between the above described operations merely illustrative. The multiple operations may be combined into a single operation, a single operation may be distributed in additional operations and operations may be executed at least partially overlapping in time. Moreover, alternative embodiments may include multiple instances of a particular operation, and the order of operations may be altered in various other embodiments.

[00129] The terminology used herein is for the purpose of describing particular embodiments only and is not intended to be limiting of the invention. As used herein, the singular forms "a", "an"

and "the" are intended to include the plural forms as well, unless the context clearly indicates otherwise. It will be further understood that the terms "comprises" and/or "comprising," when used in this specification, specify the presence of stated features, integers, steps, operations, elements, and/or components, but do not preclude the presence or addition of one or more other features, integers, steps, operations, elements, components, and/or groups thereof.

[00130] In the claims, any reference signs placed between parentheses shall not be construed as limiting the claim. The use of introductory phrases such as "at least one" and "one or more" in the claims should not be construed to imply that the introduction of another claim element by the indefinite articles "a" or "an" limits any particular claim containing such introduced claim element to inventions containing only one such element, even when the same claim includes the introductory phrases "one or more" or "at least one" and indefinite articles such as "a" or "an." The same holds true for the use of definite articles. Unless stated otherwise, terms such as "first," "second," etc. are used to arbitrarily distinguish between the elements such terms describe. Thus, these terms are not necessarily intended to indicate temporal or other prioritization of such elements. The mere fact that certain measures are recited in mutually different claims does not indicate that a combination of these measures cannot be used to advantage.

[00131] The corresponding structures, materials, acts, and equivalents of all means or step plus function elements in the claims below are intended to include any structure, material, or act for performing the function in combination with other claimed elements as specifically claimed. The description of the present invention has been presented for purposes of illustration and description, but is not intended to be exhaustive or limited to the invention in the form disclosed. As numerous modifications and changes will readily occur to those skilled in the art, it is intended that the invention not be limited to the limited number of embodiments described

herein. Accordingly, it will be appreciated that all suitable variations, modifications and equivalents may be resorted to, falling within the spirit and scope of the present invention. The embodiments were chosen and described in order to best explain the principles of the invention and the practical application, and to enable others of ordinary skill in the art to understand the invention for various embodiments with various modifications as are suited to the particular use contemplated.

CLAIMS

1. A method of reducing motion artifacts in a blood pressure measurement device, the method comprising:

sensing pressure from at least one of a user's radial, ulnar and brachial arteries utilizing at least one pressure sensor to yield a blood pressure waveform therefrom;

measuring the user's motion utilizing at least one motion sensor to yield movement correlated data therefrom;

detecting activity from said movement correlated data and generating an activity indication signal thereby; and

discarding said blood pressure waveform when said activity indication signal exceeds a predetermined threshold.

2. The method according to claim 1, further comprising storing, displaying and/or analyzing said blood pressure waveform when said activity indication signal is below said threshold.

3. The method according to claim 1, wherein said at least one pressure sensor is selected from the group consisting of a microelectromechanical system (MEMS) capacitive pressure sensor, a patch sensor applied to the brachial artery, an array of pressure sensors simultaneously collecting pressure data, a pressure sensor array operative to generate a single pressure measurement, a pressure sensor array operative to generate a plurality of pressure measurements; and a pressure sensor array time domain multiplexed based on each sensor's respective signal quality.

4. The method according to claim 1, wherein said at least one motion sensor is selected from the group consisting of an accelerometer, gyroscope, tilt sensor, and magnetometer.

5. The method according to claim 1, wherein the activity indication signal comprises a calculated coefficient of variance and/or an interquartile range of acceleration measurements, collected within a certain time period.

6. A method of reducing motion artifacts in a blood pressure measurement device, the method comprising:

sensing pressure from at least one of a user's radial, ulnar and brachial arteries utilizing at least one pressure sensor to yield a blood pressure waveform therefrom;

measuring the user's motion utilizing at least one motion sensor to yield motion correlated data therefrom;

filtering said motion correlated data to yield filtered motion correlated data therefrom; and

subtracting said filtered motion correlated data from said blood pressure waveform to yield clean blood pressure waveform data thereby.

7. The method according to claim 6, further comprising storing, displaying and/or analyzing said clean blood pressure waveform.

8. The method according to claim 6, wherein said at least one pressure sensor is selected from the group consisting of a microelectromechanical system (MEMS) capacitive pressure sensor, a patch sensor applied to the brachial artery, an array of pressure sensors simultaneously collecting pressure data, a pressure sensor array operative to generate a single pressure measurement, a pressure sensor array operative to generate a plurality of

pressure measurements; and a pressure sensor array time domain multiplexed based on each sensor's respective signal quality.

9. The method according to claim 6, wherein said at least one motion sensor is selected from the group consisting of an accelerometer, gyroscope, tilt sensor, and magnetometer.

10. The method according to claim 6, wherein said filtering comprises removing motion artifacts from said blood pressure waveform utilizing a finite impulse response (FIR) filter adapted using at least one of least mean squares (LMS), recursive least squares (RLS) and direct solution of Wiener Hopf (WH) equations.

11. A method of reducing motion artifacts in a blood pressure measurement device, the method comprising:

first sensing pressure from at least one of a user's radial and ulnar arteries utilizing a first at least one pressure sensor to yield a first blood pressure waveform therefrom;

second sensing pressure from the user's brachial artery utilizing a second at least one pressure sensor to yield a second blood pressure waveform therefrom;

measuring the user's motion utilizing at least one motion sensor to yield movement correlated data therefrom;

calibrating said first blood pressure waveform using said second blood pressure waveform to yield a calibrated blood pressure waveform therefrom;

detecting activity from said movement correlated data and generating an activity indication signal thereby; and

discarding said calibrated blood pressure waveform when said activity indication signal exceeds a predetermined threshold.

12. The method according to claim 11, further comprising storing, displaying and/or analyzing said calibrated blood pressure waveform when said activity indication signal is below said threshold.

13. The method according to claim 11, wherein said first at least one pressure sensor and said second at least one pressure sensor are selected from the group consisting of a microelectromechanical system (MEMS) capacitive pressure sensor, a patch sensor applied to the brachial artery, an array of pressure sensors simultaneously collecting pressure data, a pressure sensor array operative to generate a single pressure measurement, a pressure sensor array operative to generate a plurality of pressure measurements; and a pressure sensor array time domain multiplexed based on each sensor's respective signal quality.

14. The method according to claim 11, wherein said at least one motion sensor is selected from the group consisting of an accelerometer, gyroscope, tilt sensor, and magnetometer

15. The method according to claim 11, wherein the activity indication signal comprises a calculated coefficient of variance or an interquartile range of acceleration measurements, collected within a certain time period.

16. The method according to claim 11, wherein calibrating is performed either periodically or one time at start of a measurement session.

17. A method of reducing motion artifacts in a blood pressure measurement device, the method comprising:

first sensing pressure from at least one of a user's radial and ulnar arteries utilizing a first at least one pressure sensor to yield a first blood pressure waveform therefrom;

second sensing pressure from the user's brachial artery utilizing a second at least one pressure sensor to yield a second blood pressure waveform therefrom;

measuring the user's motion utilizing at least one motion sensor to yield movement correlated data therefrom;

calibrating said first blood pressure waveform using said second blood pressure waveform to yield a calibrated blood pressure waveform therefrom;

filtering said motion correlated data to yield filtered motion correlated data therefrom; and

subtracting said filtered motion correlated data from said correlated blood pressure waveform to yield clean, calibrated blood pressure waveform data thereby.

18. The method according to claim 17, further comprising storing, displaying and/or analyzing said clean, calibrated blood pressure waveform when said activity indication signal is below said threshold.

19. The method according to claim 17, wherein said first at least one pressure sensor and said second at least one pressure sensor are selected from the group consisting of a microelectromechanical system (MEMS) capacitive pressure sensor, a patch sensor applied to the brachial artery, an array of pressure sensors simultaneously collecting pressure data, a pressure sensor array operative to generate a single pressure measurement, a pressure sensor array operative to generate a plurality of pressure measurements; and a pressure sensor array time domain multiplexed based on each sensor's respective signal quality.

20. The method according to claim 17, wherein said at least one motion sensor is selected from the group consisting of an accelerometer, gyroscope, tilt sensor, and magnetometer.

21. The method according to claim 17, wherein calibrating is performed either periodically or one time at start of a measurement session.

22. The method according to claim 17, wherein said filtering comprises removing motion artifacts from said blood pressure waveform utilizing a finite impulse response (FIR) filter adapted using at least one of least mean squares (LMS), recursive least squares (RLS) and direct solution of Wiener Hopf (WH) equations.

23. A wearable device, comprising:

a housing;

a circuit disposed within said housing, said circuit, comprising:

a processor;

a memory coupled to said processor;

a communication module coupled to said processor;

a blood pressure measurement mechanism coupled to said processor, said blood pressure measurement mechanism comprising:

at least one pressure sensor operative to sense pressure from one or more of a user's brachial, radial and ulnar arteries;

at least one motion sensor operative to detect periods of user activity and rest; and

wherein said processor is configured to implement one or more of an avoidance mechanism, cancellation mechanism and a calibration mechanism utilizing said blood pressure measurement mechanism.

24. The device according to claim 25, wherein said processor is configured to store, display and/or analyze a blood pressure waveform when an activity indication signal is below a threshold.

25. The device according to claim 25, wherein said at least one pressure sensor is selected from the group consisting of a microelectromechanical system (MEMS) capacitive pressure sensor, a patch sensor applied to the brachial artery, an array of pressure sensors simultaneously collecting pressure data, a pressure sensor array operative to generate a single pressure measurement, a pressure sensor array operative to generate a plurality of pressure measurements; and a pressure sensor array time domain multiplexed based on each sensor's respective signal quality.

26. The device according to claim 25, wherein said at least one motion sensor is selected from the group consisting of an accelerometer, gyroscope, tilt sensor, and magnetometer.

27. The device according to claim 25, wherein said communication module implements at least one of a Bluetooth protocol, and wireless fidelity (Wi-Fi) protocol.

28. The device according to claim 25, wherein said power source comprises at least one of a lithium ion rechargeable battery, and a lithium ion polymer rechargeable battery.

29. The device according to claim 25, wherein said circuit further comprises at least one of a display device, body temperature measurement device, and a photoplathysmograph (PPG) sensor.

30. The device according to claim 25, wherein said communication module is operative to establish a communications link with a host unit, wherein said host unit is operative to

display blood pressure waveform and/or blood pressure measurement data produced by said blood pressure measurement mechanism.

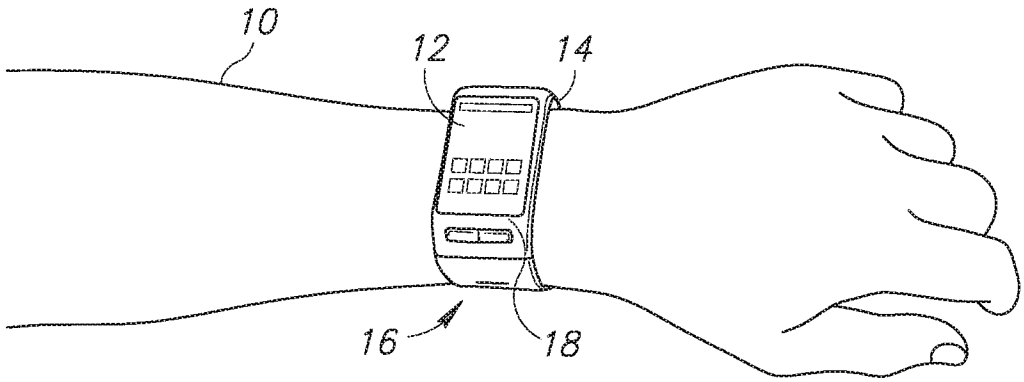


FIG. 1

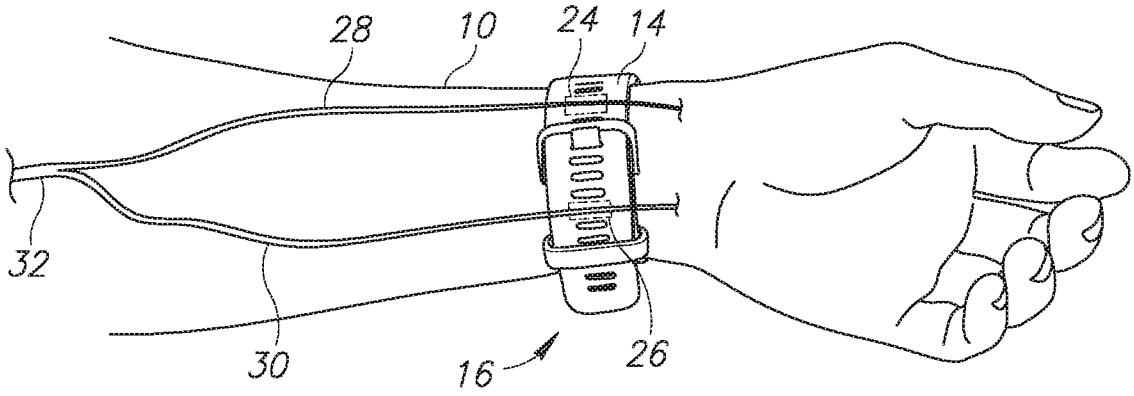


FIG. 2

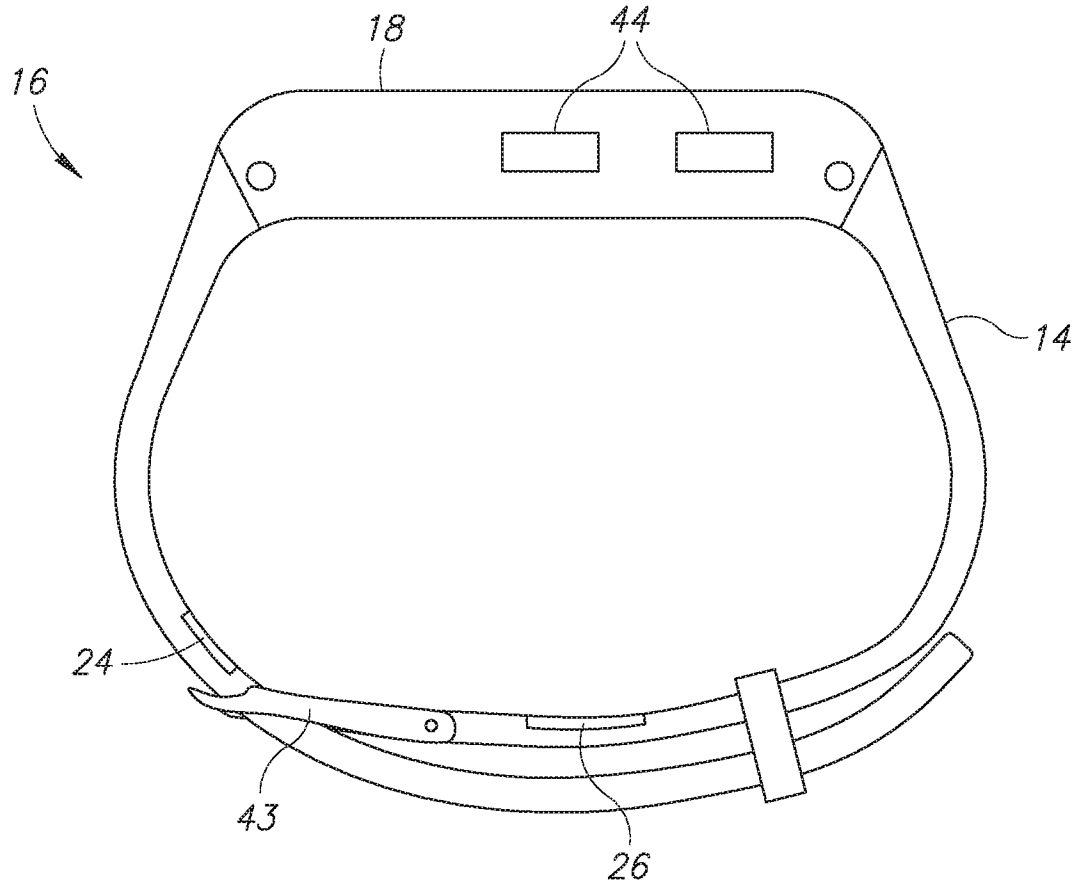
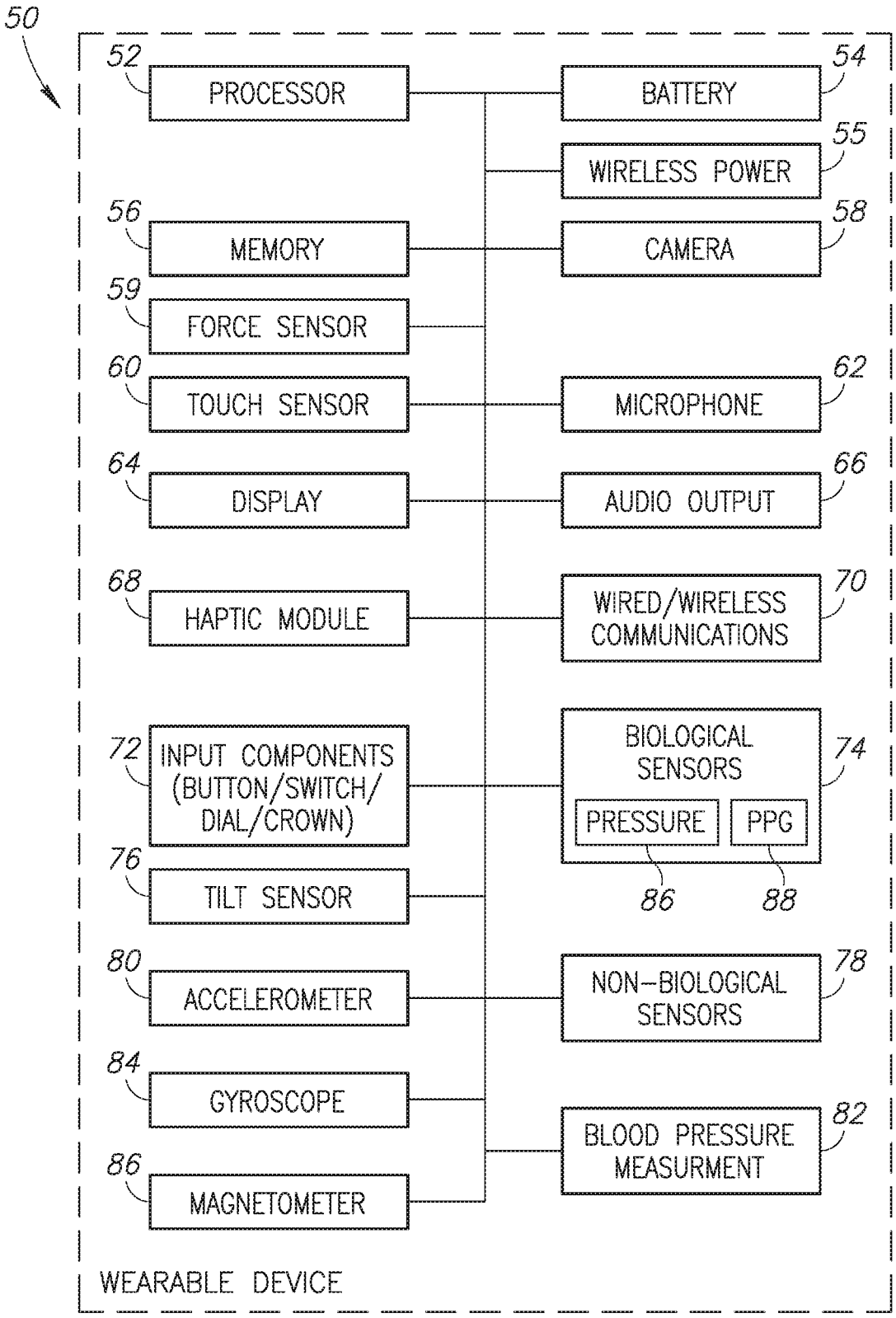


FIG. 3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52
PROCESSOR
54
BATTERY
55
WIRELESS POWER
56
MEMORY
58
CAMERA
59
FORCE SENSOR
60
TOUCH SENSOR
62
MICROPHONE
64
DISPLAY
66
AUDIO OUTPUT
68
HAPTIC MODULE
70
WIRED/WIRELESS COMMUNICATIONS
72
INPUT COMPONENTS (BUTTON/SWITCH/ DIAL/CROWN)
BIOLOGICAL SENSORS
74
PRESSURE
PPG
86
88
76
TILT SENSOR
80
ACCELEROMETER
NON-BIOLOGICAL SENSORS
78
84
GYROSCOPE
BLOOD PRESSURE MEASURMENT
82
86
MAGNETOMETER
WEARABLE DEVICE

FIG. 4

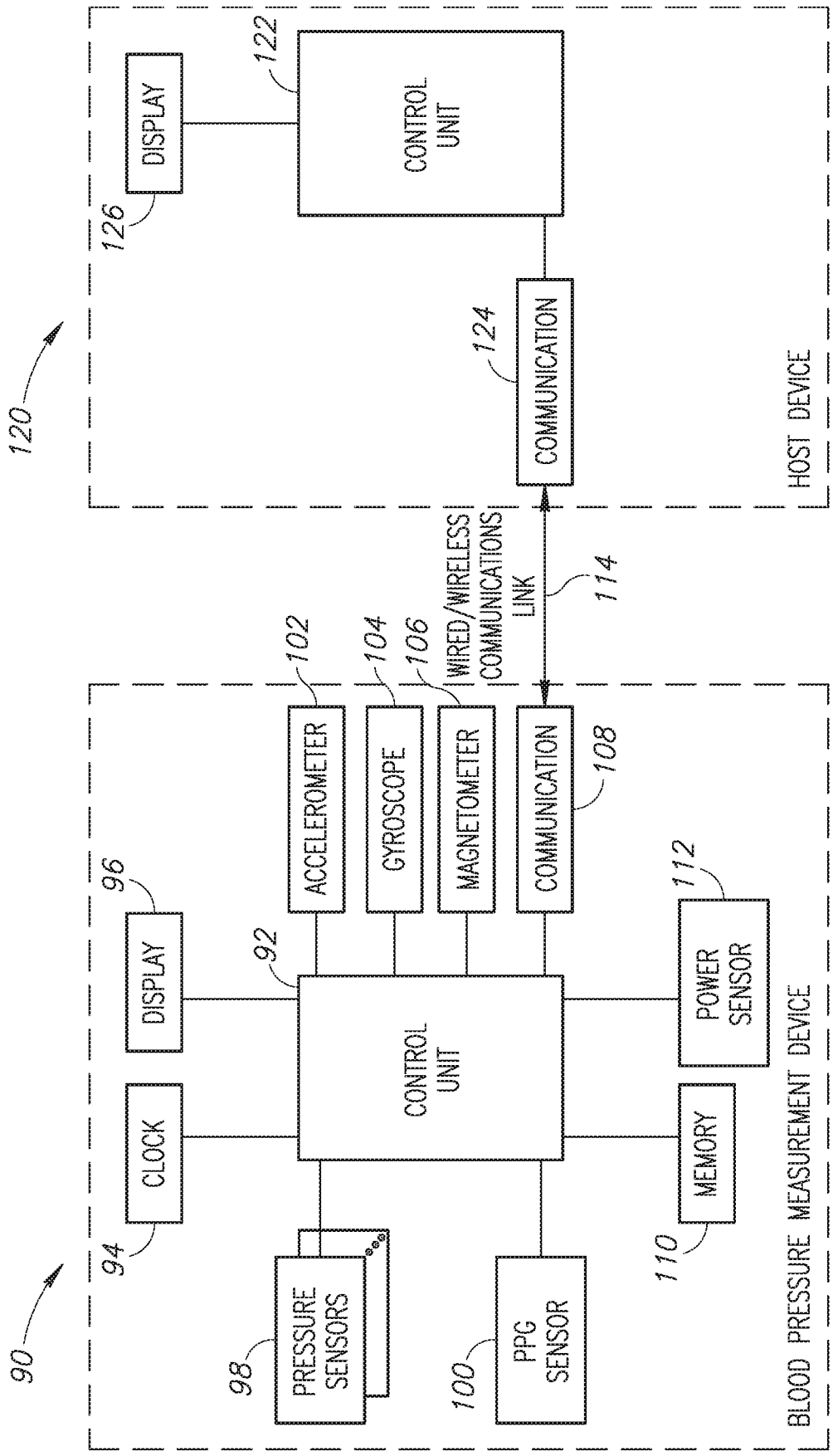
120
HOST DEVICE
DISPLAY
126
CONTROL UNIT
122
COMMUNICATION
124
WIRED/WIRELESS COMMUNICATIONS LINK
114
90
BLOOD PRESSURE MEASUREMENT DEVICE
ACCELEROMETER
102
GYROSCOPE
104
MAGNETOMETER
106
COMMUNICATION
108
DISPLAY
96
CONTROL UNIT
92
CLOCK
94
POWER SENSOR
112
MEMORY
110
PRESSURE SENSORS
98
PPG SENSOR
100

FIG. 5

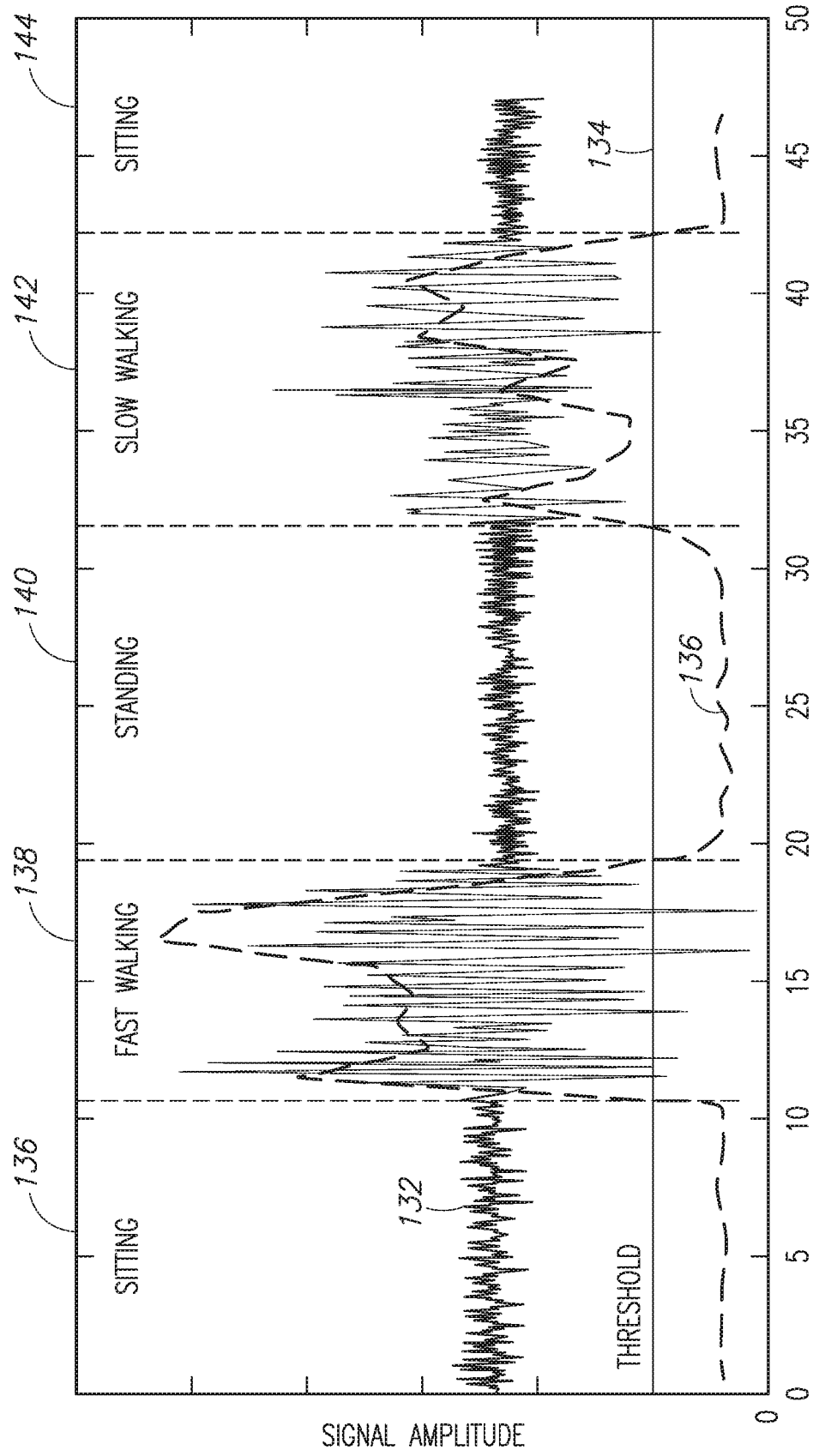
144
142
140
138
136
SITTING
SLOW WALKING
STANDING
FAST WALKING
SITTING
134
136
132
THRESHOLD
0
5
10
15
20
25
30
35
40
45
50
TIME(S)
SIGNAL AMPLITUDE

FIG. 6

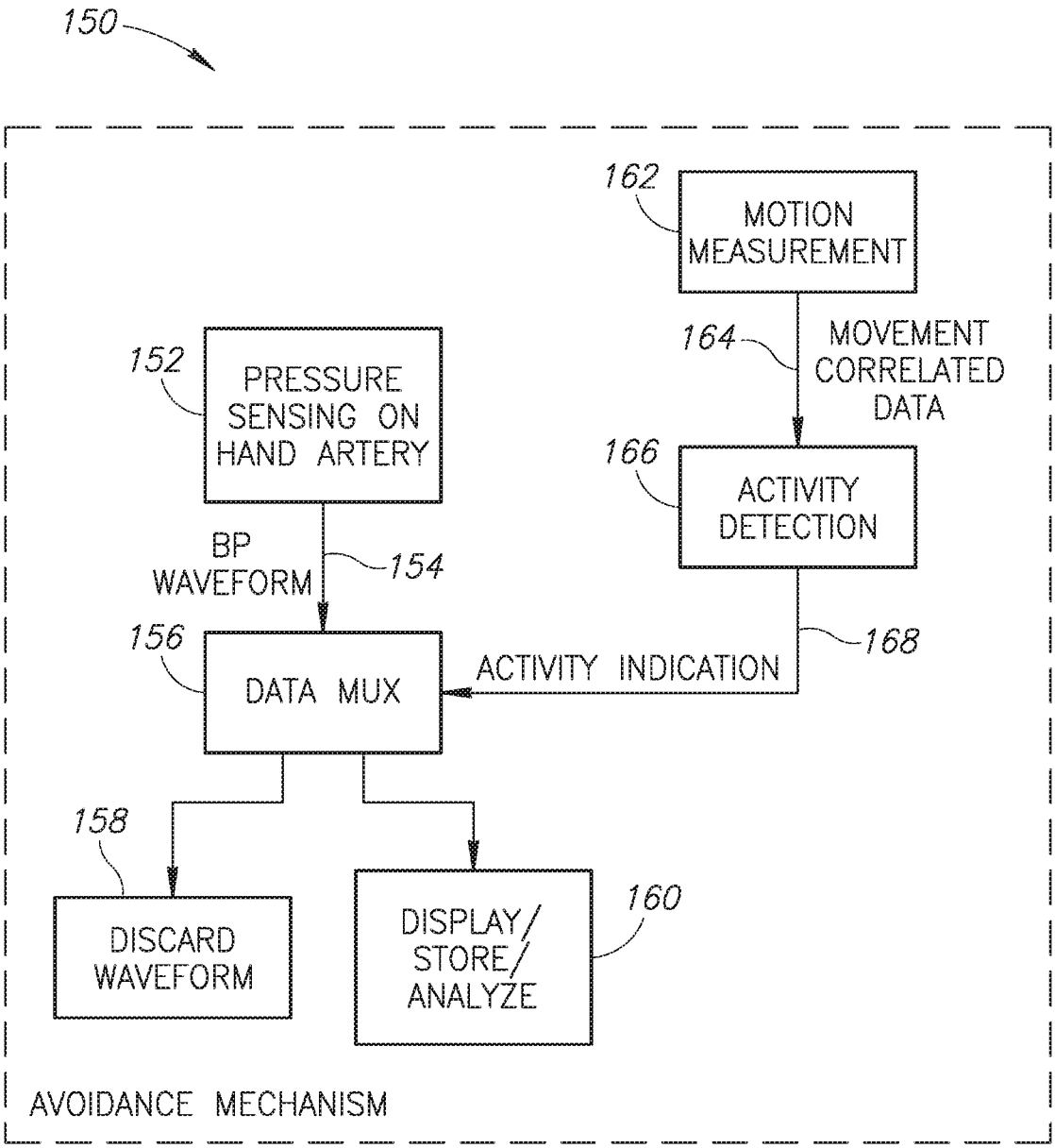
150
162
MOTION MEASUREMENT
164
MOVEMENT CORRELATED DATA
152
PRESSURE SENSING ON HAND ARTERY
166
ACTIVITY DETECTION
BP WAVEFORM
154
156
DATA MUX
ACTIVITY INDICATION
168
158
DISCARD WAVEFORM
DISPLAY/ STORE/ ANALYZE
160
AVOIDANCE MECHANISM

FIG. 7

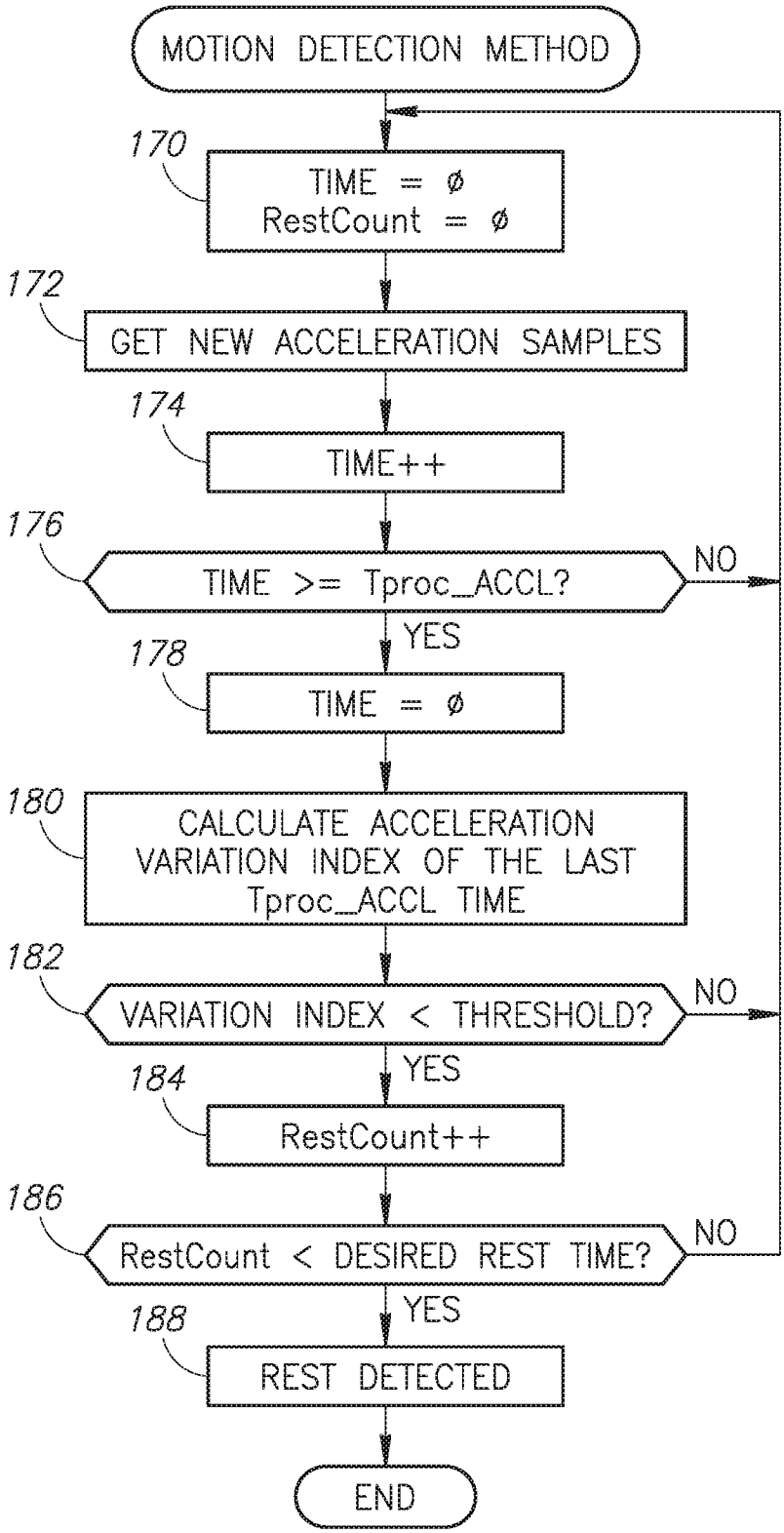
MOTION DETECTION METHOD
170
TIME = ø
RestCount = ø
172
GET NEW ACCELERATION SAMPLES
174
TIME++
176
TIME >= Tproc_ACCL?
NO
YES
178
TIME = ø
180
CALCULATE ACCELERATION VARIATION INDEX OF THE LAST Tproc_ACCL TIME
182
VARIATION INDEX < THRESHOLD?
NO
YES
184
RestCount++
186
RestCount < DESIRED REST TIME?
NO
YES
188
REST DETECTED
END

FIG. 8

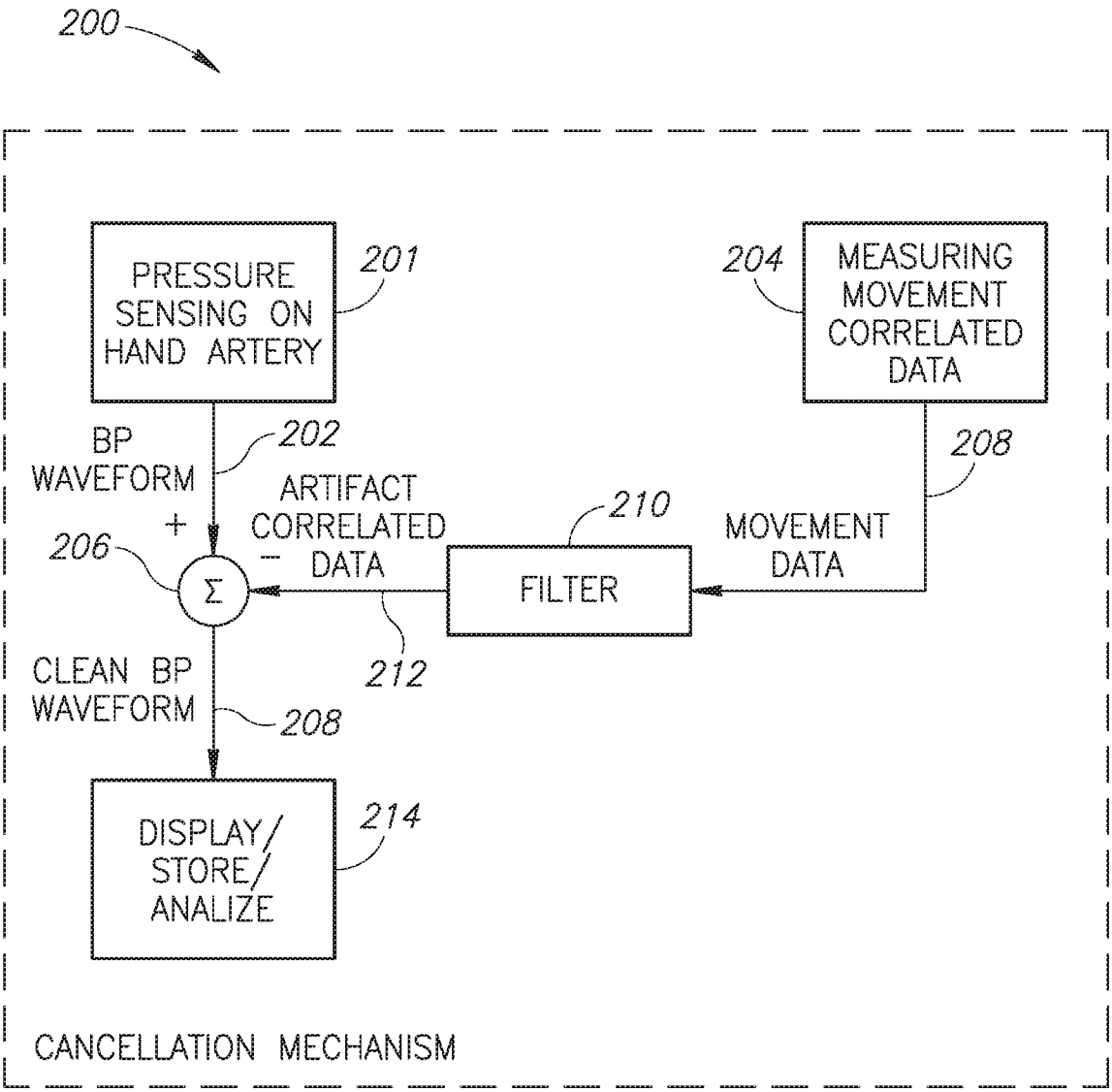
200
PRESSURE SENSING ON HAND ARTERY
201
204
MEASURING MOVEMENT CORRELATED DATA
BP WAVEFORM
202
208
+
ARTIFACT CORRELATED DATA
210
206
Σ
FILTER
MOVEMENT DATA
212
CLEAN BP WAVEFORM
208
DISPLAY/ STORE/ ANALIZE
214
CANCELLATION MECHANISM

FIG. 9

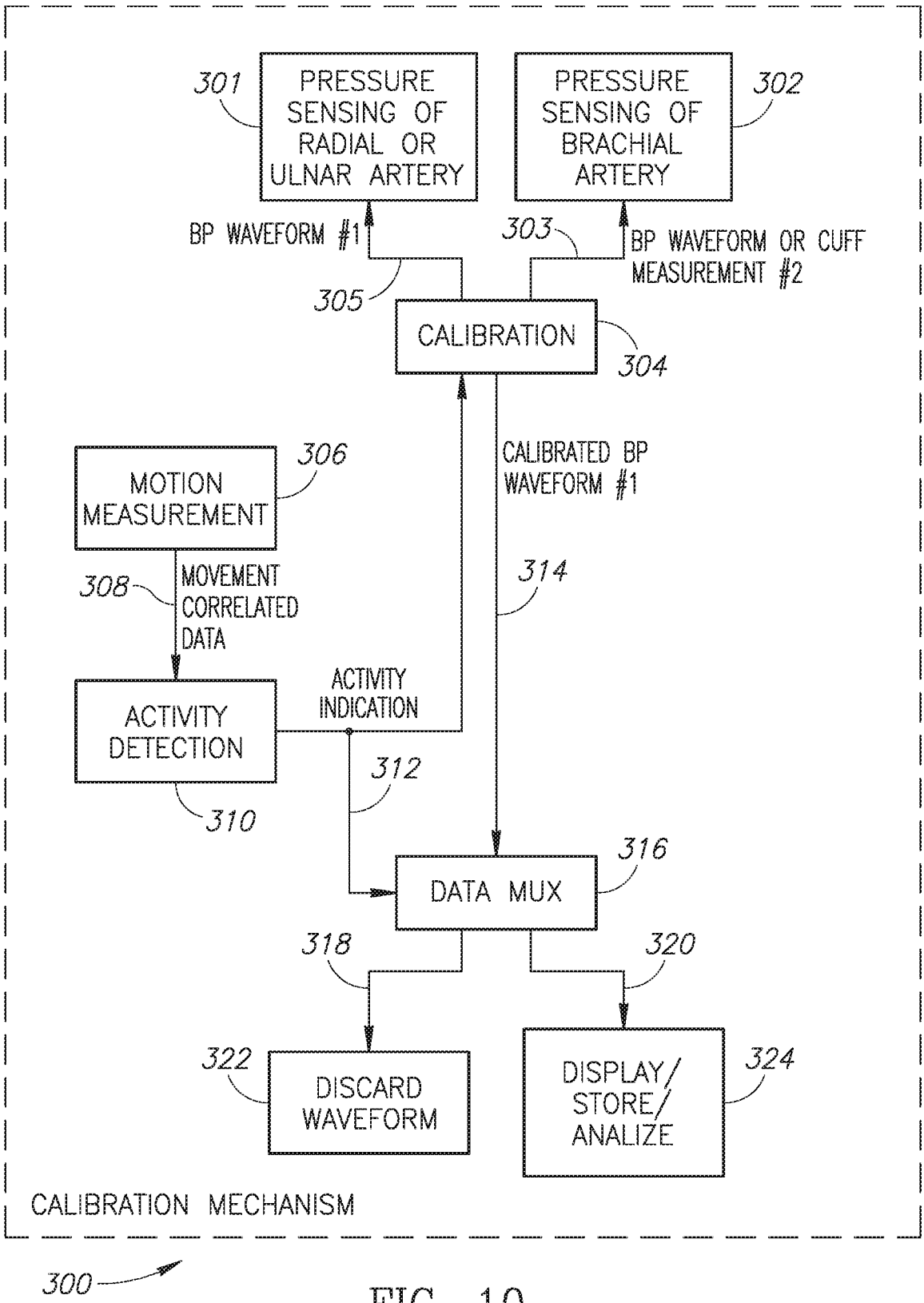
301
PRESSURE SENSING OF RADIAL OR ULNAR ARTERY
302
PRESSURE SENSING OF BRACHIAL ARTERY
BP WAVEFORM #1
303
BP WAVEFORM OR CUFF MEASUREMENT #2
305
CALIBRATION
304
306
MOTION MEASUREMENT
CALIBRATED BP WAVEFORM #1
308
MOVEMENT CORRELATED DATA
314
ACTIVITY INDICATION
ACTIVITY DETECTION
312
310
316
DATA MUX
318
320
322
DISCARD WAVEFORM
DISPLAY/ STORE/ ANALIZE
324
CALIBRATION MECHANISM
300

FIG. 10

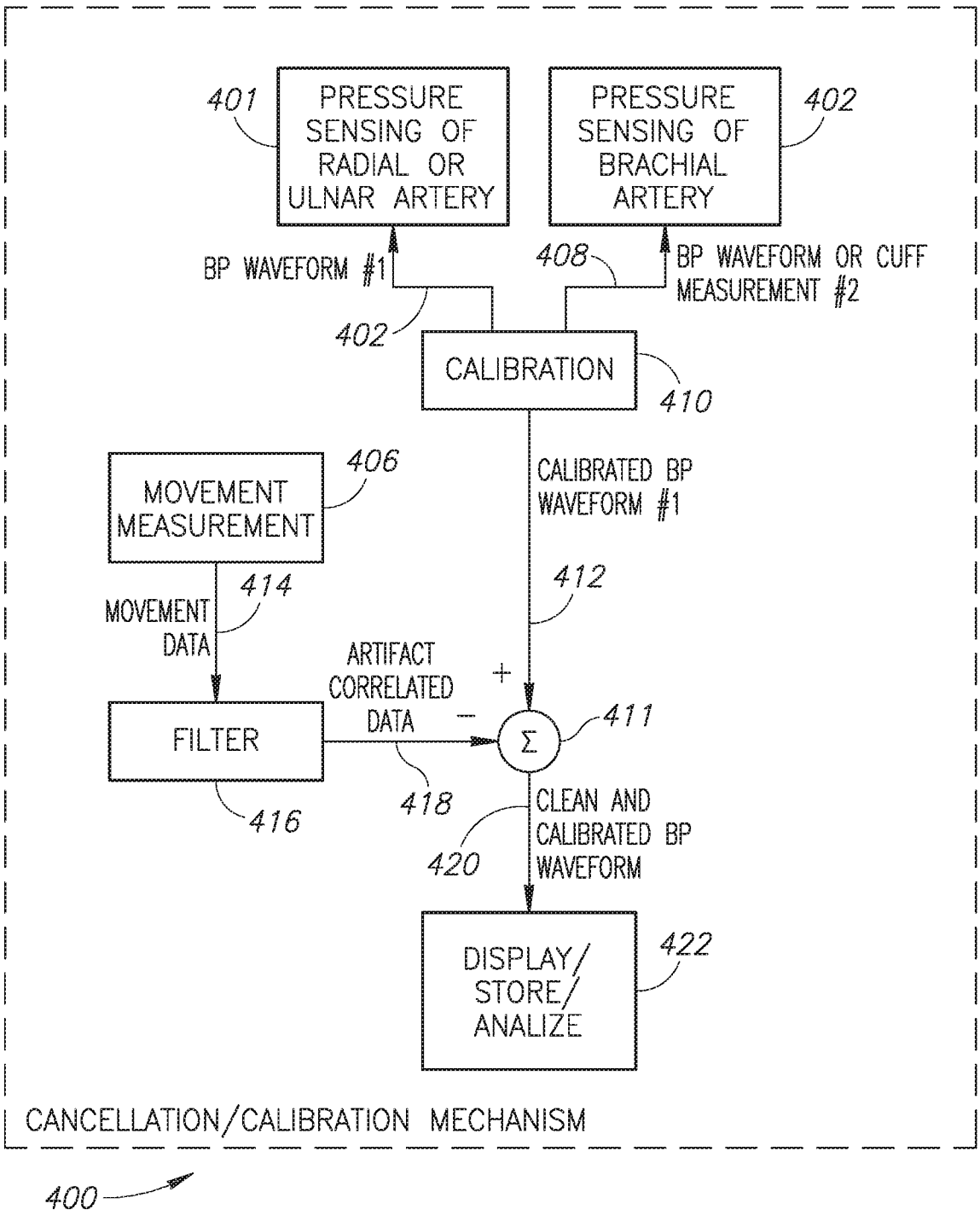
401
PRESSURE SENSING OF RADIAL OR ULNAR ARTERY
PRESSURE SENSING OF BRACHIAL ARTERY
402
BP WAVEFORM #1
408
BP WAVEFORM OR CUFF MEASUREMENT #2
402
CALIBRATION
410
406
MOVEMENT MEASUREMENT
CALIBRATED BP WAVEFORM #1
414
412
MOVEMENT DATA
ARTIFACT CORRELATED DATA
+
−
FILTER
Σ
411
418
416
CLEAN AND CALIBRATED BP WAVEFORM
420
DISPLAY/ STORE/ ANALIZE
422
CANCELLATION/CALIBRATION MECHANISM
400

FIG. 11

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2016/056958

A. CLASSIFICATION OF SUBJECT MATTER
IPC (2017.01) A61B 5/04

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC (2017.01) A61B 5/04

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
Databases consulted: THOMSON INNOVATION, Esp@cenet, Google Patents

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 7395105 B2 Schmidt et al 01 Jul 2008 (2008/07/01) Abstract, Col. 2 lines 41-48, Col. 5 lines 6-24, Fig. 1	1-30
A	Yousefi et al.: "Adaptive Cancellation of Motion Artifact in Wearable Biosensors", 34th Annual International Conference of the IEEE EMBS, San Diego, California, USA, August 28 - September 1, 2012, Pages, 2004-2208, ISSN: 978-1-4577-1787-1/12 URL: http://ecs.utdallas.edu/research/researchlabs/Q0LT/f11es/pdfs/EMBC12_Adaptive.pdf [Retieved on January 26, 2017] Yousefi et al 28 Aug 2012 (2012/08/28) Whole document	1-30

☐ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier application or patent but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
26 Jan 2017	26 Jan 2017
Name and mailing address of the ISA: Israel Patent Office Technology Park, Bldg.5, Malcha, Jerusalem, 9695101, Israel Facsimile No. 972-2-5651616	Authorized officer BRODET Eyal Telephone No. 972-5651778

INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.
PCT/US2016/056958

Patent document cited search report	Publication date	Patent family member(s)	Publication Date
US 7395105 B2	01 Jul 2008	US 2006149146 A1	06 Jul 2006
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		EP 1575424 B1	30 Jun 2010
		JP 2006508752 A	16 Mar 2006
		WO 2004052190 A1	24 Jun 2004