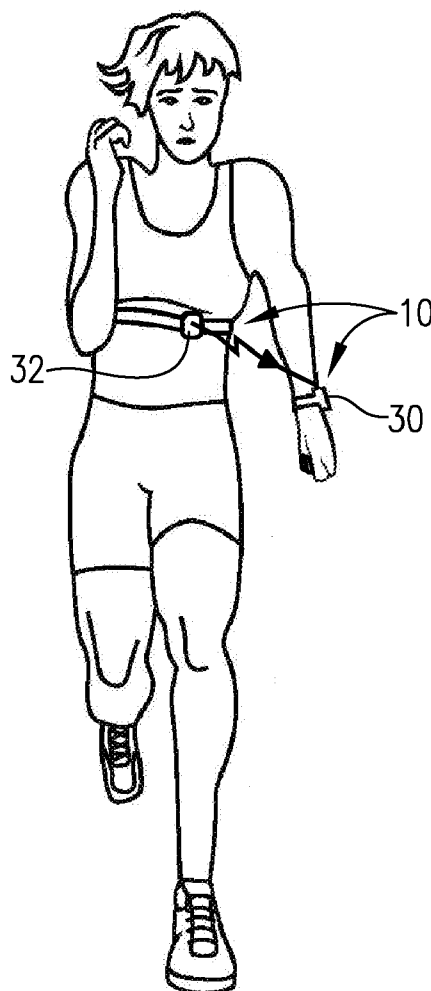




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Kulach et al.(10) **Pub. No.: US 2013/0178958 A1**(43) **Pub. Date: Jul. 11, 2013**(54) **METHOD AND SYSTEM FOR DETERMINING
USER PERFORMANCE CHARACTERISTICS****Publication Classification**(71) Applicant: **GARMIN SWITZERLAND GMBH,**
Schaffhausen (CH)(51) **Int. Cl.**
A63B 24/00 (2006.01)(72) Inventors: **Christopher J. Kulach**, Calgary (CA);
James K. Rooney, Cochrane (CA);
Andrew Skarsgard, Cochrane (CA)(52) **U.S. Cl.**
CPC **A63B 24/0021** (2013.01)
USPC **700/91**(73) Assignee: **GARMIN SWITZERLAND GMBH,**
Schaffhausen (CH)(57) **ABSTRACT**(21) Appl. No.: **13/736,246**(22) Filed: **Jan. 8, 2013****Related U.S. Application Data**(60) Provisional application No. 61/584,467, filed on Jan.
9, 2012.

A system for determining user performance characteristics includes an inertial sensor and a processing system. The inertial sensor may be coupled with the user's torso and generates one or more signals corresponding to the motion of the user's torso. The processing system is in communication with the inertial sensor and is operable to use the one or more signals to determine one or more user performance characteristics. The user performance characteristics may include speed, cadence, time energy cost, distance energy cost and acceleration energy cost.



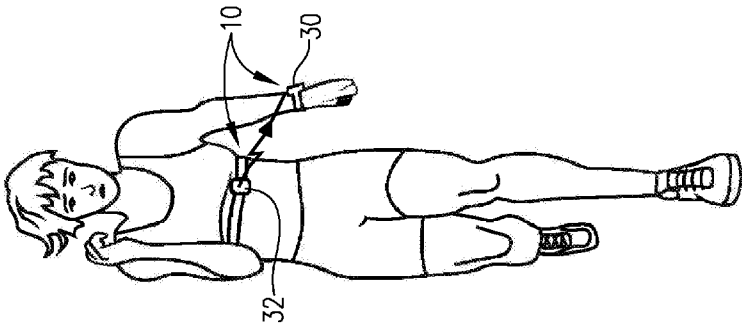


FIG. 1

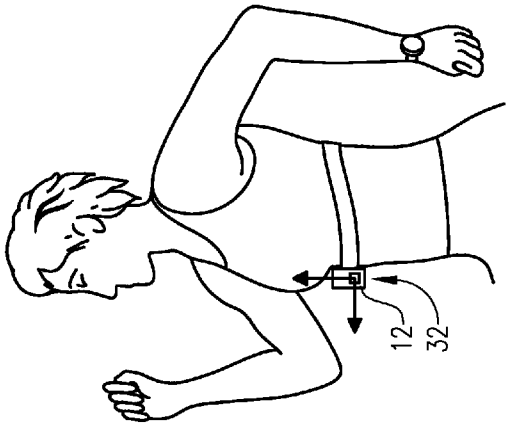


FIG. 2

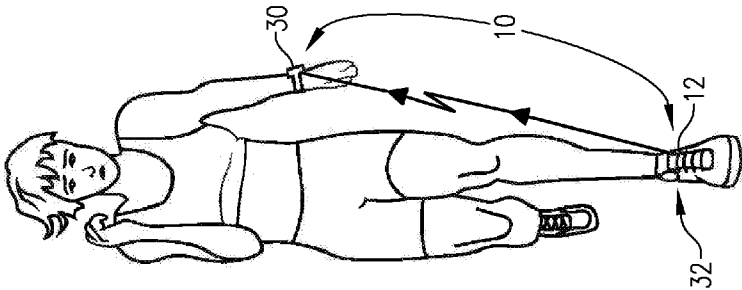


FIG. 3

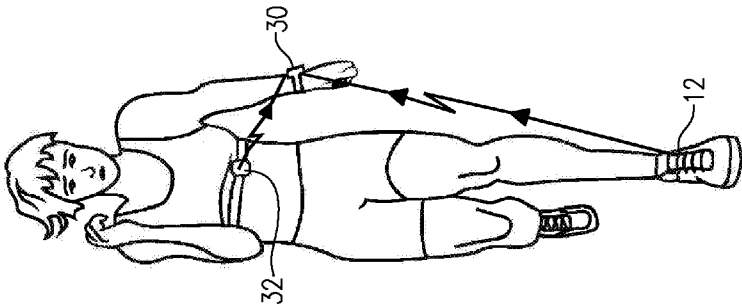


FIG. 5

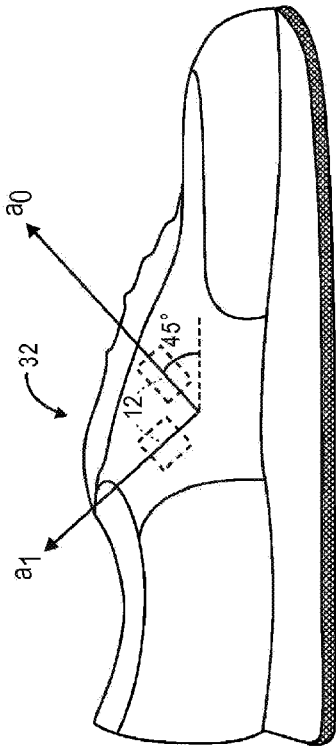


FIG. 4

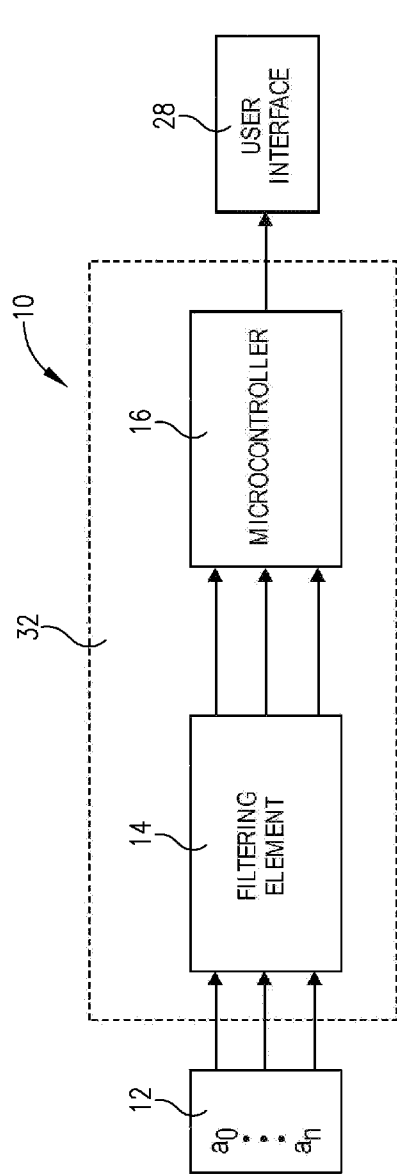


FIG. 6

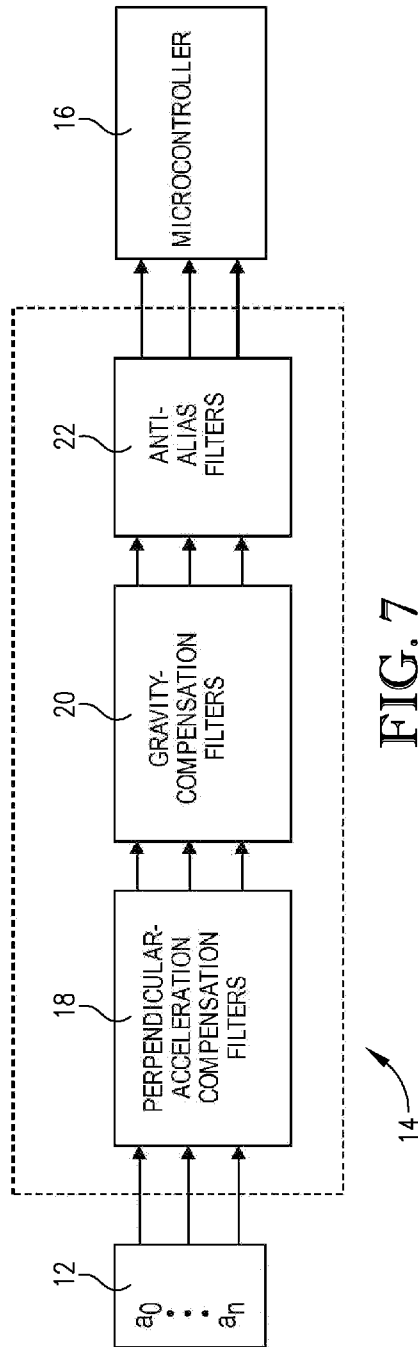


FIG. 7

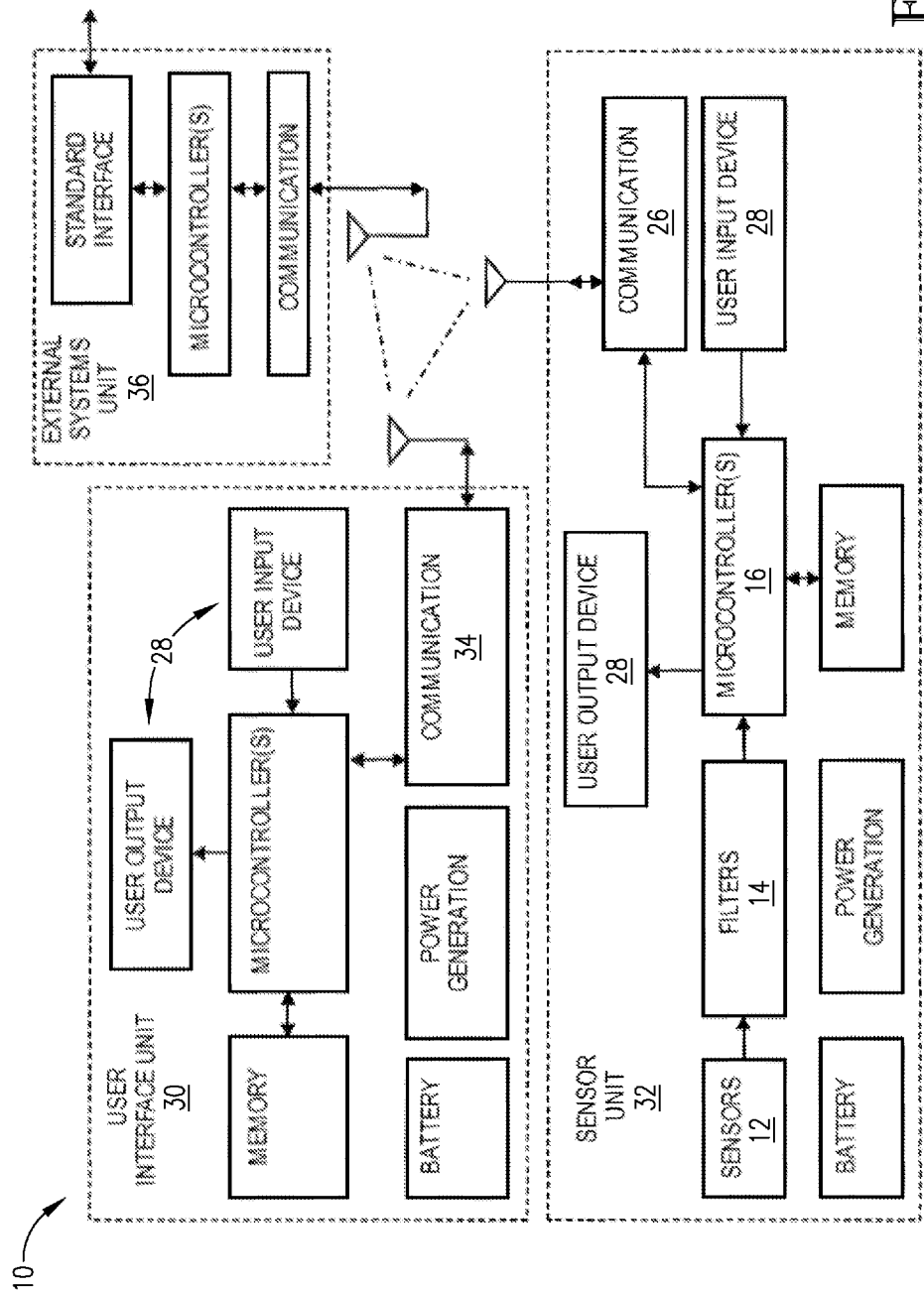


FIG. 8

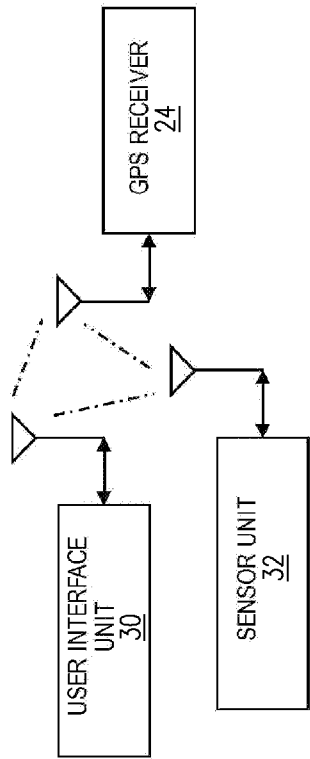


FIG. 9

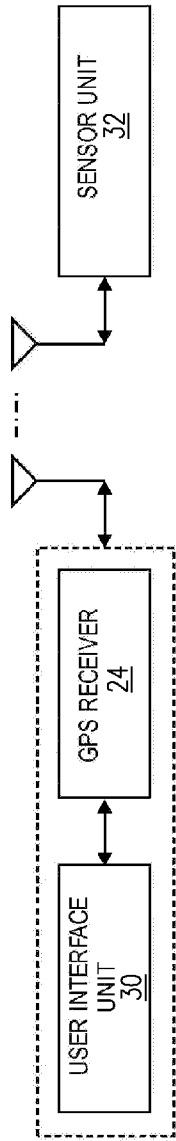


FIG. 10

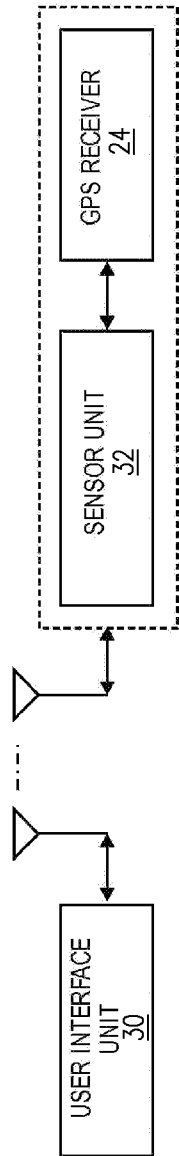


FIG. 11

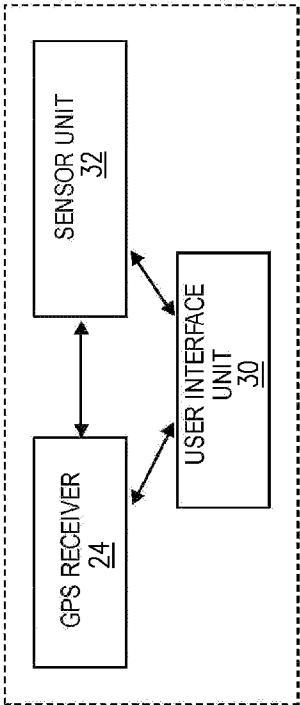


FIG. 12

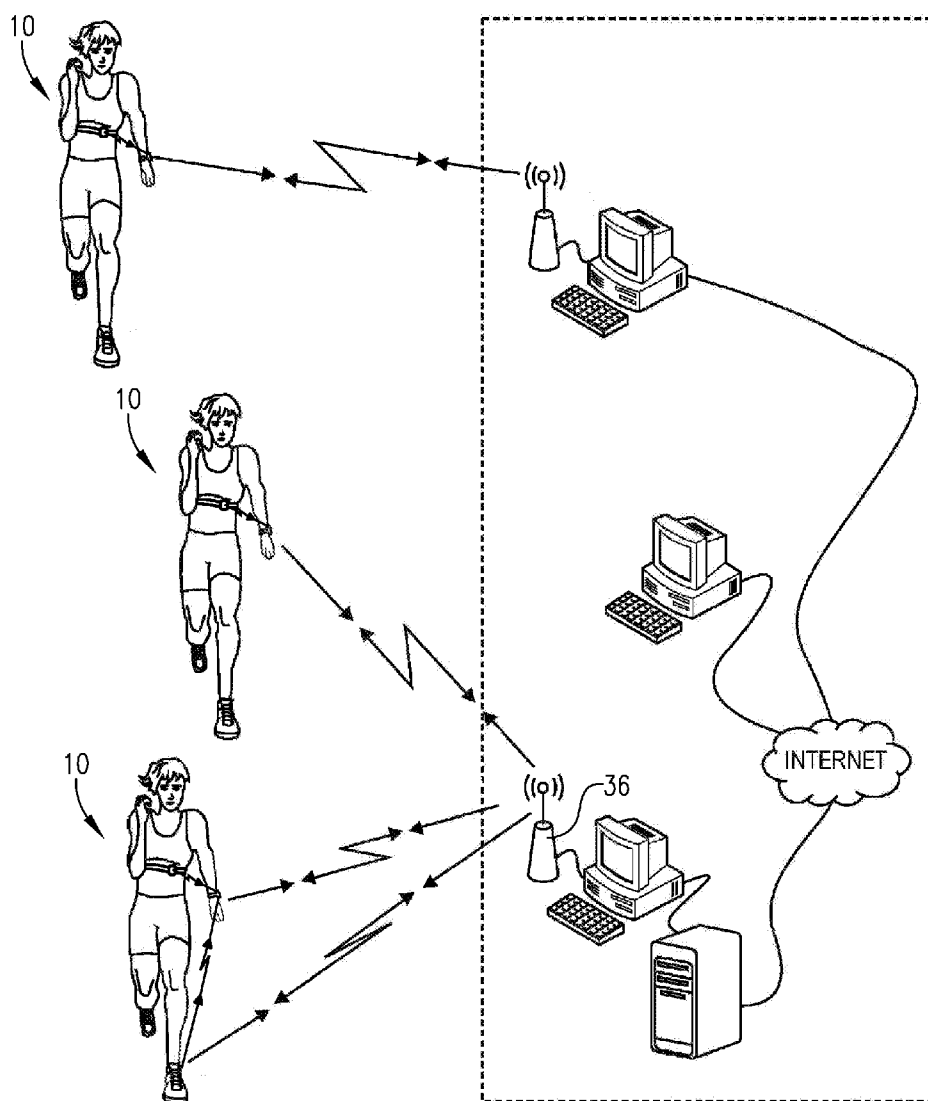


FIG. 13

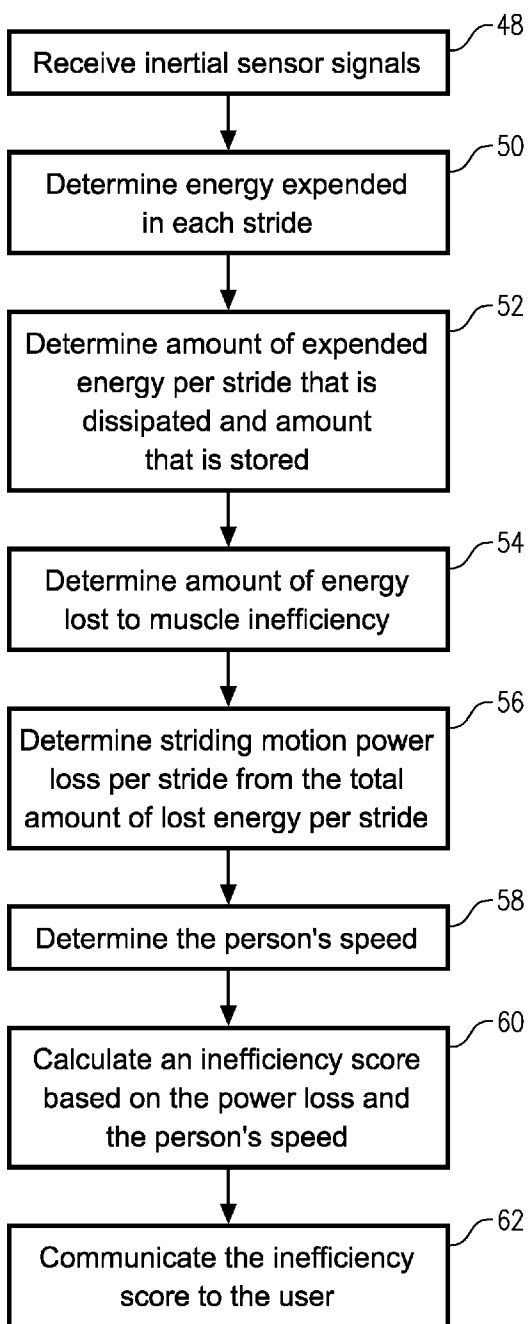


FIG. 14

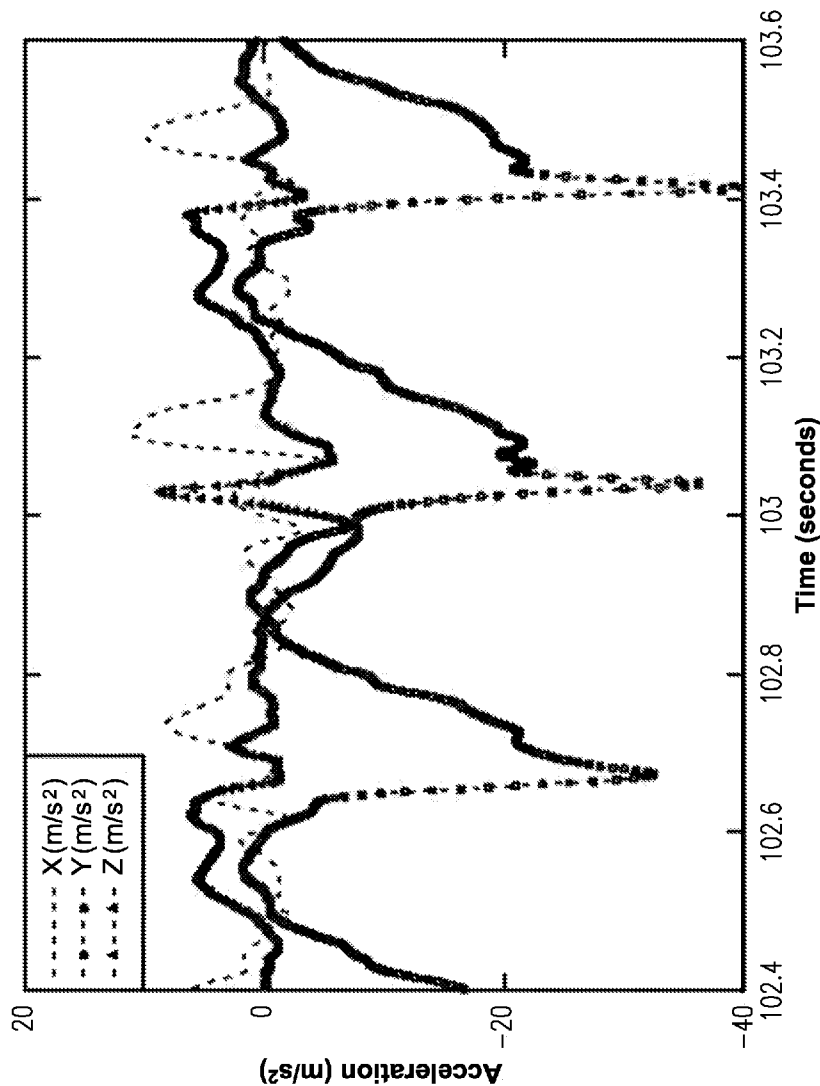


FIG. 15

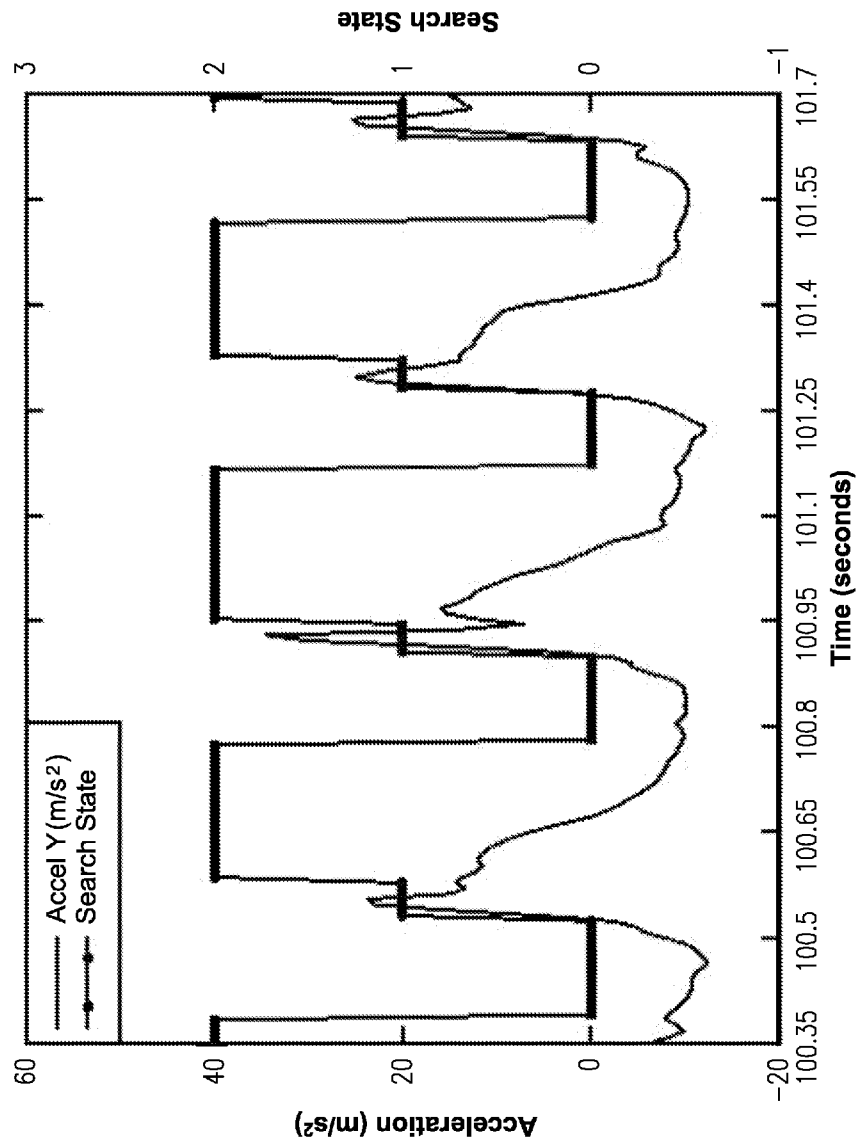


FIG. 16

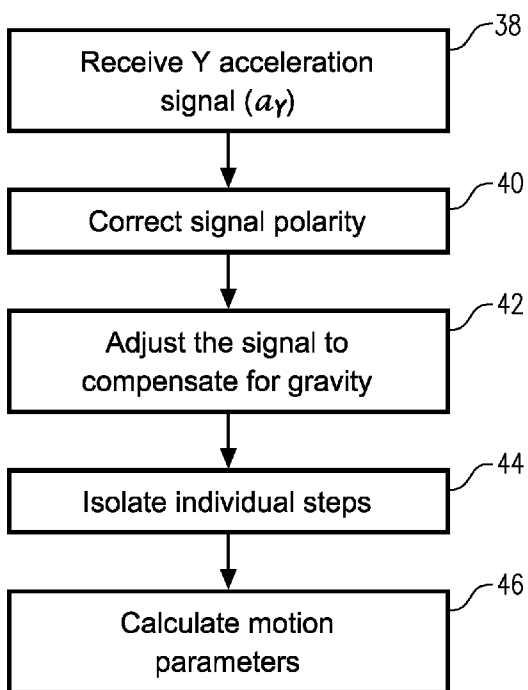


FIG. 17

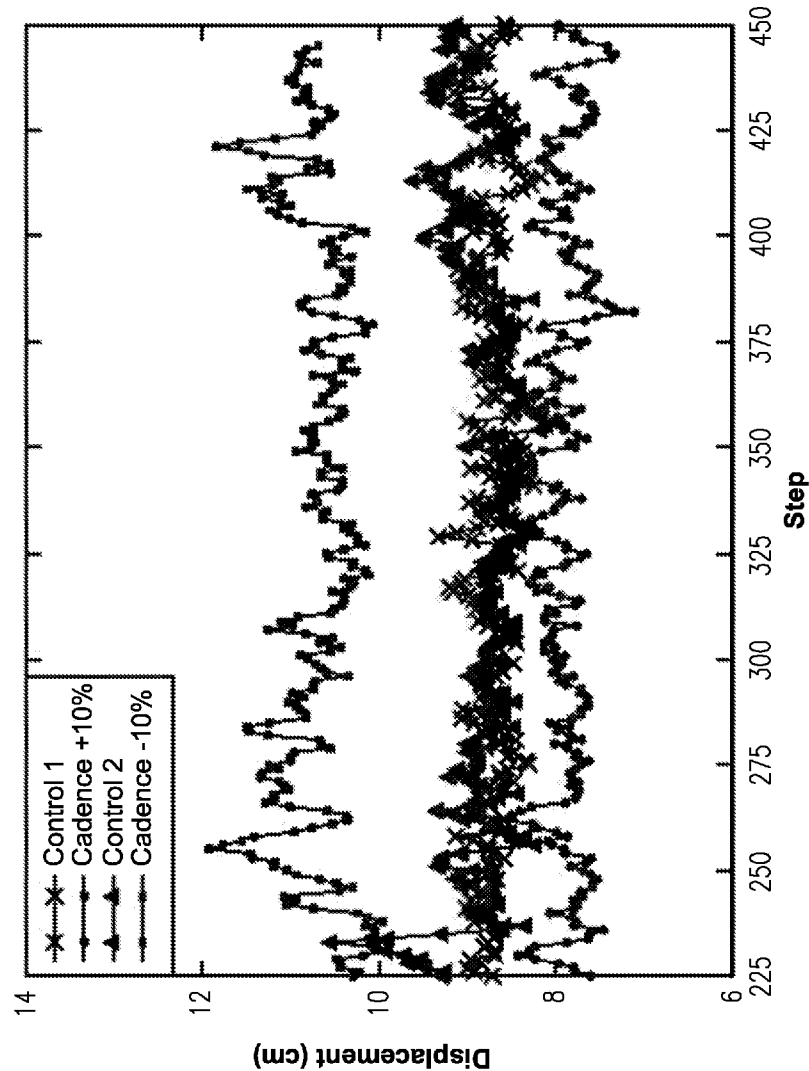


FIG. 18

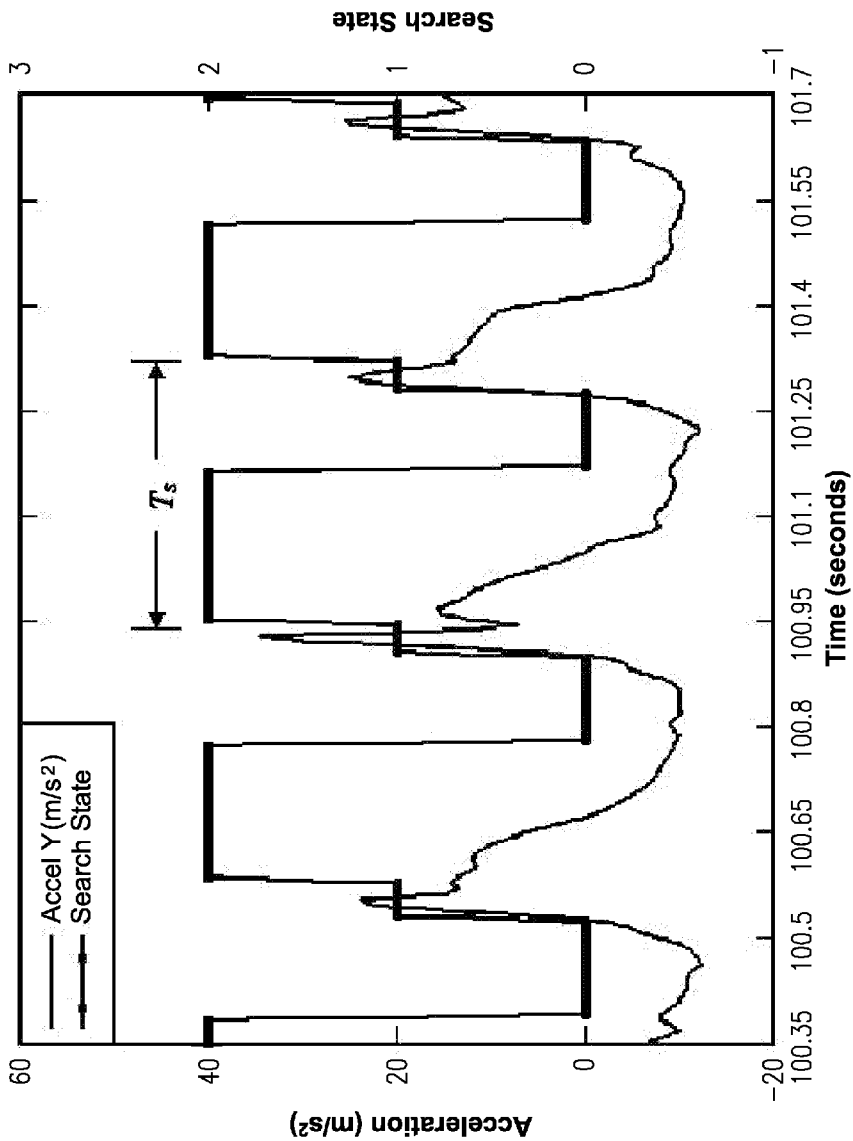


FIG. 19

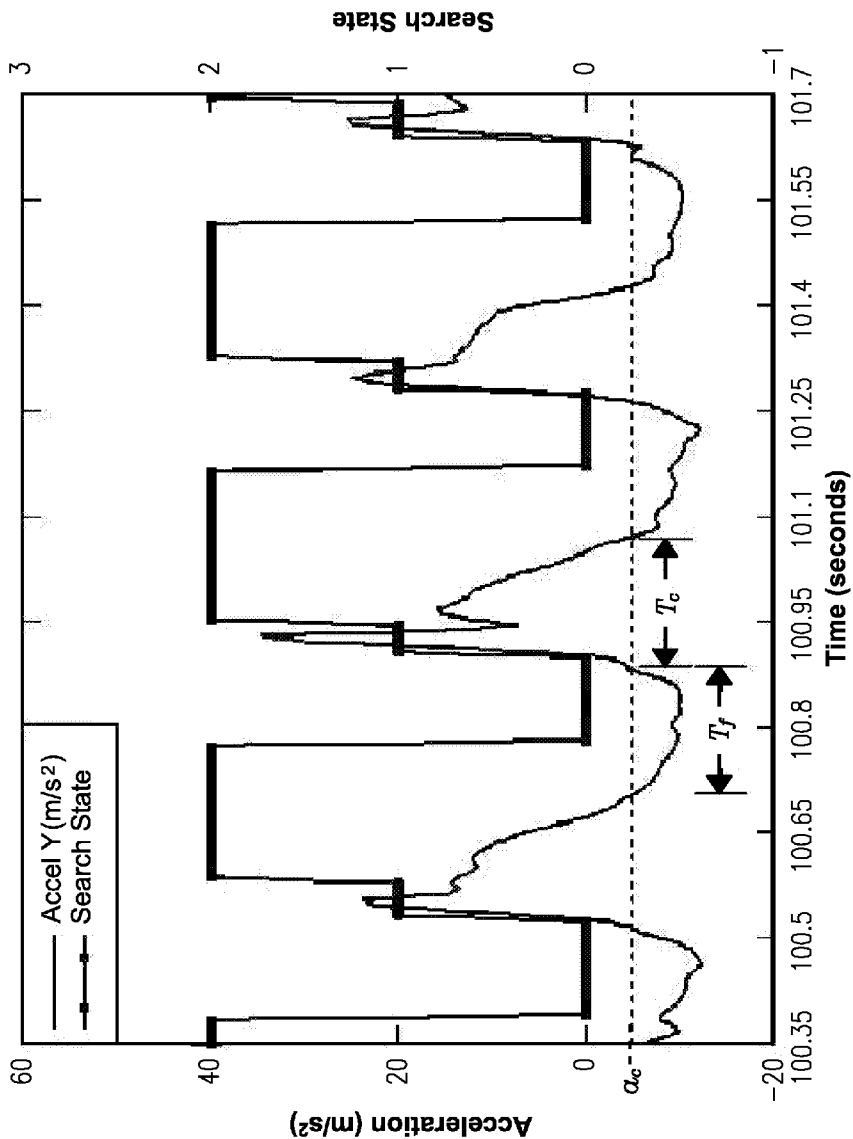


FIG. 20

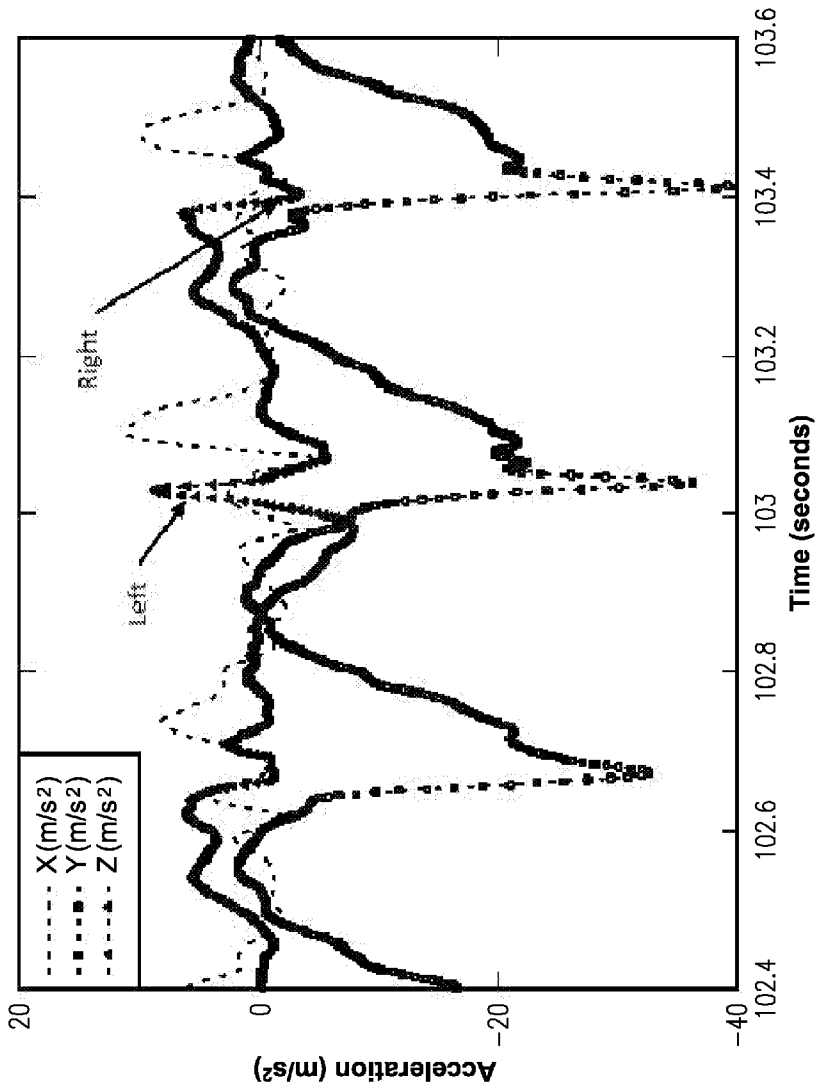


FIG. 21

METHOD AND SYSTEM FOR DETERMINING USER PERFORMANCE CHARACTERISTICS

RELATED APPLICATIONS

[0001] This application claims the priority benefit under 35 U.S.C. §119(e) of U.S. Provisional Patent Application Ser. No. 61/584,467, filed Jan. 9, 2012, entitled “RUNNING EFFICIENCY AND RUNNING POWER MEASUREMENT METHODS,” the entire disclosure of which is incorporated herein by reference.

BACKGROUND

[0002] Motion sensing apparatuses are often used to sense the motion of an object, animal, or person. For example, such apparatuses may sense motion parameters such as acceleration, average velocity, stride distance, total distance, speed, cadence, and the like, for use in the training and evaluation of athletes and animals, the rehabilitation of the injured and disabled, and in various recreational activities.

[0003] Some motion sensing apparatuses employ Global Positioning System (GPS) receivers and inertial sensors such as accelerometers to generate signals for motion parameter estimation. Inertial sensors are used to sense the motion and/or orientation of specific body parts, such as feet and legs, to provide more detailed user motion data.

SUMMARY

[0004] Embodiments of the present invention provide a system for determining user performance characteristics. The system includes an inertial sensor and a processing system. The inertial sensor may be coupled with a user's torso and generates one or more signals corresponding to the motion of the user's torso. The processing system is in communication with the inertial sensor and is operable to use the one or more signals to determine one or more user performance characteristics. The user performance characteristics may include speed, cadence, time energy cost, distance energy cost and acceleration energy cost.

[0005] It is to be understood that both the foregoing general description and the following detailed description are exemplary and explanatory only and are not necessarily restrictive of the invention claimed. The accompanying drawings, which are incorporated in and constitute a part of the specification, illustrate embodiments of the invention and together with the general description, serve to explain the principles of the invention.

DRAWINGS

[0006] Embodiments of the present invention are described in detail below with reference to the attached drawing figures, wherein:

[0007] FIG. 1 is a schematic diagram illustrating a user employing a torso-mounted sensor unit and a user interface unit configured in accordance with various embodiments of the present invention.

[0008] FIG. 2 is a schematic diagram illustrating an exemplary orientation of various sensors associated with a user's torso.

[0009] FIG. 3 is a schematic diagram illustrating a user employing a foot-mounted sensor unit and a user interface unit configured in accordance with various embodiments of the present invention.

[0010] FIG. 4 is a schematic diagram illustrating an exemplary orientation of various sensors within or on a shoe.

[0011] FIG. 5 is a schematic diagram illustrating a user employing a foot-mounted sensor unit, a torso-mounted sensor unit and a user interface unit configured in accordance with various embodiments of the present invention.

[0012] FIG. 6 is a block diagram illustrating some of the components operable to be utilized by various embodiments of the present invention.

[0013] FIG. 7 is a block diagram illustrating some of the components of FIG. 6 in more detail.

[0014] FIG. 8 is a block diagram illustrating an external systems unit in communication with the sensor unit and user interface unit of FIG. 1, FIG. 3 or FIG. 5.

[0015] FIG. 9 is a block diagram illustrating the user interface unit and sensor unit of FIG. 8 in communication with a GPS receiver.

[0016] FIG. 10 is a block diagram illustrating another configuration of the user interface unit and GPS receiver of FIG. 8.

[0017] FIG. 11 is a block diagram illustrating another configuration of the sensor unit and GPS receiver of FIG. 8.

[0018] FIG. 12 is a block diagram illustrating another configuration of the GPS receiver, user interface unit, and sensor unit of FIG. 8.

[0019] FIG. 13 is a schematic diagram showing the interaction of a plurality of apparatuses configured in accordance with various embodiments of the present invention.

[0020] FIG. 14 is a block diagram illustrating various steps associated with determining an inefficiency score that may be performed by embodiments of the present invention.

[0021] FIG. 15 is an exemplary acceleration signature for a torso-mounted sensor unit, the signature including acceleration data from movement along three different axes.

[0022] FIG. 16 is an exemplary acceleration signature for a torso-mounted sensor unit supplemented by an exemplary search state signal.

[0023] FIG. 17 is a block diagram illustrating various steps associated with analyzing a vertical acceleration signal that may be performed by embodiments of the present invention.

[0024] FIG. 18 illustrates exemplary vertical torso displacement measurements for various cadences.

[0025] FIG. 19 is the acceleration signature of FIG. 16 illustrating how step time may be measured from the search state signal.

[0026] FIG. 20 is the acceleration signature of FIG. 16 illustrating how contact time per step and flight time per step may be measured from the search state signal.

[0027] FIG. 21 is an exemplary acceleration signature for a torso-mounted sensor unit emphasizing lateral acceleration features.

[0028] The drawing figures do not limit the present invention to the specific embodiments disclosed and described herein. The drawings are not necessarily to scale, emphasis instead being placed upon clearly illustrating the principles of the invention.

DETAILED DESCRIPTION

[0029] The following detailed description of embodiments of the invention references the accompanying drawings. The embodiments are intended to describe aspects of the invention in sufficient detail to enable those skilled in the art to practice the invention. Other embodiments can be utilized and changes can be made without departing from the scope of the

claims. The following detailed description is, therefore, not to be taken in a limiting sense. The scope of the present invention is defined only by the appended claims, along with the full scope of equivalents to which such claims are entitled.

[0030] In this description, references to “one embodiment”, “an embodiment”, or “embodiments” mean that the feature or features being referred to are included in at least one embodiment of the technology. Separate references to “one embodiment”, “an embodiment”, or “embodiments” in this description do not necessarily refer to the same embodiment and are also not mutually exclusive unless so stated and/or except as will be readily apparent to those skilled in the art from the description. For example, a feature, structure, act, etc. described in one embodiment may also be included in other embodiments, but is not necessarily included. Thus, the present technology can include a variety of combinations and/or integrations of the embodiments described herein.

[0031] Various embodiments of the present invention provide a motion sensing system **10** operable to detect and analyze various parameters of a user's motion using data received or estimated from one or more sources, such as inertial sensors and GPS devices. The motion parameters may be communicated to the user and/or used to generate user performance characteristics such as, for example, information related to striding motion inefficiency or striding motion power.

[0032] With initial reference to FIGS. 1-13, in various embodiments the system **10** may include one or more inertial sensors such as, for example, accelerometers **12**, a filtering element **14**, and a processing system **16**. The accelerometers **12**, filtering element **14**, and processing system **16** may be integrated together or form discrete elements that may be associated with each other. The processing system **16** is generally operable to analyze measurements provided by the accelerometers **12**, determine one or more motion parameters and generate performance information.

[0033] The accelerometers **12** are each operable to measure an acceleration and generate an acceleration measurement corresponding to the measured acceleration. The acceleration measurement may be embodied as a signal operable to be utilized by the filtering element **14** and/or processing system **16**. In some embodiments, one or more of the accelerometers **12** may be operable to output an analog signal corresponding to an acceleration measurement. For instance, each accelerometer **12** may output an analog voltage signal that is proportional to measured accelerations. In some embodiments, one or more of the accelerometers **12** may include the ADXL321 accelerometer manufactured by ANALOG DEVICES of Norwood, Mass. However, the accelerometers **12** may include any digital and analog components operable to generate a signal corresponding to a measured acceleration. Thus, in some embodiments, one or more of the accelerometers **12** are operable to output a digital signal representing measured accelerations. Further, in some embodiments, one or more of the accelerometers **12** may comprise linear accelerometers.

[0034] In some embodiments, more than one of the accelerometers **12** may be integrated into the same integrated circuit package to allow the single package to provide acceleration measurements along more than one axis. For example, as shown in FIGS. 2 and 4, the system **10** may include two or more accelerometers **12** each operable to output a signal corresponding to a measured acceleration. In some embodiments, the system **10** includes at least two accelerometers **12**

adapted to measure accelerations in two directions separated by an angle greater than zero degrees and each provide a signal corresponding to the measured acceleration. Further, the system **10** may include at least three accelerometers **12** adapted to measure accelerations in three directions each separated by an angle greater than zero degrees and each providing a signal corresponding to the measured acceleration. In some embodiments, the three accelerometers **12** may be oriented in a mutually perpendicular configuration. However, the system **10** may include any number of accelerometers **12**, including a single accelerometer **12**, positioned in any configuration to provide acceleration measurements for use by the filtering element **14** and/or processing system **16**.

[0035] The accelerometers **12** may be operable to communicate with other elements of the system **10**, or elements external to the system **10**, through wired or wireless connections. Thus, the accelerometers **12** may be coupled with the filtering element **14** and/or processing system **16** through wires or the like. One or more of the accelerometers **12** may also be configured to wirelessly transmit data to other system elements and devices external to the system **10**. For instance, one or more of the accelerometers **12** may be configured for wireless communication using various RF protocols such as Bluetooth, Zigbee, ANT®, and/or any other wireless protocols.

[0036] The filtering element **14** is operable to couple with the one or more accelerometers **12** and filter acceleration measurements and/or signals corresponding to acceleration measurements. In some embodiments, the system **10** does not include the filtering element **14** and the processing system **16** is operable to use unfiltered acceleration measurements and corresponding signals. In other embodiments, the filtering element **14** may be integral with one or more of the accelerometers **12**, the processing system **16**, or both the accelerometers **12** and the processing system **16**. For example, a first portion of the filtering element **14** may be integral with one or more of the accelerometers **12** and a second portion of the filtering element **14** may be integral with the processing system **16**. In other embodiments, the filtering element **14** may be discrete from both the accelerometers **12** and the processing system **16**.

[0037] The filtering element **14** may include analog and digital components operable to filter and/or provide other pre-processing functionality to facilitate the estimation of motion parameters by the processing system **16**. In various embodiments and as shown in FIG. 7, the filtering element **14** is operable to filter signals provided by the one or more accelerometers **12**, or signals derived therefrom, to attenuate perpendicular acceleration, to compensate for gravity, and/or to minimize aliasing. The filtering element **14** may include discrete components for performing each of these filtering functions or use the same components and hardware for these, and other, filtering functions.

[0038] The filtering element **14** may include any analog and/or digital components for filtering signals and measurements, including passive and active electronic components, processors, controllers, programmable logic devices, digital signal processing elements, combinations thereof, and the like. In some embodiments, the filtering element **14** may include a digital microcontroller, such as the MSP430F149 microcontroller manufactured by TEXAS INSTRUMENTS to provide various static and/or adaptive filters. The filtering element **14** may also include an analog-to-digital converter to convert analog signals provided by the one or more accelerometers

ometers **12** to digitize signals for use by the processing system. The filtering element **14** may also include conventional pre-sampling filters.

[0039] In some embodiments, a low-pass filter **18** may be an adaptive filter operable to employ static and/or varying cut-off frequencies between about 0.5 Hz and 10 Hz. In some embodiments where parameters corresponding to human strides are estimated, the low-pass filter **18** may employ cut-off frequencies between about 1 Hz and 3 Hz. The filtering element **14** may acquire the cut-off frequency from the processing system **16** based on computations performed by the processing system **16** corresponding to the particular stride frequency of the user. The low-pass filter **18** may additionally or alternatively be adapted to employ a cut-off frequency corresponding to a gait type identified by the processing system **16**.

[0040] In other embodiments, the cut-off frequency for the low-pass filter **18** may be a static value based upon the typical stride frequency of a running or walking human. For instance, the cut-off frequency may correspond to a frequency between one and two times the typical stride frequency of a running and/or walking human, such as a static frequency between 1 Hz and 3 Hz. Specifically, in some embodiments, the cut-off frequency may be about 1.45 Hz for walking humans and about 2.1 Hz for jogging humans.

[0041] The gravity compensation provided by the filtering element **14** generally compensates for the constant acceleration provided by gravity that may be sensed by one or more of the accelerometers **12**. In some embodiments, the filtering element **14** includes a high-pass filter **20** operable to filter or attenuate components of signals corresponding to measured accelerations below a given cut-off frequency. The cut-off frequency of the high-pass filter **20** may correspond to a frequency approaching 0 Hz, such as 0.1 Hz, to adequately provide compensation for gravity-related acceleration.

[0042] The anti-aliasing provided by the filtering element **14** generally reduces or prevents aliasing caused by sampling of the signals provided by, or derived from, the one or more accelerometers **12**. In some embodiments, the filtering element **14** includes a relatively wideband filter designed to attenuate signal frequencies in excess of one-half of the sampling frequency used in any subsequent analog-to-digital conversions provided by the processing system or other devices associated with the system. In some embodiments, the filtering element **14** may provide other filtering components instead of, or in addition to, the wideband filter **22** to compensate for aliasing. For instance, the filtering element **14** may include one or more analog and/or digital filters to perform any combination of the various filtering functionality discussed herein. In some embodiments, a single filtering element may be utilized to perform each of the filtering functions discussed above such that separate or discrete filters are not necessarily employed for different filtering functions.

[0043] The processing system **16** is generally operable to couple with the one or more accelerometers **12** and/or the filtering element **14** to generate motion characteristics and performance information. The processing system **16** may include various analog and digital components operable to perform the various functions discussed herein. In some embodiments, the processing system **16** may include a microprocessor, a microcontroller, a programmable logic device, digital and analog logic devices, computing elements such as personal computers, servers, portable computing devices, combinations thereof, and the like.

[0044] The processing system **16**, filtering element **14**, accelerometers **12**, and/or other portions of the system **10** may limit or expand the dynamic range of acceleration measurements used to generate the motion characteristics and performance information. For example, acceleration measurements outside a specified dynamic range, such as plus or minus 8 g, may be saturated at the dynamic range limits to further limit the effects of perpendicular acceleration. Alternatively, linear or non-linear amplifiers may be used to increase or reduce the dynamic range. The dynamic range may be varied by the processing system based on the particular motion parameter being estimated or according to other sensed or generated measurements.

[0045] The processing system **16** may also include, or be operable to couple with, a memory. The memory may include any non-transitory computer-readable memory or combination of computer-readable memories operable to store data for use by the processing system **16**. For instance, the memory may be operable to store acceleration data, motion parameter metric data, statistical data, motion parameter data, filtering data, configuration data, combinations thereof, and the like.

[0046] The processing system **16** may be discrete from the various accelerometers **12** and filtering element **14** discussed above. In other embodiments, the processing system **16** may be integral with other portions of the system **10**. For instance, the same microcontroller or microprocessor may be utilized to implement the filtering element **14** and the processing system **16**.

[0047] In some embodiments, data and information generated by the accelerometers **12**, filtering element **14**, and/or processing system **16** may be stored in the memory associated with the processing system **16**, or in any other computer-readable memory, to allow later analysis by the processing system **16** or other devices associated therewith. The stored information may be time-correlated to facilitate analysis and compressed to reduce the required capacity of the memory.

[0048] The processing system **16** may additionally or alternatively utilize information acquired from sensors other than the one or more accelerometers **12**. For instance, in some embodiments the processing system **16** may couple with other sensors to acquire variables such as geographic location and/or altitude. For example, to acquire additional information, the processing system **16** may couple with, and/or include, radio-frequency transceivers, altimeters, compasses, inclinometers, pressure sensors, angular velocity sensors and other inertial sensors, computing devices such as personal computers, cellular phones, and personal digital assistants, other similarly configured apparatuses, combinations thereof, and the like.

[0049] In some embodiments, as shown in FIGS. 9 through 12, the system **10** may be operable to receive information from at least one navigation device **24**. The navigation device **24** may be adapted to provide geographic location information to the system **10** and users of the system **10**. The navigation device **24** may include a GPS receiver much like those disclosed in U.S. Pat. No. 6,434,485, which is incorporated herein by specific reference in its entirety. However, the navigation device **24** may use cellular or other positioning signals instead of, or in addition to, the GPS to facilitate determination of geographic locations. The navigation device **24** may be operable to generate navigation information such as the speed of the navigation device **24**, the current and previous locations of the navigation device **24**, the bearing and heading

of the navigation device 24, the altitude of the navigation device 24, combinations thereof, and the like.

[0050] The filtering element 14 and processing system 16 may additionally be operable to compensate for part-to-part manufacturing variability present in the one or more accelerometers 12, including characterization over temperature of zero-g bias point, sensitivity, cross-axis sensitivity, nonlinearity, output impedance, combinations thereof, and the like.

[0051] In some embodiments, compensation parameters are periodically adjusted during device use. For example, if the processing system 16 detects that the system 10 is substantially stationary, the sum of accelerations provided by the one or more accelerometers 12 may be compared to an expected acceleration sum of 1 g (g is the gravitational constant, 9.81 m/s²), and the difference may be used by the processing system 16 to adjust any one of or a combination of compensation parameters.

[0052] Thus, for example, if x_m , y_m , z_m are acceleration measurements produced by three accelerometers 12 oriented in substantially mutually perpendicular directions and the accelerometers 12 are at rest, the combined measured acceleration can be expected to be $x_m^2 + y_m^2 + z_m^2 = g^2$. If it is assumed that x_m and y_m are accurate, then in $x_m^2 + y_m^2 + z_c^2 = g^2$ the only unknown is z_c , and the processing system 16 can compute z_c from x_m and y_m whenever the unit is mostly stationary, and compare this value to measured z_m . The difference between the measured acceleration z_m and the computed acceleration z_c can be assumed to be attributable to inadequate compensation of the z measurement for part-to-part manufacturing variability, temperature sensitivity, humidity sensitivity, etc. Consequently, an adjustment to one or more of the compensation parameters can be made based on the difference. By periodically adjusting compensation parameters based on stationary gravitational assumptions, it may thus be possible to eliminate or reduce the complexity of compensation parameter modeling in some embodiments. However, embodiments of the present invention may employ or not employ any combination of compensation methods and parameters.

[0053] In some embodiments, and as shown in FIG. 8, the system 10 may include a communications element 26 to enable the system 10 to communicate with other computing devices, exercise devices, navigation devices, sensors, and any other enabled devices through a communication network, such as the Internet, a local area network, a wide area network, an ad hoc or peer to peer network, combinations thereof, and the like. Similarly, the communications element 26 may be configured to allow direct communication between similarly configured apparatuses using USB, ANT®, Bluetooth, Zigbee, Firewire, and other connections, such that the system 10 need not necessarily utilize a communications network to acquire and exchange information.

[0054] In various embodiments the communications element 26 may enable the system 10 to wirelessly communicate with communications networks utilizing wireless data transfer methods such as WiFi (802.11), Wi-Max, Bluetooth, ultra-wideband, infrared, cellular telephony (GSM, CDMA, etc.), radio frequency, and the like. However, the communications element may couple with the communications network utilizing wired connections, such as an Ethernet cable, and is not limited to wireless methods.

[0055] The communications element 26 may be configured to enable the system 10 to exchange data with external computing devices to facilitate the generation and/or analysis of

information. For example, the processing system 16 may use information acquired through the communications element 26 in estimating motion parameters and/or in generating motion models. The processing system 16 may also provide generated motion parameter metrics, motion models, and estimated motion parameters through the communications element 26 for use by external devices. For instance, the external devices can be configured to store, analyze, and exchange information between a plurality of users and/or a plurality of devices attached to one or multiple users.

[0056] Consequently, the communications element 26 generally enables real-time comparison of information generated by the system 10 and other devices. The communications element also enables the system to store data on one or more of the external devices for later retrieval, analysis, aggregation, and the like. The data can be used by individuals, their trainers or others to capture history, evaluate performance, modify training programs, compare against other individuals, and the like. The data can also be used in aggregated form.

[0057] The system 10 may additionally include a user interface 28 to enable users to access various information generated and acquired by the system 10, such as attachment positions, acceleration measurements, motion parameter metrics, motion characteristics, performance information, generated motion models, navigation information acquired from the navigation device 24, information and data acquired through the communications element 26, configuration information, combinations thereof, and the like. The user interface 28 facilities, for example, powering on/off the system 10, selecting which content to display, and providing configuration information such as the attributes of the user.

[0058] The user interface 28 may include one or more displays to visually present information for consumption by users and one or more speakers to audibly present information to users. The user interface 28 may also include mechanical elements, such as buzzers and vibrators, to notify users of events through mechanical agitation. In some embodiments, and as illustrated in FIG. 1, the user interface 28 may be implemented within a watch operable to be worn on a user's wrist, forearm, and/or arm. Thus, the user interface 28 may be positioned separately from one or more of the accelerometers 12 to enable the user to easily interact with the system 10. However, in some embodiments the user interface 28 and accelerometers 12 may be integral.

[0059] The user interface 28 may also be operable to receive inputs from the user to control the functionality of the processing system 16 and/or devices and elements associated therewith. The user interface 28 may include various functional inputs such as switches and buttons, a touch-screen display, optical sensors, magnetic sensors, thermal sensors, inertial sensors, a microphone and voice-recognition capabilities, combinations thereof, and the like. The user interface 28 may also include various processing and memory devices to enable and facilitate its functionality.

[0060] The user interface 28 enables users to receive real-time feedback concerning motion parameters and characteristics, performance information and related information and data. For instance, the user interface 28 may present a motion characteristic such as torso displacement or speed, step or stride cadence and/or stride stance duration. The user interface 28 may also present performance information such as running inefficiency information, running power, time energy cost, distance energy cost, combinations thereof, and the like.

[0061] Utilizing the communications element 26, the user interface 28 also enables users to receive real-time feedback and comparisons with other users and devices. For instance, as shown in FIG. 13, a plurality of systems 10 may be employed by a plurality of runners to enable data, metrics, and parameters corresponding to each runner to be shared and presented to the user. Thus, for instance, the user may ascertain the speed and location of other users through the user interface 28.

[0062] Further, the user interface 28 may acquire comparison information from the processing system 16 and/or from other devices through the communications element 26 to enable the user to compare his or her performance using the comparison information. For instance, the user interface 28 may present a comparison of the user's current performance with a previous performance by the user, with a training model, and/or with another individual.

[0063] In various embodiments, the user may configure the system utilizing the user interface 28 to monitor motion characteristics and/or performance information and alert the user through the user interface 28 when one or more motion characteristics or performance parameters conflict with a user-defined condition such as an acceptable parameter range, threshold, and/or variance. The user may also configure the system 10 utilizing the user interface 28 to monitor various user-defined goals, such as time limits, motion parameter maximum values, and the like.

[0064] As is discussed above, the various components of the system 10 may be housed integrally or separately in any combination. In some embodiments, the system 10 includes an interface unit 30 for housing the user interface 28 and associated components and a sensor unit 32 for housing the one or more accelerometers 12 and the communications element 26. In such embodiments, the processing system 16 (housed within both or either unit 30, 32) is operable to determine the attachment position of the sensor unit 32. In some embodiments, the units 30, 32 may be housed within the same housing, as is shown in FIG. 12. However, in other embodiments the units 30, 32 may be discrete such that the sensor unit 32 may be positioned in a first location, such as on the user's shoe, and the interface unit 30 may be positioned at a second location, such as on the user's wrist.

[0065] The interface unit 30 may also include an interface communication element 34, configured in a similar manner to the communications element 26 discussed above, to enable the interface unit 30 to exchange information with the sensor unit 32, other parts of the system 10, and/or with devices external to the system 10. In embodiments where the units 30, 32 are positioned separate from each other, the communications elements 26, 34 may communicate utilizing the various wireless methods discussed above. However, the communications elements 26, 34 may also communicate utilizing wired connections or through external devices and systems.

[0066] The units 30, 32 may also each include power sources for powering the various components of the system 10, such as through the use of batteries or power-generating elements such as piezoelectric, electromechanical, thermoelectric, and photoelectric elements. In some embodiments, portions of the user interface 24 may be included with both units 30, 32 such that each unit 30, 32 and its respective components can be individually functioned by the user.

[0067] As shown in FIG. 8, the system may additionally include an external systems unit 36 to enable the interface unit 30 and sensor unit 32 to easily communicate with external

systems and devices. For example, the external systems unit 36 may include a communications element to communicate with the other communication elements 26, 34, a microcontroller to process information, and a standard interface such as a WiFi, Bluetooth, ANT®, USB, or ZigBee interface operable to easily interface with devices such as cellular phones, portable media players, personal digital assistants, navigation devices, personal and portable computing devices, combinations thereof, and the like. Thus, in some embodiments, the external systems unit 36 may be connected with an immobile personal computer and the interface unit 30 and sensor unit 32 may be positioned on a mobile user, as is shown in FIG. 13.

[0068] As is shown in FIGS. 9 through 12, the interface unit 30 and sensor unit 32 may each be operable to communicate with the navigation device 24 to receive and utilize navigation information. The navigation device 24 may be discrete from the units 30, 32 as shown in FIG. 9, the navigation device 24 may be integral with the interface unit 30, as shown in FIG. 10, the navigation device 24 may be integral with the sensor unit 32, as shown in FIG. 11, and/or the navigation device 24 may be integral with both units 30, 32 as shown in FIG. 12. Further, in some embodiments, any one or more of the units 30, 32, 36 and navigation device 24 may be automatically disabled when not in use to achieve optimum system power consumption and functionality.

[0069] In some embodiments, the sensor unit 32 may be attached to the user's wrist in an enclosure which is similar to a watch and combined with other functionality such as time-keeping or with other sensors such the navigation device 24. In other embodiments, the sensor unit 32 may be attached to the user's arm using an enclosure similar to an armband and combined with other devices such as a cellular phone, an audio device and/or the navigation device 24. In various other embodiments, the sensor unit 32 may be attached to the user with a chest strap (FIGS. 1 and 5) in an enclosure which may include other sensors such as a heart-rate monitor (HRM). In yet other embodiments, the sensor unit 32 may be attached to user's waist with, for example, a belt clip. In further embodiments, the sensor unit 32 may be attached to the top of a user's shoe with removable fasteners such as clips. In other embodiments, the sensor unit 32 may be inserted within the user's shoe (FIGS. 3 and 5), such as within a recess formed in the sole of the shoe.

[0070] In some embodiments, the sensor unit 32, and/or more generally the system 10, may be operable to attach to more than one portion of the user. For example, the sensor unit 32 may be adapted to attach to any of the various positions discussed above, including but not limited to, the user's wrist, arm, waist, chest, pocket, hat, glove, shoe (internal), and shoe (external). Such a configuration enables the same sensor unit 32, or system 10, to be easily utilized by the user in a variety of positions to generate desirable motion parameters and/or to facilitate ease of use.

[0071] In some embodiments, the system 10 may be configured to identify its position on the user's body, thereby allowing the user to carry or attach the system 10, or more particularly the sensor unit 32, in any of the above-identified positions or in any other arbitrary location, including in combination with other electronic devices such as a cellular phone.

[0072] To identify the attachment position of the sensor unit 32, the processing system 16 may analyze one or more acceleration measurements generated by the one or more accelerometers 12. For a particular motion type such as striding, each

attachment position and/or orientation will present a generally unique acceleration signature that may be identified by the processing system 16 to determine the attachment position and/or motion type of the accelerometers 12 or other portions of the system 10, depending on how and/or where the accelerometers 12 are housed.

[0073] Exemplary embodiments of the system 10, including various functions and components of the system 10, have been described and illustrated. It will be appreciated by those skilled in the art that additional or alternative components, designs and configurations may be used to enable the functionality of the system 10 as described herein without departing from the scope of the invention. Furthermore, aspects of the system 10 may be similar or include features described in U.S. Pat. No. 8,060,337, which is incorporated by specific reference in its entirety into this document.

[0074] In some embodiments, the system 10 is used to monitor motion, such as athletic motion experienced by a user during physical exercise. By way of example, the system 10 may be used to monitor vertical torso displacement, torso speed, step and/or stride cadence, contact or stance time and the like. Use of the system 10 to monitor motion will now be described in detail.

[0075] In one embodiment, the sensor unit 32 is attached to the user's torso and communicates with the user interface 28 which displays motion characteristics and parameters calculated by the processing system 16. More particularly, the sensor unit 32 may attach to the user's torso in the lower sternum area and may contain one, two or three substantially mutually perpendicular accelerometers. However, in various configurations, any number of accelerometers may be employed. A representative set of signals generated by three mutually perpendicular accelerometers contained in a single package, such as the LIS3DH produced by ST Microelectronics (Geneva, Switzerland), is presented in FIG. 15. The signals illustrated in FIG. 15 indicate acceleration of an athlete's chest for the duration of about three steps of jogging. Particularly, the X, Y and Z acceleration signals correspond to accelerometers with axes of sensitivity oriented substantially parallel to the ground in the sagittal plane, parallel to gravity and perpendicular to the sagittal plane, respectively. The most prominent of the three accelerations is the Y acceleration. In one embodiment, the sensor unit 32 processes and analyzes at least the Y acceleration signal collected by at least one sensor 12 positioned on the user's chest.

[0076] FIG. 16 illustrates the Y acceleration signal processed and analyzed by the sensor unit 32. In addition to the raw Y acceleration signal, FIG. 16 illustrates a search state signal generated by the sensor unit 32 that indicates particular features of the signal. Specifically, search state values of "0" and "1" indicate a portion of the signal corresponding to downward movement and a search state value of "2" indicates a portion of the signal corresponding to upward movement. Each 0-1-2 cycle represents a single step.

[0077] An exemplary method of determining the search state signal is illustrated in FIG. 17. First, the Y signal from the accelerometer is analyzed and its polarity is corrected to show positive acceleration when the athlete is accelerating upward, as illustrated in blocks 38 and 40. Next, acceleration due to gravity is removed from the signal, and the signal is analyzed to isolate individual steps, as depicted in blocks 42 and 44. Finally, motion parameters are calculated, as illustrated in block 46.

[0078] The sensor unit 32 may calculate the distance the user's torso moves up and down (i.e., vertical displacement) during each step. Vertical displacement of the torso in the positive direction (upwards) can be calculated by identifying the moment in time the torso is in its lowest vertical position and then integrating Y acceleration twice with respect to time until the moment the torso reaches its highest vertical position. Similarly, the vertical displacement of the torso in the negative direction can be calculated by identifying the moment in time the torso is in its highest vertical position and then integrating Y acceleration twice with respect to time until the moment the torso reaches its lowest vertical position. Other methods and configurations may similarly be used to calculate vertical displacement, including through the use of position and speed sensors and/or signals derived independently of sensed acceleration. Vertical torso displacement is indicative of the change in potential energy per cycle for the torso, since

$$E_p = mgh \quad (1)$$

where E_p is potential energy, m is torso mass, h is vertical torso displacement and g is the gravitational constant.

[0079] FIG. 18 illustrates vertical torso displacement measured over multiple steps. Four different trials are presented, with the athlete asked to jog at a given speed at a natural cadence (Control 1), then at 10% above natural cadence, then again at natural cadence (Control 2), then at 10% below natural cadence. The signal patterns depicted in FIG. 18 reflect the fact that increasing cadence normally decreases vertical torso displacement and that decreasing cadence normally increases vertical torso displacement.

[0080] The sensor unit 32 may calculate the maximum speed of the torso as the torso moves up and down during a step. The torso speed signal in the positive direction (upward) can be calculated by identifying the moment in time the torso is in its lowest vertical position (which is when the vertical speed is zero) and integrating Y acceleration with respect to time until the moment the torso reaches its highest vertical position (which is when the vertical speed is zero again). The maximum positive torso speed is the maximum of the calculated speed signal. Similarly, the maximum speed of the torso in the negative direction (downward) can be computed by integrating and analyzing the portion of the acceleration signal between the time the torso reaches its highest vertical position and the time the torso reaches its lowest vertical position. Other methods and configurations may similarly be used to calculate torso speed, including through the use of position and speed sensors and/or signals derived independently of sensed acceleration. Maximum torso speed is related to the change in vertical kinetic energy per cycle for the torso, since

$$E_{ky_{max}} = \frac{m(v_{y_{max}})^2}{2} \quad (2)$$

where $E_{ky_{max}}$ is the maximum kinetic energy in the Y direction, m is the torso mass and $v_{y_{max}}$ is the maximum speed.

[0081] The sensor unit 32 may calculate the person's step and/or stride cadence by, for example, measuring the step time (T_s) using acceleration signal analysis (see FIG. 19) and using the following relationships:

$$f_s = \frac{1}{T_s} \quad (3)$$

$$C_s = 60f_s \quad (4)$$

$$C_{str} = \frac{C_s}{2} \quad (5)$$

where f_s is the step frequency, C_s is the step cadence in steps per minute and C_{str} is the stride cadence. Alternatively, step and/or stride cadence can be calculated by counting the number of steps (N_s) or strides for a known period of time (T_{test}), and using relationships (4) and (5) and the relationship:

$$f_s = \frac{N_s}{T_{test}} \quad (6)$$

[0082] Cadence is a gait parameter which contributes to the calculation of energy consumed per second due to gait inefficiencies (in other words, wasted power). Changes in cadence also influence, for example, vertical torso displacement, horizontal torso acceleration/deceleration and energy lost due to foot repositioning. Consequently, cadence is a parameter of interest to athletes.

[0083] The sensor unit **32** may calculate the amount of time the athlete is in contact with the ground per step and/or stride. Contact time per step (T_c) can be calculated by identifying the amount of time vertical (Y) acceleration is above or below a certain acceleration threshold (a_s) per step, wherein a_c is related to acceleration due to gravity. For example, and with reference to FIG. **20**, contact time per step can be calculated by accumulating time while vertical acceleration is greater than a_c . Alternatively, contact time can be calculated by accumulating time while vertical acceleration is less than a_c to calculate flight time (T_f) and using the relationship:

$$T_c = T_s - T_f \quad (7)$$

[0084] The threshold a_c is chosen to be close to $\pm g$, the gravitational constant, but is not necessarily equal to $\pm g$ to account for possible inaccuracy in the measurement of vertical acceleration.

[0085] It will be appreciated by those skilled in the art that accumulating time while above or below a threshold may be preferable to identifying the moments in time acceleration crosses the threshold (and subsequently subtracting the times of the two events to calculate T_c or T_f), as time accumulation is more immune to signal noise.

[0086] Contact time per stride can be calculated in a similar way, except that instead of accumulating time above or below a threshold per step, the accumulation is performed over the duration of two consecutive steps. A reasonable approximation of contact time per stride may also be obtained by multiplying the contact time per step by two. Contact time may be of interest to athletes because it contributes to such performance characteristics as vertical torso displacement amplitude, horizontal torso acceleration/deceleration, and energy lost due to foot repositioning.

[0087] The sensor unit **32** may determine if the presently completed step was taken with the left foot or the right foot. The left/right foot identification may utilize the Z-axis acceleration (perpendicular to the sagittal plane). Due to the fact that human legs are not attached directly beneath the center of

gravity of the torso (when the torso is in a vertical position), but rather to the left/right of the center, the torso experiences left/right acceleration on foot impact and for some period of time afterwards, during foot contact. This behavior results in a distinctly different acceleration signal on the Z axis for the left foot as compared to the right foot.

[0088] FIG. **21** illustrates the Z-axis acceleration features indicative of left/right foot step. Note that the polarity of the indicated features is dependent on the polarity of the acceleration measurement. Having identified the feature of interest, the distinction between left and right foot impact can thus be accomplished by, for example, averaging the acceleration signal for the duration of the feature and comparing the result to a threshold.

[0089] The sensor unit **32** may use the identification of left and right foot steps to calculate separate motion parameters for the left and the right foot. For example, vertical torso displacement and/or contact time are calculated separately for each foot. Motion parameters for the individual feet may then be compared using, for example, ratios or differences, or separately reported to the user interface. In some embodiments, the sensor unit **32** utilizes Z-axis acceleration signal to quantify the amount of left/right core balance. Broadly, the more the torso is accelerated to the left and/or right during each step, the more unbalanced the athlete's core.

[0090] The sensor unit **32** may determine more than one of any of the motion parameters discussed herein. Furthermore, the sensor unit **32** may receive information from an external source, such as one or more motion parameters, environmental parameters, information about the user and/or other contextual parameters related to the user's activity. By way of example, the external source or sources may include one or more external sensors such as speed and/or distance monitors, a graphical user interface, one or more portable electronic devices (e.g., mobile phones, GPS receivers, tablet computers), stationary electronic devices (e.g., personal computers, laptops) and/or other networks (e.g., the Internet) or databases (e.g., a fitness club user database).

[0091] The sensor unit **32** may combine two or more of the measured motion parameters and/or information from one or more of the external sources to calculate additional motion parameters. For example, stride distance may be combined with cadence to calculate a user's speed. Other motion parameters which can be calculated include time energy cost, distance energy cost, backward-forward acceleration energy cost and/or leg repositioning cost.

[0092] The motion parameters measured by the sensor unit **32** may be calculated on a per step basis. Torso potential energy per cycle (E_p), for example, may be calculated using vertical torso displacement and tells the user how much energy is used to raise the torso for each step. The user may instead or in addition be interested in knowing how much energy is used to raise the torso per unit time, or in other words, how much power, on average, is used to raise the torso. Power used to raise the torso (P_p) can be calculated with the following equation:

$$P_p = E_p f_s \quad (8)$$

where f is the step frequency.

[0093] Similarly, other energy-type motion parameters (e.g., backward-forward energy per step, leg repositioning energy per step) can be converted to a corresponding power parameter by multiplying by step frequency. An energy parameter presented in a per-unit-of-time format can be used

to determine, for example, how much energy the person will use during one hour of a particular activity, or when the person will run out of energy at a particular activity level.

[0094] In addition to or instead of the per-step or per-second parameters, the sensor unit 32 may determine an amount of energy consumed per unit distance. For example, power used to raise the torso can be combined with average speed to calculate energy used to raise the torso per unit distance (E_p/d) using the following equation:

$$\frac{E_p}{d} = \frac{P_p}{v} \quad (9)$$

where v is the average torso speed. Similarly, other energy-type motion parameters can be converted to a corresponding energy per unit distance parameter using step frequency and torso speed. An energy parameter presented in a per unit distance format can be used to determine how much energy the user will use to travel a known distance at a particular activity level, and whether the user has enough energy to complete a distance goal at a particular energy level.

[0095] The sensor unit 32 may determine the energy used to accelerate and decelerate the torso during each step in the direction parallel to the direction of motion (X). In the X direction, the torso decelerates on impact and during the initial portion of foot ground contact, and then accelerates during the remaining portion of foot ground contact. This acceleration/deceleration cycle results in an increase/decrease in speed in the X direction during each step, and consequently the torso kinetic energy in the X direction increases and decreases during each step. The amount of torso kinetic energy in the X direction is described by the following equation:

$$E_{kX} = \frac{mv_x^2}{2} \quad (10)$$

where v_x is torso speed in the X direction. The change in torso kinetic energy per step in the X direction (ΔE) is, therefore

$$\Delta E_{kX} = \frac{m(v_{x_{max}}^2 - v_{0X}^2)}{2} \quad (11)$$

[0096] where v_{0X} is the torso speed in the X direction at the beginning of the foot contact phase and $v_{x_{max}}$ is the maximum (during the step) torso speed in the X direction. Since the torso speed in the X direction is given by

$$v_x(t) = \int a_x(t) dt + v_{0X} \quad (12)$$

it is possible to calculate instantaneous torso speed in the X direction $v_x(t)$ from X acceleration ($a_x(t)$) and initial speed in the X direction, and thus it is possible to calculate the maximum torso speed in the X direction. In some embodiments, the sensor unit 32 uses average speed in the X direction (v_{xave}) to approximate the initial speed in the X direction (at the beginning of the foot contact phase), and measured acceleration in the X direction to calculate maximum torso speed in the X direction and change in torso kinetic energy per step in the X direction.

[0097] In some embodiments, during the foot-contact phase, the sensor unit 32 estimates the acceleration in the X direction, $a_x(t)$, instead of measuring it directly with an accelerometer, from measured acceleration in the Y direction ($a_y(t)$) using

$$a_x(t) \approx \frac{a_y(t)v_{xave}t}{h} \quad (13)$$

where h is the person's leg length and t is time, measured from the moment the torso is directly above the foot. In some embodiments h is estimated from, for example, the person's height or inseam length.

[0098] The sensor unit 32 may determine the energy used to accelerate the leg to reposition the foot from one place on the ground to the next during each step. On average, the foot moves at the same speed as the torso. However, the foot can only move when it is not in contact with the ground. The energy transferred to the leg to accomplish the motion is stored momentarily as kinetic energy of the leg during the flight phase, and largely dissipated on contact with the ground. The leg repositioning energy per step (E_{kL}) can thus be approximated as:

$$E_{kL} = \frac{km_L(T_s v_{xave} / c T_f)^2}{2} \quad (14)$$

where m_L is the leg mass, k is a scaling factor to account for the fact that not the entire leg is being accelerated to foot speed, and c is a scaling factor to account for the difference between peak and average velocity of the foot during the flight phase.

[0099] When used to monitor motion, the system 10 may be implemented as a small, portable, electronic, environmentally resistant device with wireless communication capability as described above. The system 10 may be implemented as a stand-alone physical device operable to communicate with other devices using wireless or wired communication. In one embodiment, the system 10 is combined in a physical enclosure with another sensor, such as a heart-rate monitor, to reduce system complexity and cost. In this embodiment, some of the system parts may be shared between the different sensors, e.g. microcontroller, memory, wireless communication hardware, PCB to reduce cost relative to separate physical devices. This embodiment also improves system usability and reliability by, for example, reducing the number of necessary communication links during training and reducing the number of devices the user needs to configure and maintain between training sessions.

[0100] In some embodiments, the system 10 is used to determine striding motion inefficiency. Energy is expended during striding motion in a number of ways. For motion on a level surface at approximately constant speed, a runner's energy is consumed by, among other things, air friction, joint friction, internal tissue friction and foot-ground friction. To maximize running efficiency and increase performance, runners may try to minimize the input power required to run at a particular speed.

[0101] Even in the absence of energy loss due to air, joint and foot-ground friction, it would not be possible for a striding person to completely eliminate expending energy while in

motion because striding motion necessarily involves cyclical accelerations and decelerations of at least the lower limbs. For every stride, energy expended to accelerate the person's legs is subsequently lost to internal tissue friction when the leg is decelerated. Other portions of the body can also experience cyclical accelerations which leads to further energy dissipation.

[0102] Human gait can be broadly classified as walking or running (including jogging and sprinting). A walking gait is characterized by a striding motion wherein at least one foot is in contact with the ground at all times. Running, in contrast, includes a period of time when both feet are off the ground. These different gait classes are characterized by distinctly different inefficiency profiles.

[0103] A foot in contact with ground has little or no kinetic energy (it may have some kinetic energy if it is rolling from heel to toe while maintaining contact with the ground). The foot's kinetic energy quickly increases after toe-off and reaches its maximum when the foot is moving at its peak speed during a stride. During this period between toe-off and maximum foot speed, the person expends energy to accelerate the foot. Some of this energy is stored as kinetic energy in the foot and the balance is lost to energy conversion inefficiency and dissipated as heat in muscles and joints. Sometime later, in anticipation of ground contact, the person begins decelerating the foot and eventually the foot makes contact with the ground. Most of the kinetic energy stored in the foot at its peak speed is lost during this phase and is dissipated through internal tissue friction and foot-ground friction.

[0104] This energy cycle applies not only to the foot, but, to a varying degree, the entire leg. Broadly, leg portions closer to the hip joint experience less kinetic energy fluctuations than portions closer to the foot.

[0105] During walking, the various segments of the leg move mostly perpendicular to gravity. Running motion is somewhat more complicated and, consequently, in addition to the kinetic energy cycle, the leg may experience potential energy cycles leading to further energy loss. Leg potential energy loss increases with increasing height of the center of mass of the leg during a stride.

[0106] The amount of kinetic energy transferred to the foot is proportional to the square of maximum foot speed. As the average foot speed is equal to the average torso speed and because the foot can move forward only when it is not contacting the ground, for a constant torso speed the maximum foot speed increases with decreasing flight time (i.e., the amount of time the foot is in the air). Consequently, at a particular speed and cadence, foot kinetic energy losses increase with decreasing flight time.

[0107] For a particular speed, cadence can be increased to compensate for decreasing stride length. However, even if the average (across multiple strides) flight duty cycle (flight time as a fraction of total stride time) is kept the same as cadence increases, the foot must reach a higher peak velocity at higher cadence in order to maintain the same average velocity. This is because at higher cadence, more time is spent, on the average, accelerating and decelerating the foot rather than coasting at peak speed. Thus, foot kinetic energy loss per stride increases with increasing cadence. Furthermore, since the stride frequency increases, the frequency of kinetic energy cycles increases leading to an increase in lost power.

[0108] Research suggests that the efficiency of conversion of chemical to mechanical energy in muscles decreases with the duration of application of force. Thus, increasing cadence

at a constant speed ultimately leads to high muscular inefficiency and therefore high energy loss within the muscles relative to the energy transferred to the leg.

[0109] To summarize, the following principles relate to leg motion inefficiency:

[0110] Leg potential energy change per cycle increases with increasing mass height center.

[0111] Leg kinetic energy change per cycle increases with decreasing flight duty cycle.

[0112] Leg kinetic energy change per cycle increases with increasing cadence.

[0113] Leg kinetic energy cycle frequency increases with increasing cadence.

[0114] Leg muscle efficiency decreases with increasing cadence.

[0115] A person's torso contains a large portion of person's total mass, such that even relatively small acceleration cycles of the torso can result in appreciable energy loss. During a stride, the torso experiences acceleration cycles parallel with and perpendicular to gravity. Acceleration perpendicular to gravity transfers energy to torso kinetic energy, while acceleration parallel to gravity transfers energy to torso potential energy. Both kinetic energy and potential energy are mostly lost at the end of each cycle.

[0116] During walking motion, a person accelerates and decelerates the torso in the direction perpendicular to gravity. The torso starts accelerating approximately when a first foot in contact with the ground passes a point directly below the person's center of mass and reaches maximum acceleration and horizontal velocity shortly before toe-off (a point at which the foot leaves the ground). The second foot contacts the ground ahead of the person's center of mass shortly before the first foot toe-off, at which point torso velocity starts decreasing. Torso velocity continues to decrease for as long as the second foot is ahead of the person's center of mass, at which point the cycle restarts with the other foot. Thus, the torso acceleration cycle frequency is twice the foot acceleration cycle frequency (but there are two foot acceleration cycles going on at all times—one for each foot).

[0117] Starting with the moment when the first foot in contact with the ground passes the point directly below the person's center of mass, torso velocity and acceleration start increasing until the second foot touches the ground. Thus, for a particular speed, the amount the torso accelerates increases with an increase in this time period. Since this time period increases with decreasing cadence, at a constant speed, peak torso speed and kinetic energy increases with decreasing cadence for walking. On the other hand, the frequency of torso kinetic energy cycles increases with increasing cadence. It turns out that as cadence decreases, torso peak kinetic energy per cycle increases faster than the decrease in frequency of kinetic energy cycles, and consequently, torso kinetic energy power loss increases with decreasing cadence.

[0118] Potential energy cycles exist to a lesser or greater extent while walking depending on the person's specific gait. The more of a "bounce" in a person's stride, the larger the amplitude of the potential energy cycle. Human walking gait is frequently approximated by the motion of an inverted pendulum. Since the end of the inverted pendulum experiences increasing vertical displacement with increasing horizontal displacement, potential energy cycle amplitude increases with increasing stride length, and since for a given speed increasing stride length implies decreasing cadence, torso energy cycle amplitude increases with decreasing cadence.

On the other hand, the frequency of torso potential energy cycles decreases with decreasing cadence (for a constant speed). It turns out that the frequency of potential energy cycles decreases faster than torso potential energy per cycle increases, and consequently, for walking gaits where a bounce is appreciable, potential-energy power loss decreases with decreasing cadence. It should be noted, however, that most walking gaits do not exhibit an appreciable bounce, as the knee joint is normally used to decrease or eliminate bounce in the walking gait. Thus, for walking, potential energy power loss is typically relatively insignificant.

[0119] Running gait includes at least two additional features related to torso energy cycles: 1) a period of free-fall, and 2) energy storage in soft tissues, such as the Achilles tendon.

[0120] In running, torso horizontal speed starts increasing when a first foot in contact with the ground passes the point below the person's center of mass and reaches maximum speed at toe-off. Neglecting the effects of air friction, during free-fall torso horizontal speed maintains the maximum speed, then starts decelerating when the second foot contacts the ground. Torso deceleration continues until the person's center of mass passes over the second foot, at which point the cycle resumes.

[0121] Torso vertical position (and potential energy) in running is minimum shortly after a foot contacts the ground and reaches maximum at approximately mid-free-fall. In order to estimate how much the torso moves parallel to gravity it is useful to note that in free-fall the person's acceleration is approximately equivalent to the gravitational constant ("g"), approximately 9.8 m/s^2 , and that approximately all of the potential energy stored when the person is at the highest position is converted to vertical kinetic energy as the person falls towards the ground. Since amount of kinetic energy just before contact time in free-fall increases with the square of free-fall time and assuming that free-fall time increases linearly with stride time, torso potential-energy power loss increases with decreasing cadence.

[0122] As mentioned above, during running torso horizontal speed starts decreasing at the moment free-fall ends with a foot making ground contact. The force vector which causes horizontal speed deceleration is approximately oriented parallel to a line between the contact point and the hip joint, in the direction of the hip joint. The magnitude of the force vector must be sufficiently large to stop the downwards torso motion resulting from the free-fall. Assuming a constant free-fall final velocity, the magnitude of the force vector increases with increasing angle between the force vector (leg) and the vertical (stride impact angle). Furthermore, assuming a constant force vector, the component of the force vector in the negative horizontal direction also increases with the stride impact angle. Consequently, negative horizontal acceleration quickly increases with the stride impact angle. Since the stride impact angle increases with stride length, and since for a given speed stride length increases with decreasing cadence, negative horizontal acceleration (and therefore torso kinetic energy loss per cycle) increases with decreasing cadence. Combining the physical relationships representing the above comments shows that for constant velocity, reducing cadence increases the torso kinetic-energy power loss linearly for short steps, and increasingly faster than linearly as cadence decreases.

[0123] For some running gaits, not all of the energy expended by the runner to raise torso potential and kinetic

energies during each stride is dissipated into heat at the end of each striding cycle. Foot strike type, in particular, is believed to play a major role in leg's ability to store some of the impact energy and return it on toe-off. Forefoot strike (striking the ground first with the ball of foot) is believed to enable the user to use the Achilles tendon to act as a spring which is loaded on foot strike, and unloaded on toe-off.

[0124] To summarize, the following principles relate to torso motion inefficiency:

[0125] Walking torso kinetic energy change per cycle increases with decreasing cadence.

[0126] Walking torso kinetic energy power loss increases with decreasing cadence.

[0127] Walking torso potential energy power loss decreases with decreasing cadence.

[0128] Running torso potential energy power loss increases with decreasing cadence.

[0129] Running torso kinetic energy power loss increases with decreasing cadence.

[0130] Some of the potential and kinetic energy required for striding motion may be stored in soft tissues on impact and returned on toe-off.

[0131] During striding motion energy is lost due to motion of the legs and the torso, therefore multiple inertial sensors on the legs and torso could be used to fully monitor a user's movements and determine the inefficiency of a user's motion. Motion models or physiological sensors could also be used to account for effects such as changes in muscle efficiency. For example, multiple inertial sensors (such as accelerometers and/or orientation sensors) could be attached at different torso positions (e.g., waist, chest and/or shoulders), multiple inertial sensors could be attached to legs (e.g., feet, ankles and/or knees), multiple inertial sensors could be attached to arms (e.g., hands and/or elbows) and sensors could be attached to the head, to help quantify the striding inefficiency components described above. However, measuring even a subset of all inefficiency variables could be used to determine or estimate motion inefficiencies and therefore would benefit an athlete or a fitness-conscious person.

[0132] There exist at least two approaches to quantifying motion inefficiency. In the first approach, biomechanical models for the various motion inefficiency components are designed. Using these models together with user-specific and motion input variables such as cadence, speed, mass of various body parts, limb length, acceleration of various points, and so forth, power-input relationships can be derived and used to quantify component and total running inefficiency. In the second approach, one or more intermediate variables representative of the sum of one or more inefficiency components is captured and used to calculate or estimate the one or more inefficiency components. As an example of the second approach, a measurement of an athlete's heat loss would be representative of expended energy, and thus could be related to the sum of all inefficiency components. The first approach may require a relatively large set of user-specific input variables, some of which may be difficult to quantify, and therefore may be undesirable or impractical to use.

[0133] Torso motion inefficiency contributes a large portion—and sometimes the largest portion—to overall striding motion inefficiency. Thus, athletes could derive a considerable benefit from being able to monitor the amount of power expended for torso motion.

[0134] Even though the torso is not a completely rigid body during striding motion, a reasonably good approximation of

the torso center of mass is on the user's chest close to the sternum (such as, for example, the location of most chest-mounted heart rate monitors). An inertial sensor **12** (such as an accelerometer) placed at the center of mass of the torso can monitor the motion of the torso, and in particular, the horizontal and vertical acceleration fluctuations during striding motion. The system **10** illustrated in FIG. 1, for example, provides a sensor unit **32** on the user's chest.

[0135] While an angular position or rate sensor (e.g. gyroscope or magnetometer) would provide additional useful information, as a first approximation the torso may be assumed to be relatively rotation-free during striding motion (which is relatively correct outside of rapid acceleration and deceleration periods). The orientation of the accelerometer **12** relative to gravity may be either assumed to be known due to the method of attachment to athlete's body (e.g. chest strap similar to that of a heart-rate monitor) or may be determined with a measurement of gravity during non-striding periods or during specific stride phases (e.g. stance or impact). Other sensor locations on the torso (i.e., other than on the chest) are also likely to be suitable for sensing acceleration signals useful for analyzing torso striding-motion inefficiency. In particular, a waist-mounted sensor would have the advantage of reduced rotation in the sagittal plane as compared to a chest-mounted sensor, which would increase accuracy of acceleration-vector integration in a system which does not include an angular position or rate sensors.

[0136] Acceleration signals collected on the torso contain information related to both kinetic and potential energy cycles during striding motion. Acceleration perpendicular to gravity can be integrated to obtain torso horizontal velocity differentials over a stride, which, combined with average torso velocity, can be used to calculate kinetic energy changes over the stride period. Similarly, acceleration parallel to gravity can be integrated to obtain torso vertical velocity differentials over a stride, which can be used to calculate potential energy changes over a stride by recognizing that any potential energy additions during flight phase must exist as kinetic energy at toe-off. It should be recognized that integration of the orthogonal acceleration components as indicated above is equivalent to integration of the acceleration vector to obtain a torso velocity vector. Variation of torso kinetic energy (computed from velocity magnitude) over a stride is indicative of torso striding motion inefficiency.

[0137] It is possible that useful information about torso striding inefficiency can be obtained by analysis of the acceleration magnitude (combining two or three acceleration components) rather than by treating the orthogonal directions separately. Ability to do so may simplify the system by not needing to measure or estimate system orientation, and by reducing computational complexity. These, in turn could reduce the system cost and power requirements. Because the torso orientation experiences little change in steady state running, simple integration of acceleration magnitude to obtain velocity and kinetic energy differentials may be sufficiently accurate.

[0138] An estimate of energy fluctuations per unit time (and per unit torso mass) at the end of each stride would yield an estimate of the power/kg transferred to and from the torso. This power is partially dissipated and partially stored in soft tissues of the leg at the end of each stride. An insight into what percentage of power is dissipated and what percentage is stored may be obtained from the frequency-spectrum distribution of the acceleration signal, especially at foot impact. A

forefoot strike allows the athlete to store more energy than a heel strike. A forefoot strike also generates less energy at higher frequencies than a heel strike. Consequently, it may be possible to determine how much of the power transferred from the torso is dissipated and how much is stored by analyzing high-frequency acceleration signal energy.

[0139] The final estimate of torso inefficiency combines the estimate of the power transferred to and from the torso, the estimate of the portion of this power which is dissipated, and user speed estimate to arrive at a metric in Watts/(m/s)/kg. Rather than presenting an absolute metric to the user, it may be desirable to present the metric as a ratio to some baseline, such that the user sees a number in the range of e.g. 1-10, with "1" being very efficient, and "10" being very inefficient.

[0140] As explained above, a stride inefficiency monitor based on a torso-mounted acceleration sensor can utilize the acceleration signals to calculate or estimate torso energy transfer per stride either using a full model of individual energy input components, or by calculating an intermediate variable representing multiple energy components (e.g. instantaneous torso velocity or vertical oscillation amplitude) and using this variable to calculate the combined cyclical energy transfer to the torso.

[0141] Optionally, in addition to either approach leg energy transfer can be calculated or estimated using a model and one or more inputs such as stride cadence, stride speed, stride stance duration and/or user-specific parameters such as height and/or in-seam length. A portion of some of the components of cyclical energy transfer may be stored in soft tissues such as the Achilles tendon. This portion may be estimated using a model (e.g. based on acceleration spectral distribution, as explained above) to allow for computation/estimate of energy required per stride. A muscle efficiency model (e.g., an empirical cadence-based model described in Doke, J., Donelan, J. M., Kuo, A. D., "Mechanics and energetics of swinging the human leg" J. Exp. Biology 208, 439-45 (2004)) can be used to calculate/estimate striding motion power loss. Finally an "Inefficiency Score" can be calculated by combining striding motion power loss with average speed using, for example, the following equation:

$$\text{Score} = \frac{P_{str} / v}{k} \quad (15)$$

Where P_{str} is the striding motion power loss, v is the average torso speed over the stride, and k is a modifier defined as:

$$\frac{\text{nominal striding motion power loss}}{\text{nominal stride average torso speed}} \quad (16)$$

"Nominal" may be, for example, representative (e.g., average) of a sample population at comfortable jogging speed. Alternatively, the modifier k may be any other constant which suitably modifies the dynamic range of the Inefficiency Score for ease of understanding and communication to the user. The value of k may also be a variable which is directly or indirectly configurable by the user, to allow the user to set a personal baseline for the Inefficiency Score.

[0142] Thus, in one embodiment, an Inefficiency Score of "1" would indicate that the athlete is typically inefficient. An inefficiency score of "2" would indicate that the athlete loses

twice as much power per unit of speed as a typical athlete. If striding motion power loss stays constant while speed increases, inefficiency score decreases proportionally to indicate that proportionally less energy will be consumed to travel a unit of distance. Conversely, if an athlete's striding motion power increases while speed remains constant, inefficiency score increases proportionally to show that proportionally more energy is being consumed per unit of distance.

[0143] Optionally, an altimeter or an output power meter, may be used as another input into the inefficiency score, to recognize the additional (to running at some speed) benefit derived by the athlete from the energy input.

[0144] Like the torso-mounted monitor, a foot-mounted striding inefficiency monitor could utilize theoretical and/or empirical modeling of the individual leg motion inefficiency components, or could utilize foot-mounted sensors to calculate or estimate energy transfer per stride to and from the leg. The system **10** illustrated in FIG. **3** is an example of a foot-mounted striding inefficiency monitor.

[0145] Theoretical or empirical models may use three variables: stride duration, stride length and stance time. Consequently, a detailed stride-signature analysis algorithm may be required to support the models. Theoretical and/or experimental relationships are required to map at least the above variables to metrics representing the individual leg motion inefficiency components. Total energy loss per stride can be computed from the individual components.

[0146] The sensor-based approach depends on being able to measure and estimate the peak foot speed during a stride. Due to the high rotational component of typical foot motion, it may be necessary to obtain angular position information for the foot in order to facilitate integration of acceleration vectors. Angular position, velocity or acceleration may be sensed with, for example, magnetic sensors, gyroscopes or a pair of parallel acceleration sensors. An estimate or measurement of peak foot velocity can be used to estimate foot and/or leg kinetic energy loss per stride.

[0147] Regardless of which approach is used (modeled or sensed), an empirical model may be needed to estimate loss of muscle efficiency as a function of cadence. Existing published empirical results may be used for this purpose.

[0148] An estimate of energy loss per stride, together with stride duration and stride speed can be combined to calculate foot-motion inefficiency in Watts/(m/s)/kg. As with the torso-mounted monitor, rather than presenting an absolute metric to the user, it may be desirable to present the metric as a ratio to some baseline, such that the user sees a number in the range of, for example, 1-10, with "1" being very efficient, and "10" being very inefficient.

[0149] A foot-mounted striding inefficiency monitor could be configured to also estimate at least some of the torso inefficiency components using one or more inputs such as stride cadence, stride speed, stride length, stride stance duration and/or user-specific parameters such as height and/or in-seam length. This can be accomplished through theoretical or empirical models of torso striding inefficiency as a function of the above inputs.

[0150] A portion of some of the components of cyclical energy transfer may be stored in soft tissues such as the Achilles tendon. This portion can be estimated using a model (e.g. based on acceleration spectral distribution) to allow for computation/estimate of energy required per stride. Note that the proposed method for estimating energy storage in soft tissue based on acceleration spectral distribution is expected

to benefit from acceleration sensor placement above the ankle. A muscle efficiency model can be used to calculate/estimate striding motion power loss. Finally an Inefficiency Score can be calculated by combining striding motion power loss with average speed, as explained above.

[0151] An exemplary method of determining an inefficiency score is illustrated in FIG. **14**. First, signals from one or more inertial sensors are received, as illustrated in block **48**, and an amount of energy expended in each stride is determined, as illustrated in block **50** and as explained above. The inertial sensors may be located on the user's torso, feet or legs, as explained above and illustrated in FIGS. **1**, **3** and **5**. Next, an amount of the expended energy per stride that is stored in soft tissue is determined, as illustrated in block **52**, using a soft-tissue energy storage model as explained above. The portion of the energy expended in each stride that is not stored in soft tissue is dissipated. Next, the total amount of metabolic energy required to generate the dissipated portion of the energy is determined using muscle inefficiency models, as depicted in block **54**, and the striding motion power lost per stride is determined from the total amount of metabolic energy lost per stride, as depicted in block **56**.

[0152] The person's speed is then determined, as depicted in block **58**, and an efficiency score is calculated based on power loss and the person's speed, as depicted in block **60**. The inefficiency score is communicated to the user via the interface unit **30**, for example, and as depicted in block **62**.

[0153] In some embodiments, the system **10** is configured to determine and monitor running power, a concept that is related to running inefficiency. Running power includes not only energy input due to striding motion, but also relatively low frequency energy input due to factors such as wind friction, elevation change, and speed change. Thus, an athlete running at a particular inefficiency level and speed will increase power input when running up a hill or when facing increased headwind. The torso velocity signal described above contains information related to running power, and therefore can be used to derive a measurement of running power.

[0154] When a person is running, the motion experienced in each step is in many ways similar to that of a projectile. For purposes of illustration, the motion of a projectile, such as a cannon ball, launched from the barrel of a gun or cannon will be described and then compared to the motion experienced by a running person. Kinetic energy is added to the projectile as it travels through the barrel. As soon as the projectile exits the barrel, some of the projectile's kinetic energy is lost to air friction and some is converted to potential energy as the projectile moves along an inclined path and gains elevation. At any point in time before contact with another object, the sum of the projectile's kinetic and potential energy is equal to the sum of the projectile's kinetic and potential energy immediately after leaving the barrel less any energy lost to air friction.

[0155] If the projectile's path begins and ends at the same elevation, the potential energy of the projectile at the beginning of the path (where it exits the barrel) is the same as at the end of the path (when it hits the ground). Consequently, the kinetic energy of the ball when it hits the ground is equal to the kinetic energy at barrel exit less any energy lost to air friction. Thus, the difference in kinetic energy between the beginning and the end of the projectile's flight represents the energy lost to air friction.

[0156] If the projectile's path ends at a higher elevation than where it began, and if the projectile experiences no air friction during flight, the projectile's kinetic energy at the end of the path will be equal to the kinetic energy at the beginning of the path less the energy transferred to potential energy due to the elevation increase. Thus, the difference in kinetic energy between the beginning and the end of the projectile's flight corresponds to energy transferred to potential energy.

[0157] In many circumstances, the projectile will experience air friction and will end its flight at a different elevation than where it began its flight. In these situations, the kinetic energy difference the beginning and the end of the path reflects the sum of energy lost to air friction as well as the change in potential energy, as characterized by the following equation:

$$\Delta E_k = \Delta E_{af} + \Delta E_p \quad (17)$$

where ΔE_k is the change in kinetic energy, ΔE_{af} is the change in energy due to air friction, and ΔE_p is the change in potential energy. The instantaneous value of kinetic energy (E_k) is defined as:

$$E_k = \frac{ms^2}{2} \quad (18)$$

where m and s represent the mass and speed of the projectile, respectively. Thus, if the projectile's mass and speed at the beginning and end of the flight path are known, the change in the projectile's kinetic energy can be derived.

[0158] The running gait, by definition, involves a period of time when the person is not contacting the ground (torso flight). The torso flight portion of a running step is similar to that of the projectile's motion described above. Energy is added to the person during ground contact portion of the step. As soon as the person loses contact with the ground, the person's kinetic energy is both lost to air friction and is converted to potential energy. The person touches the ground at the same or a different elevation. Again, knowledge of the person's mass and speed at the beginning and end of the trajectory allows for the calculation of change in kinetic energy which reflects energy consumed by air friction and potential energy change. Power consumed during the torso flight phase due to the effects of air friction and changes in elevation can be calculated as:

$$\Delta P_{tf} = \frac{\Delta E_k}{T_f} \quad (19)$$

Where ΔP_{tf} is the power consumed during torso flight, ΔE_k is the change in kinetic energy experienced by the person during the flight, and T_f is the flight time.

[0159] The power consumed due to air friction and elevation change during a ground contact phase of the striding motion can be estimated as being approximately equal to power consumed during torso flight. Alternatively, in some implementations the power consumed during a ground contact phase of the striding motion can be estimated as being proportional to power consumed during torso flight. Thus, power consumed by air friction and elevation change over the entire step (the ground contact phase of the step as well as the torso flight phase) may be defined as:

$$\Delta P_{step} = \frac{T_f P_f + T_c P_c}{T_{step}} \quad (20)$$

Where ΔP_{step} is the power consumed over the entire step, T_f is flight time, P_f is power consumed during the torso flight phase of the step, T_c is the contact time, P_c is the power consumed during the contact phase of the step, and T_{step} is the total step time.

[0160] The total power delivered by the person's muscles is the sum of the power consumed by air friction and elevation change and the power lost to striding motion inefficiency as described above. Total power spent by the person is the sum of the total power delivered by the muscles and power lost to muscular inefficiency. Power lost to muscular inefficiency may be theoretically or empirically modeled as described previously.

[0161] The determination of running power requires precise measurement of user's speed at multiple points during the step cycle. Acceleration measured by accelerometer(s) (such as the LIS3DH manufactured by STMicroelectronics of Geneva, Switzerland) may be integrated to calculate velocity change. Thus, one or more accelerometers 12 may be included in a small, portable device, such as the sensor unit 32, and used to measure instantaneous torso acceleration. In some embodiments, the unit 32 is mounted on the person's torso where the body motion is least complex, and sensitivity axes of the one or more accelerometers 12 are substantially mutually perpendicular.

[0162] In one embodiment, the orientation of the accelerometers 12 relative to the direction of motion is assumed to be approximately constant for the duration of each step, and consequently the acceleration vector as measured by the one or more accelerometers 12 may be integrated by integrating the individual acceleration components through the step. The assumption that the unit 32 orientation remains relatively constant through each step is approximately true when mounted on the torso, and in particular when mounted on the waist.

[0163] In another embodiment, one or more direct or indirect means to measure angular torso position are included in the unit 32 (e.g. magnetometers, gyroscopes, pairs of accelerometers with parallel axes of sensitivity). The one or more means to measure angular torso position may be oriented to measure angular torso position in mutually perpendicular planes. Angular torso position (or torso orientation) information may be used to improve the precision of measurement of the acceleration vector relative to the direction of motion by allowing for rotation of the acceleration vector measured by the accelerometer to a constant frame of reference relative to the direction of motion. In one embodiment, only one means to measure angular torso position is included and oriented to measure angular position in the sagittal plane of the person.

[0164] The unit 32 includes a means for analyzing the one or more acceleration signals to identify portions of the acceleration signals corresponding to individual steps, and further to identify different phases of the step (e.g. contact phase, torso flight phase) and time the step phases (e.g. flight time, contact time, total step time). For any given step, upon identification of the beginning of the torso flight phase, integration of the acceleration vector may be started, and subsequently stopped upon identification of the beginning of the contact phase. The integration yields a velocity vector representing

the torso velocity difference between the beginning and the end of the torso flight phase. The torso speed at the beginning of the flight phase may be approximated using the average torso speed obtained by means such as a foot-mounted running speed/distance sensor (e.g. FR60 foot pod sold by Garmin International headquartered in Olathe, Kansas), or a GPS sensor (e.g. Forerunner 610 sold by Garmin International). More specifically, the torso speed at the beginning of the flight phase may be approximated as equal or proportional to the average torso speed using an empirical or theoretical relationship. The torso speed at the end of the torso flight phase may be approximated as the sum of the torso speed at the beginning of the flight phase and the torso speed change during flight. The torso speed change during flight is the magnitude of the torso velocity difference vector between the beginning and the end of the torso flight phase.

[0165] The total torso kinetic energy change during the torso flight phase may then be calculated as:

$$\Delta E_{fk} = \frac{m[(S_{fb})^2 - (S_{fe})^2]}{2} \quad (21)$$

where ΔE_{fk} is the change in torso kinetic energy during the flight phase, m is the person's mass, S_{fb} is the torso speed at the beginning of the torso flight phase and S_{fe} is the torso speed at the end of the torso flight phase.

[0166] Changes in power consumption due to air friction and elevation changes during the torso flight phase, during the contact phase, and over the entire step may then be computed as previously described.

[0167] The running power metric(s) may be computed in real time and available to be communicated to the user while the athlete is engaged in an activity, in order to help guide the athlete. However, the running-power metrics may also be computed after the activity using data stored during the activity.

[0168] Although the invention has been described with reference to various exemplary embodiments illustrated in the attached drawing figures, it is noted that equivalents may be employed and substitutions made herein without departing from the scope of the invention as recited in the claims.

[0169] Having thus described embodiments of the invention, what is claimed as new and desired to be protected by Letters Patent includes the following:

1. A system for determining performance characteristics of a user, the system comprising:
 - an inertial sensor for coupling with the user and generating one or more signals corresponding to striding motion of the user's torso; and
 - a processing system in communication with the inertial sensor and operable to use the one or more signals to determine vertical torso displacement.
2. The system of claim 1, the inertial sensor including at least one accelerometer.
3. The system of claim 1, the processing system operable to use the one or more signals to determine a change in the potential energy of the torso.

4. The system of claim 1, the processing system operable to use the one or more signals to determine the change in potential energy from the vertical torso displacement.

5. The system of claim 1, the processing system operable to use the one or more signals to determine a change in vertical kinetic energy of the torso.

6. The system of claim 5, the processing system operable to use the one or more signals to determine a maximum vertical torso speed, and to use the maximum vertical torso speed to determine the change in vertical kinetic energy.

7. The system of claim 1, the processing system operable to determine the vertical torso displacement by twice integrating a vertical acceleration signal with respect to time.

8. The system of claim 1, the processing system operable to use the one or more signals to determine cadence.

9. The system of claim 1, the processing system operable to use the one or more signals to determine contact time per step.

10. The system of claim 1, further including a display coupled with the processing system, the display operable to present an indication of one or more calculated user performance characteristics associated with the determined vertical torso displacement.

11. The system of claim 1, the processing system operable to use the one or more signals to determine an amount of power used to raise the user's torso.

12. The system of claim 1, the processing system operable to use the one or more signals to identify the foot of the user associated with the striding motion.

13. The system of claim 1, the processing system operable to use the one or more signals to determine an amount of energy used per unit of distance.

14. The system of claim 1, the processing system operable to use the one or more signals to determine an amount of energy used to accelerate and decelerate the user's torso in a direction perpendicular to gravity.

15. The system of claim 1, the processing system operable to use the one or more signals to determine an amount of energy used to reposition one of the user's legs.

16. The system of claim 1, wherein the inertial sensor is integrated with a torso-mounted heart rate monitor.

17. A method of determining user performance characteristics, the method comprising:

receiving, with a processing system, one or more signals corresponding to the user's torso motion, the one or more signals being generated by an inertial sensor coupled with the user;

determining, with the processing system, vertical torso displacement using the one or more signals; and

presenting a visual indication of a user performance characteristic associated with the determined vertical torso displacement.

18. The method of claim 17, further including determining one or more user performance characteristics including determining a change in potential energy of the torso.

19. The method of claim 17, further including determining one or more user performance characteristics including determining a change in horizontal kinetic energy of the torso.

20. The method of claim 17, further including determining one or more user performance characteristics including determining an amount of energy used.

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