LOW POWER DEVICE WITH CONTINGENT SCHEDULING

Inventor: Kent Leyde, Sammamish, WA (US)

Correspondence Address:
WOODCOCK WASHBURN LLP
CIRA CENTRE, 12TH FLOOR, 2929 ARCH STREET
PHILADELPHIA, PA 19104-2891

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ABSTRACT

Medical device systems and methods for operating medical device systems conserve energy by efficiently managing computational demands of the systems. A first analysis, having relatively lower computational processing demand than at least a second analysis, processes signals from a subject to determine a first estimate of a propensity for the subject to have a neurological event. If the first estimate meets a set of specified criteria, a second analysis is performed to determine a second estimate of the propensity for the subject to have a neurological event.
Measure Signals 110
Generate Input Data 112
Perform First Level Analysis 114
Estimate First Propensity 116

Does the 1st Estimate Meet the Criteria? 118

Yes
Perform Second Level Analysis 120
Estimate Second Propensity 122
Communicate Result to the Subject 124
Return to Monitoring 126

No

FIG. 3
LOW POWER DEVICE WITH CONTINGENT SCHEDULING

FIELD

[0001] The present invention relates generally to medical device systems.

BACKGROUND

[0002] A variety of medical device systems are used to measure physiological signals from a subject to detect and to process the signals and provide indications of potential or actual problem conditions. Computational demands of processing systems associated with the medical devices and systems produce drains on power sources of these devices and can have a major impact on overall battery life. Moreover, in many medical device systems, it is desirable to keep the system as small and unobtrusive as possible so that the patient can have it available at all times.

[0003] In the case of implantable systems, power source replacement may involve surgery with its attendant costs and risks to the subject. Moreover, power source replacement may involve replacement of the implantable system itself because such units are typically hermetically sealed to reduce the likelihood of infection.

SUMMARY

[0004] The invention provides medical device systems and methods for operating medical device systems that provide energy savings by efficiently managing computational demands of the system. Some such systems comprise detectors to receive input from a subject, communications systems to deliver signals indicative of the input to a processor, processing systems to analyze the signals and determine one or more conditions of the subject, and a communication system to provide indications of the one or more conditions to the subject.

[0005] The various embodiments describe ways for a medical device to provide at least two stages of processing for signals measured from a subject. A first set of computer instructions, programmable logic, or circuitry, for example, one or more feature extractors and one or more classifiers process the signals to determine a first estimate of a susceptibility or propensity of the subject to have a neurological event. If the first estimate meets a set of criteria, a second set of computer instructions, programmable logic or circuitry, typically more computationally demanding and/or more sensitive and possibly providing more specific results than the first, is enabled to provide a second estimate of the propensity for the subject to have a neurological event. If desired, information related to the estimate may be output to the subject. The systems and methods can proceed in such a manner for any number of iterations. For example, a third set of computer instructions, programmable logic or circuitry may be enabled if the second estimate meets a second set of criteria, and so forth. Information related to the estimate may be output to the subject. The computer instructions, programmable logic or circuitry may be enabled on a processing system that is external to the subject, on a processing system that is implanted in the subject, or on combinations of external and implanted processing systems.

BRIEF DESCRIPTION OF THE DRAWINGS

[0006] FIG. 1 is a block diagram illustrating aspects of contingent use of feature extractors and classifiers;
[0007] FIG. 2 is an example of a classifier output;
[0008] FIG. 3 is a flow chart of an embodiment of contingent analysis;
[0009] FIG. 4 is an example timeline for an embodiment of an analysis scheduling that varies temporally.
[0010] FIG. 5 is a simplified diagram of a system that embodies a contingent scheduling system;
[0011] FIG. 6 is a block diagram of an implanted communications unit that may be used in accordance with the systems and methods described herein;
[0012] FIG. 7 is a block diagram of an external data device that may be used in accordance with the systems and methods described herein;
[0013] FIG. 8 is an example timeline for a typical therapeutic regimen for the treatment of epilepsy; and
[0014] FIG. 9 is an example timeline for a therapeutic regimen for the treatment of epilepsy that may be enabled by the system and methods described herein.

DETAILED DESCRIPTION

[0015] Certain specific details are set forth in the following description and figures to provide a full understanding of various embodiments of the invention. Certain well-known details, associated electronics and medical devices are not set forth in the following disclosure to avoid unnecessarily obscuring the various embodiments of the invention. Further, those of ordinary skill in the relevant art will understand that they can practice other embodiments of the invention without one or more of the details described below. Finally, while various processes are described with reference to steps and sequences in the following disclosure, the description is for providing a clear implementation of particular embodiments of the invention, and the steps and sequences of steps should not be taken as required to practice this invention.

[0016] As described in the background, a variety of medical device systems are used to measure physiological signals from a subject and to process those signals. Some such medical device systems, especially those comprising ambulatory and implantable devices, operate on portable power sources such as batteries. Computational processing demands, especially in the case of substantially continuous or repeated monitoring of the subject, can cause energy drains and may have a negative impact on battery life. The various embodiments of the systems and methods provided herein reduce the computational burden on such systems to extend the battery life.

[0017] Although some of the discussion below focuses on measuring EEG signals of subjects and subject populations for the detection and prediction of epileptic seizures, it should be appreciated that the invention is not limited to measuring EEG signals or to predicting epileptic seizures. For example, the invention could also be used in systems that measure one or more of a blood pressure, pulse oximetry, temperature of the brain or of portions of the subject, blood flow measurements, ECG/EKG, heart rate signals, respiratory signals, chemical concentrations of neurotransmitters, chemical con-
centrations of medications, pH in the blood, or other physiological or biochemical parameters of a subject.

Furthermore, aspects of the invention may be useful for monitoring and assisting in the treatments for a variety of conditions such as sleep apnea and other sleep disorders, migraine headaches, depression, Alzheimer’s, Parkinson’s Disease, dementia, attention deficit disorder, stroke, eating disorders, other neurological or psychiatric disorders, cardiac disease, diabetes, cancer, or the like.

Using epilepsy as an illustrative example, epilepsy is a disorder of the brain characterized by neurological events in the form of chronic, recurring seizures and affects an estimated 50 million people worldwide. Seizures are a result of uncontrolled discharges of electrical activity in the brain. A seizure typically manifests itself as sudden involuntary, disruptive, and often destructive sensory, motor, and cognitive phenomena. Epilepsy is usually treated, though not cured, with medication. Surgery may be indicated in cases in which seizure focus is identifiable, and the seizure focus is not located in the eloquent cortex.

A single neurological event most often does not cause significant morbidity or mortality, but severe or recurring neurological events can result in major medical, social, and economic consequences. Epilepsy is more often diagnosed in children and young adults. People with uncontrolled epilepsy are often significantly limited in their ability to work in many industries and may not be able to legally drive an automobile.

The cause of epilepsy is often uncertain. Symptomatic epilepsies arise due to some structural or metabolic abnormality of the brain and may result from a wide variety of causes including genetic conditions, stroke, head trauma, complications during pregnancy or birth, infections such as bacterial or viral encephalitis, or parasites. Idiopathic epilepsies are those for which no other condition has been implicated as a cause and are often genetic and generalized. In the majority of cases, the cause of a subject’s epilepsy is unknown.

One of the most disabling aspects of neurological disorders such as epilepsy is the seeming unpredictability of neurological events such as seizures. Mechanisms underlying the generation of seizures are thought to operate over a period of seconds to minutes before the clinical onset of a seizure. Typically, electrographic manifestations of a neurological event are detectable some time before clinical manifestations occur. Most work in the quantitative analysis of neurological events has been aimed at detecting these electrographic manifestations. NeuroPace, Inc. has been developing systems to detect the electrographic onset of a neurological event so that some action, such as direct electrical stimulation of certain brain structures, may be taken in an attempt to preempt the clinical onset of a neurological event. However, the detection of the electrographic onset of a neurological event may not come far enough in advance of the clinical onset for electrical stimulation or other therapies, such as the administration of anticonvulsant drugs, to be effective in preventing the clinical onset. Additionally, seizure activity may already be causing harm to the brain before the clinical onset of the seizure.

It is desirable to be able to predict neurological events well before their electrographic onset. Embodiments of predictive systems generally comprise a collection of detectors for acquiring data from a subject and an analysis system for processing the data. Predictive analysis systems are routinely considered to be comprised of arrangements of feature extractors and classifiers. Feature extractors are used to quantify or characterize certain aspects of the measured input signals. Classifiers are then used to combine the results obtained from the feature extractors into an overall answer or result. Systems may be designed to detect different types of conditions that may be reflective of neural condition. These could include, but are not limited to, systems designed to detect if the subject’s neural condition is indicative of an increased susceptibility or propensity for a neurological event or systems designed to detect deviation from a normal condition. As can be appreciated, for other neurological or non-neurological disorders, the classification of the subject’s neural condition will be based on systems, feature extractors and classifiers that are deemed to be relevant to the particular disorder.

FIG. 1 depicts an example of the overall structure of a system for estimating a propensity for the onset of a neurological event such as, for example, an epileptic seizure. The input data 102 may comprise representations of physiological signals obtained from monitoring a subject. Any number of signal channels may be used. Examples of physiological signals that may be used as input data 102 include, but are not limited to, electrical signals generated by electrodes placed on or within the brain or nervous system (EEG signals), temperature of the brain or of portions of the brain, blood pressure or blood flow measurements, pulse oximetry, ECG/ECG, blood pH, chemical concentrations of neurotransmitters, chemical concentrations of medications, combinations of the preceding, and the like.

The input data may be in the form of analog signal data or digital signal data that has been converted by way of an analog to digital converter (not shown). The signals may also be amplified, preprocessed, and/or conditioned to filter out spurious signals or noise. For purposes of simplicity the input data of all of the preceding forms is referred to herein as input data 102.

The input data 102 from the selected physiological signals is supplied to one or more feature extractors 104a, 104b, 105. A feature extractor 104a, 104b, 105 may be, for example, a set of computer executable instructions stored on a computer readable medium, or a corresponding instantiated object or process that executes on a computing device. Certain feature extractors may also be implemented as programmable logic or as circuitry. In general, a feature extractor 104a, 104b, 105 can process data 102 and identify some characteristic of the data 102. Such a characteristic of the data is referred to herein as an extracted feature.

Operation of a feature extractor 104a, 104b, 105 requires expenditure of electrical energy to process data and identify characteristics. The amount of electrical energy required may depend on the complexity, quantity, and quality of the input data and on the complexity of the processing system applied to the input data. Feature extractors 104a, 104b, 105 that are more complex generally require correspondingly larger amounts of electrical energy. As described more fully below, in some embodiments, some feature extractors 105 may be optionally applied or omitted in various circumstances. For example, when the application of one set of feature extractors 104a, 104b is sufficient to estimate that a propensity for a neurological event is sufficiently low, then other feature extractors 105 may not be applied to the input data 102. If the set of feature extractors 104a, 104b indicates a higher propensity for a neurological event, then additional feature extractors 105 may be applied to the input data 102.
Each feature extractor 104a, 104b, 105 may be univariate (operating on a single input data channel), bivariate (operating on two data channels), or multivariate (operating on multiple data channels). Some examples of potentially useful characteristics to extract from signals for use in determining the subject’s propensity for a neurological event include but are not limited to, alpha band power (8-13 Hz), beta band power (13-18 Hz), delta band power (0.1-4 Hz), theta band power (4-8 Hz), low beta band power (12-15 Hz), mid-beta band power (15-18 Hz), high beta band power (18-30 Hz), gamma band power (30-48 Hz), second, third and fourth (and higher) statistical moments of the EEG amplitudes, spectral edge frequency, decorrelation time, Hjorth mobility (HM), Hjorth complexity (HC), the largest Lyapunov exponent $L_{\text{max}}$, effective correlation dimension, local flow, entropy, loss of recurrence $L_R$ as a measure of non-stationarity, mean phase coherence, conditional probability, brain dynamics (synchronization or desynchronization of neural activity, STI, max. T-index, angular frequency, and entropy), line length calculations, area under the curve, first, second and higher derivatives, integrals, or a combination thereof. Of course, for other neurological conditions, additional or alternative characteristic extractors may be used with the systems described herein.

The extracted characteristics can be supplied to one or more classifiers 106, 107. Like the feature extractors 104a, 104b, 105, each classifier 106, 107 may be, for example, a set of computer executable instructions stored on a computer readable medium or a corresponding instantiated object or process that executes on a computing device. Certain classifiers may also be implemented as programmable logic or as circuitry. Operation of a classifier 106, 107 requires electrical energy. The classifiers can vary in complexity. Classifiers 106, 107 that are more complex may require correspondingly larger amounts of electrical energy. In some embodiments, some classifiers may be optionally applied or omitted in various circumstances. For example, when the application of one or more classifiers 106 is sufficient to estimate that a propensity for a neurological event is sufficiently low, then other classifiers 107 may not be applied to the extracted characteristics. If the classifiers 106 indicate a higher propensity for a neurological event, then additional classifiers 107 may be applied to the extracted characteristics.

The classifiers 106, 107 analyze one or more of the extracted characteristics and possibly other subject dependent parameters to provide a result 108 that may characterize, for example, a subject’s neural condition. Some examples of classifiers include k-nearest neighbor (“KNN”), neural networks, and support vector machines (“SVM”). Each classifier 106, 107 may provide a variety of output results, such as a logical result or a weighted result. The classifiers 106, 107 may be customized for the individual subject and may be adapted to use only a subset of the characteristics that are most useful for the specific subject. For example, the classifier may detect pre-onset characteristics of a neurological event. Additionally, over time, the classifiers 106, 107 may be further adapted to the subject, based, for example, in part on the result of previous analyses and may reselect extracted characteristics that are used for the specific subject.

As it relates to epilepsy, for example, one implementation of a classification of neural conditions defined by the classifiers 106, 107 may include (1) an inter-ictal condition (sometimes referred to as a “normal” condition), (2) a pre-ictal condition (sometimes referred to as an “abnormal” or “pre-seizure” condition), (3) an ictal condition (sometimes referred to as a “seizure” condition), and (4) a post-ictal condition (sometimes referred to as a “post-seizure” condition). In another embodiment, it may be desirable to have the classifier classify the subject as being in one of two conditions—a pre-ictal condition or inter-ictal condition—which could correspond, respectively, to either an elevated or high propensity for a future seizure or a low propensity for a future seizure.

As noted above, instead of providing a logical answer, it may be desirable for a classifier 106, 107 to provide a weighted answer so as to further delineate within the pre-ictal condition to further allow the system to provide a more specific output communication for the subject. For example, instead of a simple logical answer (e.g., pre-ictal or inter-ictal) it may be desirable to provide a weighted output or other output that quantifies the subject’s propensity, probability, likelihood and/or risk of a future neurological event using some predetermined scale (e.g., scale of 1-10, with a “1” meaning “normal” and a “10” meaning a neurological event is imminent). For example, if it is determined that the subject has an increased propensity for a neurological event (e.g., subject has entered the pre-ictal condition), but the neurological event is likely to occur on a long time horizon, the output signal could be weighted to be reflective of the long time horizon, e.g., an output of “5”. However, if the output indicates that the subject is pre-ictal and it is predicted that the neurological event is imminent within the next 10 minutes, the output could be weighted to be reflective of the shorter time horizon to the neurological event, e.g., an output of “9”. On the other hand, if the subject is normal, the system may provide an output of “1”.

Other implementations involve classifier 106 outputs expressing the inter-ictal and pre-ictal conditions as a continuum, with a scalar or vector of parameters describing the actual condition and its variations. FIG. 2 depicts an example of a graphical display of the output of one embodiment of a classifier over a period of time. The output of the classifier at any point in time is a vector of two estimated probabilities: an estimated probability 152 that the input data is indicative of an inter-ictal condition and an estimated probability 154 that the input data is indicative of a pre-ictal condition. The sum of the two probabilities 152, 154, at any given time is one. The estimated probabilities 152, 154 are plotted over a period of time beginning approximately 360 minutes before the onset of a neurological event at time zero indicated by the vertical axis 150. In the example graph, the estimated probability 152 that the data is indicative of an inter-ictal state was larger than the estimated probability 154 that the data was indicative of a pre-ictal state, until approximately 80 minutes before the onset 150 of the neurological event. The estimated probability 152 then dropped to very small values beginning approximately 50 minutes before the onset 150. The estimated probability 154 that the data is indicative of a pre-ictal state remained low until approximately 80 minutes before the onset 150 of the neurological event at which time it began to trend upward rapidly.

As described above, the computational demands of the processing provided by feature extractors 104a, 104b, 105 and classification provided by classifiers 106, 107 can be extensive. In the case of ambulatory systems supplied by portable power sources, such as implanted batteries, supplying the energy required to meet the computational demands can severely limit power source life. In some applications,
physiological signals may be measured and analyzed continuously or often over long periods of time and the need to conserve energy may be particularly acute.

[0035] FIG. 3 depicts a simplified block diagram of a method of operating medical devices for analyzing signals that provides energy savings by enabling different parts of an overall algorithm to process signals only as needed in order to reduce energy consumption and optimize system performance. One or more physiological signals from a subject are measured 110. In one embodiment, sixteen channels of physiological signals are measure. More or fewer channels may be measured according to the particular kinds of analysis being employed. The measured signals may be pre-processed, such as, for example, by amplification, filtering, and/or conversion from analog to digital, to generate input data 112 for the analysis. Input data 112 may also comprise other subject dependent parameters (such as subject inputs and/or subject history data) that may be indicative and/or predictive of a subject's propensity for a neurological event.

[0036] Typically, the physiological signal(s) from the subject are measured during a sliding observation window or epoch. Characteristics of the sliding window may be adapted based on previous measurements and analysis. In particular, the sliding windows may operate continuously, periodically during specified intervals, or during an adaptively modified schedule (for example, to customize it to the specific subject's cycles). In some embodiments, adaptations to the sliding window can be made automatically by the system. In some embodiments, adaptations to the window may be made by a clinician. For example, if it is known that the subject is prone to have a neurological event in the morning, a clinician may program the system to continuously monitor the subject during the morning hours, while only periodically monitoring the subject during the remainder of the day. As another example, it may be less desirable to monitor a subject and provide an output to a subject when the subject is asleep. In such cases, the system may be programmed to discontinue monitoring or change the monitoring and communication protocol with the subject during a specified “sleep time” or whenever a subject inputs into the system that the subject is asleep or when the system determines that the subject is asleep. This could include intermittent monitoring, monitoring with a varying duty cycle, decreasing of the sampling frequency, or other energy saving or data minimization strategy during a time period in which the risk for a neurological event is low. Additionally, the system could enter into a low risk mode for a time period following each medication dose.

[0037] Input data 112 is subjected to a first stage analysis 114. The first stage analysis 114 may be performed by logic embodied in, for example, computer-executable instructions, such as program modules, executed by one or more computers or other devices. Generally, program modules include routines, programs, objects, components, data structures, and the like that perform particular tasks or implement particular abstract data types. Typically the functionality of the program modules may be combined or distributed as desired in various embodiments. The first stage analysis 114 may comprise the application of one or more feature extractors and a classifier such as described above. Typically, the first stage analysis 114 will comprise the application of a subset of available feature extractors applied to the input data to identify some characteristics of the signals. Preferably, the first stage analysis will be relatively low in computational demands and will have a relatively high sensitivity, but not necessarily a high specificity. In general terms, the sensitivity of the analysis is related to the probability that analysis indicates the presence of a condition given that the condition actually exists. In general terms, the specificity of the analysis is related to the probability that the analysis indicates the absence of a condition given that the condition is actually absent. The detection of particular frequencies in EEG signals is one example of feature extractor having a relatively low computational demand. The output(s) from the first set of feature extractors may be combined using a first classifier.

[0038] Based on the first stage analysis 114, a first estimate of a susceptibility or propensity for the subject to have a neurological event is determined 116. The first estimate may take the form of a qualitative characterization or may be represented quantitatively or by a combination of qualitative and quantitative characterizations. A qualitative characterization may, for example, relate to the presence of pre-onset characteristics for a neurological event. A quantitative characterization may be a single number, such as, for example, by a probability of a neurological event occurring in a predetermined time period following the measurement of the signals or an estimated time horizon during which an estimated propensity for the subject to have a neurological event is below a predetermined threshold, or a collection of values that characterize the analysis.

[0039] The first estimate 116 is then examined 118 to determine whether it meets one or more specified criteria. The specified criteria may be universal or may be adapted to a particular subject. By way of examples, the criteria may include the presence or absence of certain features in the signals or the exceedance of a threshold probability. The criteria may be modified over time. The criteria may be adapted in response to various conditions of the subject such as, for example, the subject’s state of wakefulness or current activity level. The criteria may also adapted in response to current conditions of the medical device such as, for example, the current charge state of a battery.

[0040] If the criteria are not met, a second stage of analysis 120 is not performed and the system may return to a monitoring condition 126. In this instance, the computational and energy costs of the second stage analysis 120 are not incurred. For additional energy savings, for example if it is determined that a seizure is very unlikely, the system may also reduce the sampling rate or cease monitoring and turn off or go to sleep for some specified amount of time. Such embodiments will depend on the predictive value of collecting continuous monitoring data. For example, if it can be determined that the value of such data is low, turning off may be a viable option for some amount of time.

[0041] If the criteria in step 118 are met, for example if the estimate derived from the first analysis indicates an increased susceptibility or propensity for the monitored condition to exist or occur (for example, prediction of the pre-ictal condition), then the algorithm may transition from the base mode to a second or advanced mode wherein a second stage analysis 120 is performed to determine a second estimate of a propensity for the subject to have a neurological event 122. The second stage analysis 120 may be performed by logic embodied in, for example, computer-executable instructions, such as program modules, executed by one or more computers or other devices.

[0042] Depending on the particular embodiment, the set of feature extractors employed in the second stage analysis 120 may be used in conjunction with the set of feature extractors
employed in the first stage analysis 114 or as an alternative to the first set of feature extractors. The set of feature extractors employed in the second stage analysis 120 will typically afford a higher level of computational complexity and/or may have a higher specificity and/or sensitivity than the set of feature extractors employed in the first stage analysis 114. In one embodiment, the second stage analysis 120 may perform more refined versions of the analyses performed by the first stage analysis 114. In another embodiment, the second stage analysis 120 may perform different kinds of analyses. In yet other embodiments, the feature extractors in the first stage analysis and second stage analysis may have multi-resolution predictions and may provide for divergent spatial predictions. For example, the first stage analysis may include feature extractors that more accurately predict over a long time horizon, while the second stage analysis may more accurately predict over a short time horizon.

[0043] The output from the second set of feature extractors may be combined in the classifier used in the first stage analysis 114 or a second classifier. The result from either classifier may, in one embodiment, have both an improved sensitivity and specificity, relative to the sensitivity and specificity of the classification based on only the first set of feature extractors. The second estimate 122 is preferably more refined than the first estimate 116 and may take the form of a qualitative or a quantitative characterization or a combination thereof. It will be appreciated, however, that battery life is saved regardless of whether more or less computation is required to produce the second estimate 122 than the first estimate 116.

[0044] Once the subject’s susceptibility or propensity for seizure is estimated by the predictive algorithm, a signal that is indicative of the propensity for the future seizure may optionally be communicated to the subject 124. In some embodiments, the predictive algorithm provides an output that indicates when the subject has an elevated propensity for seizure. In such embodiments, the communication output to the subject may simply be a warning or a recommendation to the subject that was programmed into the system by the clinician. In other embodiments, the predictive algorithm may output a graded propensity assessment, a quantitative assessment of the subject’s condition, a time horizon until the predicted seizure will occur, or some combination thereof. In such embodiments, the communication output to the subject may provide a recommendation or instruction that is a function of the risk assessment, probability, or time horizon.

[0045] It will be recognized by those skilled in the art that the method described herein can readily be extended to encompass more than two stages of analysis. In one embodiment, the result of the first stage analysis may determine which of a plurality of second stage algorithms is selected to run. In another embodiment, the result of a second stage analysis may be used to decide whether a third stage of analysis is run, which result may trigger a fourth stage analysis, and so on.

[0046] In alternative embodiments of the energy saving methods disclosed herein, the predictive algorithms are run less often when previous results indicate that it is unlikely that a neurological event is imminent. For example, if the result of a previous execution of the algorithm indicates that it is relatively more likely that a neurological event will occur within a given time interval, the predictive algorithm may be scheduled to execute more frequently. Such variable scheduling techniques may be usefully combined with the other scheduling techniques discussed in detail herein.

[0047] FIG. 4 depicts an illustrative example of one such alternative embodiment. Each bar represents a result of the predictive system as measuring and analysis cycles were run at various times, t1, t2, etc. At time t1, a relatively low propensity of a neurological event was estimated and the next running of the analysis was scheduled for time t2. A similarly low propensity was estimated at time t3, and so the system was scheduled to run again at time t4, where the time interval t1-t4 is the same as the time interval t4-t5. At time t4, an elevated propensity was estimated and so the analysis was scheduled to execute more frequently, with a shorter interval between succeeding executions. The estimated propensity did not change again until the system was executed at time t5, at which time the estimated propensity was once again lower and so the system was scheduled to run on the baseline schedule as it had been at t1. At t1, a highly elevated propensity was estimated, and so the system was scheduled to run on a much more frequent schedule which continued until a lowered propensity was estimated at time t10.

[0048] The length and frequency of measurement and analysis cycles may be tailored to the prediction horizon. As an example, if the predictive system indicates that it is unlikely for a neurological event to occur in the next hour, the system could be scheduled to run more often than once per hour, but not so often as several hundred times per hour. Preferred scheduling frequencies would be between about 2 and about 100 times the reciprocal of the system’s neurological event prediction horizon. By varying the frequency of measuring and analysis cycles according to the estimated propensity, energy savings would be realized.

[0049] In an alternative embodiment, different prediction subsystems may be run depending on the results of prior calculations. For example, if the current propensity for a neurological event is remote, a corresponding exceptionally low operating power analysis subsystem would be scheduled. If the low operating power analysis subsystem indicates an elevated propensity for a neurological event, a second, more computationally demanding and more specific subsystem would be scheduled. If the output of the second subsystem indicates a propensity above a certain threshold, a third subsystem may be scheduled, and so forth. In yet another alternative embodiment, the approaches of the two preceding embodiments may be combined. The selection of subsystems and their rates of execution may depend on the results of prior analyses.

[0050] The systems described herein may be embodied as software, hardware, firmware, or combinations thereof. In some instances, it may be desirable to have first or lower stage systems operating only in hardware in order to minimize energy requirements. The systems described above may be embodied in a device external to the subject, an implanted device, or distributed between an implanted device and an external device.

[0051] Because the methods of the present invention are able to consume less energy than conventional algorithms and will thereby prolong the life of the power sources, the methods of the present invention will facilitate the long-term implementation of the algorithms in a portable and/or implantable device system. FIG. 5 illustrates a system in which the algorithms of the present invention may be embodied. The system 200 is used to monitor a subject 202 for purposes of detecting and predicting neurological events. The
The system 200 of the embodiment provides for substantially continuous sampling of brain wave electrical signals such as in electroencephalograms or electrocorticograms, referred to collectively as EEGs.

Any number of sensors 204 may be employed, but the sensors 204 will preferably include between 1 sensor and 16 sensors. The sensors may take a variety of forms. In one embodiment, the sensors comprise grid electrodes, strip electrodes and/or depth electrodes which may be permanently implanted through burr holes in the head. Exact positioning of the sensors will usually depend on the desired type of measurement. In addition to measuring brain activity, other sensors (not shown) may be employed to measure other physiological signals from the subject 202.

In an embodiment, the sensors 204 will be configured to substantially continuously sample the brain activity of the groups of neurons in the immediate vicinity of the sensors 204. The sensors 204 are electrically joined via cables 206 to an implanted communication unit 208. In one embodiment, the cables 206 and communication unit 208 will be implanted in the subject 202. For example, the communication unit 208 may be implanted in a subcutaneous or subcutaneous cavity of the subject 202. In alternative embodiments, the cables 206 and communication unit 208 may be attached to the subject 202 externally.

In one embodiment, the communication unit 208 is configured to facilitate the sampling of signals from the sensors 204. Sampling of brain activity is typically carried out at a rate above about 200 Hz, and preferably between about 200 Hz and about 1000 Hz, and most preferably at 400 Hz. The sampling rates could be higher or lower, depending on the specific conditions being monitored, the subject 202, and other factors. Each sample of the subject’s brain activity is typically encoded using between about 8 bits per sample and about 32 bits per sample, and preferably about 16 bits per sample.

In alternative embodiments, the communication unit 208 may be configured to measure the signals on a non-continuous basis. In such embodiments, signals may be measured periodically or aperiodically.

An external data device 210 is preferably carried external to the body of the subject 202. The external data device 210 receives and stores signals, including measured signals and possibly other physiological signals, from the communication unit 208. External data device 210 could also receive and store extracted features, classifier outputs, patient inputs, and the like. Communication between the external data device 210 and the communication unit 208 may be carried out through wireless communication. The wireless communication link between the external data device 210 and the communication unit 208 may provide a one-way or two-way communication link for transmitting data. In alternative embodiments, it may be desirable to have a direct communications link from the external data device 210 to the communication unit 208, such as, for example, via an interface device positioned below the subject’s skin. The interface (not shown) may take the form of a magnetically attached transducer that would enable power to be continuously delivered to the communication unit 208 and would provide for relatively higher rates of data transmission. Error detection and correction methods may be used to help ensure the integrity of transmitted data. If desired, the wireless data signals can be encrypted prior to transmission to the external data device 210.

FIG. 6 depicts a block diagram of one embodiment of a communication unit 208 that may be used with the systems and methods described herein. Energy for the system is supplied by a rechargeable power supply 224. The rechargeable power supply may be a battery, or the like. The rechargeable power supply 224 may also be in communication with a transmit/receive subsystem 226 so as to receive power from outside the body by inductive coupling, radiofrequency (RF) coupling, and the like. Power supply 224 will generally be used to provide power to the other components of the implantable device. Signals 212 from the sensors 204 are received by the communication unit 208. The signals may be initially conditioned by an amplifier 214, a filter 216, and an analog-to-digital converter 218. A memory module 220 may be provided for storage of some of the sampled signals prior to transmission via a transmit/receive subsystem 226 and antenna 228 to the external data device 210. For example, the memory module 220 may be used as a buffer to temporarily store the conditioned signals from the sensors 204 if there are problems with transmitting data to the external data device 210, such as may occur if the external data device 210 experiences power problems or is out of range of the communications system. The external data device 210 can be configured to communicate a warning signal to the subject in the case of data transmission problems to inform the subject and allow him or her to correct the problem.

The communication unit 208 may optionally comprise circuitry of a digital or analog or combined digital/analog nature and/or a microprocessor, referred to herein collectively as “microprocessor” 222, for processing the signals prior to transmission to the external data device 210. The microprocessor 222 may execute at least portions of the analysis as described herein. For example, in some configurations, the microprocessor 222 may run one or more feature extractors 104a, 104b, 105 (FIG. 1) that extract characteristics of the measured signal that are relevant to the purpose of monitoring. Thus, if the system is being used for diagnosing or monitoring epileptic subjects, the extracted characteristics (either alone or in combination with other characteristics) may be indicative or predictive of a neurological event. Once the characteristic(s) are extracted, the microprocessor 222 may transmit the extracted characteristic(s) to the external data device 210 and/or store the extracted characteristic(s) in memory 220. Because the transmission of the extracted characteristics is likely to include less data than the measured signal itself, such a configuration will likely reduce the bandwidth requirements for the communication link between the communication unit 208 and the external data device 210.

In some configurations, the microprocessor 222 in the communication unit 208 may run one or more classifiers 106, 107 (FIG. 1) as described above with respect to FIG. 1. The result 108 (FIG. 1) of the classification may be communicated to the external data device 210.

While the external data device 210 may include any combination of conventional components, FIG. 8 provides a schematic diagram of some of the components that may be included. Signals from the communication unit 208 are received at an antenna 230 and conveyed to a transmit/receive...
subsystem 232. The signals received may include, for example, a raw measured signal, a processed measured signal, extracted characteristics from the measured signal, a result from analysis software that ran on the implanted microprocessor 222, or any combination thereof.

The received data may thereafter be stored in memory 234, such as a hard drive, RAM, EEPROM, removable flash memory, or the like and/or processed by a microprocessor, application specific integrated circuit (ASIC) or other dedicated circuitry of a digital or analog or combined digital/analog nature, referred to herein collectively as a "microprocessor" 236. Microprocessor 236 may be configured to request that the communication unit 208 performs various checks (e.g., sensor impedance checks) or calibrations prior to signal recording and/or at specified times to ensure proper functioning of the system.

Data may be transmitted from memory 234 to microprocessor 236 where the data may optionally undergo additional processing. For example, if the transmitted data is encrypted, it may be decrypted. The microprocessor 236 may also comprise one or more filters that filter out low-frequency or high-frequency artifacts (e.g., muscle movement artifacts, eye-blink artifacts, chewing, and the like) so as to prevent contamination of the measured signals.

External data device 210 will typically include a user interface 240 for displaying outputs to the subject and for receiving inputs from the subject. The user interface will typically comprise outputs such as auditory devices (e.g., speakers) visual devices (e.g., LCD display, LEDs), tactile devices (e.g., vibratory mechanisms), or the like, and inputs, such as a plurality of buttons, a touch screen, and/or a scroll wheel.

The user interface may be adapted to allow the subject to indicate and record certain events. For example, the subject may indicate that medication has been taken, the dosage, the type of medication, meal intake, sleep, drowsiness, occurrence of an aura, occurrence of a neurological event, or the like. Such inputs may be used in conjunction with the measured data to improve the analysis.

The LCD display may be used to output a variety of different communications to the subject including, status of the device (e.g., memory capacity remaining), battery state of one or more components of system, whether or not the external data device 210 is within communication range of the communication unit 208, a warning (e.g., a neurological event warning), a prediction (e.g., a neurological event prediction), a recommendation (e.g., "take medicine"), or the like. It may be desirable to provide an audio output or vibratory output to the subject in addition to or as an alternative to the visual display on the LCD.

External data device 210 may also include a power source 242 or other conventional power supply that is in communication with at least one other component of external data device 210. The power source 242 may be rechargeable. If the power source 242 is rechargeable, the power source may optionally have an interface for communication with a charger 244. While not shown in FIG. 8, external data device 210 will typically comprise a clock circuit (e.g., oscillator and frequency synthesizer) to provide the time base for synchronizing the external data device 210 and the communication unit 208.

Referring again to FIG. 5, in a preferred embodiment, most or all of the processing of the signals received by the communication unit 208 is done in an external data device 210 that is external to the subject's body. In such embodiments, the communication unit 208 would receive the signals from subject and may or may not pre-process the signals and transmit some or all of the measured signals transcutaneously to an external data device 210, where the prediction of the neurological event and possible therapy determination is made. Advantageously, such embodiments reduce the amount of computational processing power that needs to be implanted in the subject, thus potentially reducing energy consumption and increasing battery life. Furthermore, by having the processing external to the subject, the judgment or decision making components of the system may be more easily reprogrammed or custom tailored to the subject without having to reprogram the communication unit 208.

In alternative embodiments, the predictive systems disclosed herein and treatment systems responsive to the predictive systems may be embodied in a device that is implanted in the subject's body, external to the subject's body, or a combination thereof. For example, in one embodiment the predictive system may be stored in and processed by the communication unit 208 that is implanted in the subject's body. A treatment analysis system, in contrast, may be processed in a processor that is embodied in an external data device 210 external to the subject's body. In such embodiments, the subject's propensity for neurological event characterization (or whatever output is generated by the predictive system that is predictive of the onset of the neurological event) is transmitted to the external subject communication assembly, and the external processor performs any remaining processing to generate and display the output from the predictive system and communicate this to the subject. Such embodiments have the benefit of sharing processing power, while reducing the communications demands on the communication unit 208. Furthermore, because the treatment system is external to the subject, updating or reprogramming the treatment system may be carried out more easily.

In other embodiments, the signals 212 may be processed in a variety of ways in the communication unit 208 before transmitting data to the external data device 210 so as to reduce the total amount of data to be transmitted, thereby reducing the power demands of the transmit/receive sub-system 226. Examples include: digitally compressing the signals before transmitting them; selecting only a subset of the measured signals for transmission; selecting a limited segment of time and transmitting signals only from that time segment; extracting salient characteristics of the signals, transmitting data representative of those characteristics rather than the signals themselves, and transmitting only the result of classification. Further processing and analysis of the transmitted data may take place in the external data device 210.

In yet other embodiments, it may be possible to perform some of the prediction in the communication unit 208 and some of the prediction in the external data device 210. For example, one or more characteristics from the one or more signals may be extracted with feature extractors in the communication unit 208. Some or all of the extracted characteristics may be transmitted to the external data device 210 where the characteristics may be classified to predict the onset of a neurological event. If desired, external data device 210 may be customizable to the individual subject. Consequently, the classifier may be adapted to allow identification or receipt of only the characteristics from the communication unit 208 that are predictive for that individual subject. Advantageously, by performing feature extraction in the communication unit 208 and classification in an external device at least two benefits may be realized. First, the amount of wireless data transmitted from the communication unit 208 to the external data device 210 is reduced (versus transmitting pre-processed data). Second, classification, which embodies the decision or judgment component, may be easily repro-
grammed or custom tailored to the subject without having to reprogram the communication unit 208. [0072] In yet another embodiment, feature extraction may be performed external to the body. Pre-processed signals (e.g., filtered, amplified, converted to digital) may be transmittedaneously transmitted from communication unit 208 to the external data device 210 where one or more characteristics are extracted from the one or more signals with feature extractors. Some or all of the extracted characteristics may be transmittedaneously transmitted back into the communication unit 208, where a second stage of processing may be performed on the characteristics, such as classifying the characteristics (and other signals) to characterize the subject’s propensity for the onset of a future neurological event. If desired, to improve bandwidth, the classifier may be adapted to allow for transmission or receipt of only the characteristics from the subject communication assembly that are predictive for that individual subject. Advantageously, because feature extractors may be computationally expensive and energy hungry, it may be desirable to have the feature extractors external to the body, where it is easier to provide more processing and larger power sources.

[0073] For additional energy savings, the systems of the present invention may also embody some of the energy saving concepts described in commonly owned, copending patent application Ser. Nos. entitled “Low Powered Device with Variable Scheduling,” filed concurrently herewith (BNC Docket No. 6.00US), the complete disclosure of which is incorporated herein by reference.

[0074] More complete descriptions of systems that may embody the concepts of the present invention are described in commonly owned, copending U.S. patent applications Ser. Nos. 11/321,897, 11/321,898, 11/322,150, all filed on Dec. 28, 2005, the complete disclosures of which are incorporated herein by reference.

[0075] The inventive aspects described herein may be applicable to commercial monitoring systems. For example, the systems herein may be applied to the NeuroPace® RNS system. Such commercial systems extract half-wave amplitude and duration, sum of absolute differences as an approximation of signal curve length (which is in turn a simplification of waveform fractal dimension), and a modified sum of absolute amplitudes as an approximation of signal energy. Instead of running all of the feature extractors continuously all of the time, subsequent measurement and analysis cycles may be scheduled based on analysis of previous measurement cycles. In some embodiments, the measuring and analysis cycles are run less often when the previous measurements indicate that it is relatively unlikely that a seizure is imminent. On the other hand, if previous measurements indicate that a seizure is relatively likely to be proximate, the measurement and analysis cycles are run more frequently, up to, possibly, some predetermined maximum rate. Such a feature extractor configuration will preserve computation power, reduce battery usage, and prolong the time between battery changes.

[0076] The ability to provide long-term low-power ambulatory recording of physiological signals and prediction of neurological events can facilitate improved treatment regimens for certain neurological conditions. FIG. 8 depicts the typical course of treatment for a subject with epilepsy. Because the occurrence of neurological events 300 over time has been unpredictable, present medical therapy relies on continuous prophylactic administration of anti-epileptic drugs (“AEDs”). Constant doses 302 of one or more AEDs are administered to a subject at regular time intervals with the objective of maintaining relatively stable levels of the AEDs within the subject. Maximum doses of the AEDs are limited by the side effects of their chronic administration.

[0077] Reliable long-term essentially continuously operating neurological event prediction systems would facilitate epilepsy treatment. Therapeutic actions, such as, for example, brain stimulation, peripheral nerve stimulation (e.g., vagus nerve stimulation), cranial nerve stimulation (“TNS”), or targeted administration of AEDs, could be directed by output from a neurological event prediction system. One such course of treatment is depicted in FIG. 9. Relatively lower constant doses 304 of one or more AEDs may be administered to a subject at regular time intervals in addition to or as an alternative to the prophylactic administration of AEDs. Supplementary medication doses 306 are administered just prior to an imminent neurological event 308. By targeting the supplementary doses 306 at the appropriate times, neurological events may be more effectively controlled and potentially eliminated 308, while reducing side effects attendant with the chronic administration of higher levels of the AEDs.

[0078] While the present disclosure has been described in connection with various embodiments, illustrated in the various figures, it is understood that similar aspects may be used or modifications and additions may be made to the described aspects of the disclosed embodiments for performing the same function of the present disclosure without deviating therefrom. Other equivalent mechanisms to the described aspects are also contemplated by the teachings herein. Therefore, the present disclosure should not be limited to any single aspect, but rather construed in breadth and scope in accordance with the appended claims.

What is claimed:
1. A method of operating a medical device system, the method comprising:
   receiving at least one signal from a physiological sensor;
   processing the at least one signal by performing a first analysis to estimate a first propensity for a subject to have a neurological event; and
   performing a second analysis to estimate a second propensity for the subject to have a neurological event when the first estimate meets one or more specified criteria.
2. The method of claim 1 wherein performing the first analysis requires less computational power than performing the second analysis.
3. The method of claim 1 further comprising modifying the one or more specified criteria based on a charge measurement for a battery associated with the medical device system.
4. The method of claim 1 wherein receiving at least one signal comprises receiving one or more electrical signals generated by neural activity.
5. The method of claim 4 wherein processing the at least one signal comprises analyzing said at least one signal by a first set of feature extractors.
6. The method of claim 5 wherein the first set of feature extractors comprises one or more feature extractors selected from the group consisting of frequency based feature extractors, phase coherence feature extractors, and band power feature extractors.
7. The method of claim 5 wherein at least one of the feature extractors in the first set of feature extractors is selected based on information about the subject.
8. The method of claim 5 wherein the second analysis comprises logics to analyze the at least one signal by a second set of feature extractors.
9. The method of claim 8 wherein said second set of feature extractors is characterized by relatively high specificity and
10. The method of claim 4 wherein the estimate of a first propensity for the subject to have a neurological event is an estimate of a probability for the subject to have a neurological event within a specified time frame.
11. The method of claim 4 wherein the neurological event is a seizure.
12. The method of claim 1 further comprising communicating to the subject information indicative of the second estimate when the first estimate meets the one or more specified criteria.
13. The method of claim 1 wherein performing the first analysis and performing the second analysis is performed by a processing system that is external to the subject.
14. The method of claim 1 wherein performing the first analysis is performed by a first processing system and performing the second analysis is performed by a second processing system.
15. The method of claim 1 further comprising: pre-processing the at least one signal using a first processing system to derive data representative of the one or more signals; communicating the derived data representative of the at least one signal to a second processing system, wherein the steps of processing the at least one signal by performing a first analysis and performing a second analysis are performed by the second processing system.
16. The method of claim 16 wherein the first processing system is implanted in the subject and the second processing system is external to the subject.
17. The system of claim 24 wherein the specified criteria comprise the condition of the estimate of the first propensity indicating that a likelihood for the subject to have a neurological event exceeds a specified threshold.
18. The system of claim 25 wherein the one or more sensors comprise one or more sensors for measuring brain activity signals of the subject.
19. The system of claim 25 wherein the neurological event is an epileptic seizure.
20. The system of claim 18 wherein the processor is external to the subject and the processor is configured to perform the second logic.
21. A device comprising: means for measuring at least one signal from a subject; means for analyzing the at least one signal from a subject to estimate a first propensity for the subject to have a neurological event; means for determining whether the estimate of the first propensity meets one or more specified criteria; means for estimating a second propensity for the subject to have a neurological event when the estimate of the first propensity meets the one or more specified criteria.
22. A system for estimating a propensity for a subject to have an epileptic seizure comprising: means for measuring at least one neurological signal from the subject; first logic arranged to receive the at least one signal and to class the signal to determine the second logic; a processor configured to perform the first logic; a processor configured to perform the second logic when the estimate of the first prevalence meets at least one specified criteria; a processor configured to perform the second logic.
23. The system of claim 29 wherein the specified criteria comprise: a neurological signal stored on computer accessible media and the second logic is embodied in executable instructions stored on computer accessible media.
24. The system of claim 29 wherein the first logic is embodied in a programmable logic device and the second logic is embodied in a programmable logic device.
25. The system of claim 29 wherein the first logic is embodied in a circuit and the second logic is embodied in a circuit.
26. The system of claim 29 further comprising: an implanted device for wirelessly transmitting data representative of said at least one neurological signal from a subject; and a receiver for receiving the transmitted data wherein said receiver is operationally coupled to at least one of the first processor and the second processor.
27. The system of claim 33 further comprising an output device for communicating information related to the estimate of the second propensity to the subject.