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(54) **SWING WITH IMU FEEDBACK OF BACK SWING, CONTACT POINT, AND FOLLOW THROUGH**

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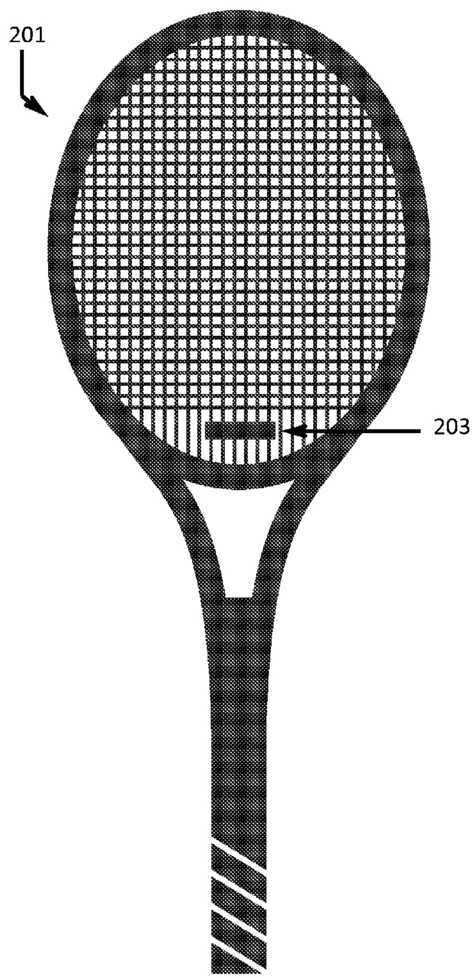
(57) **ABSTRACT**

An apparatus, method, and system are herein disclosed for improving an athlete's swing by detecting three phases of a swing—the backswing, the lead up, and the follow through—and determining whether a ball impact or highest velocity occurred between the lead up and follow through using an inertial measurement unit device affixed to a piece of sports equipment without encumbering the athlete's equipment by substantially changing the weight, balance, or structure of the equipment.



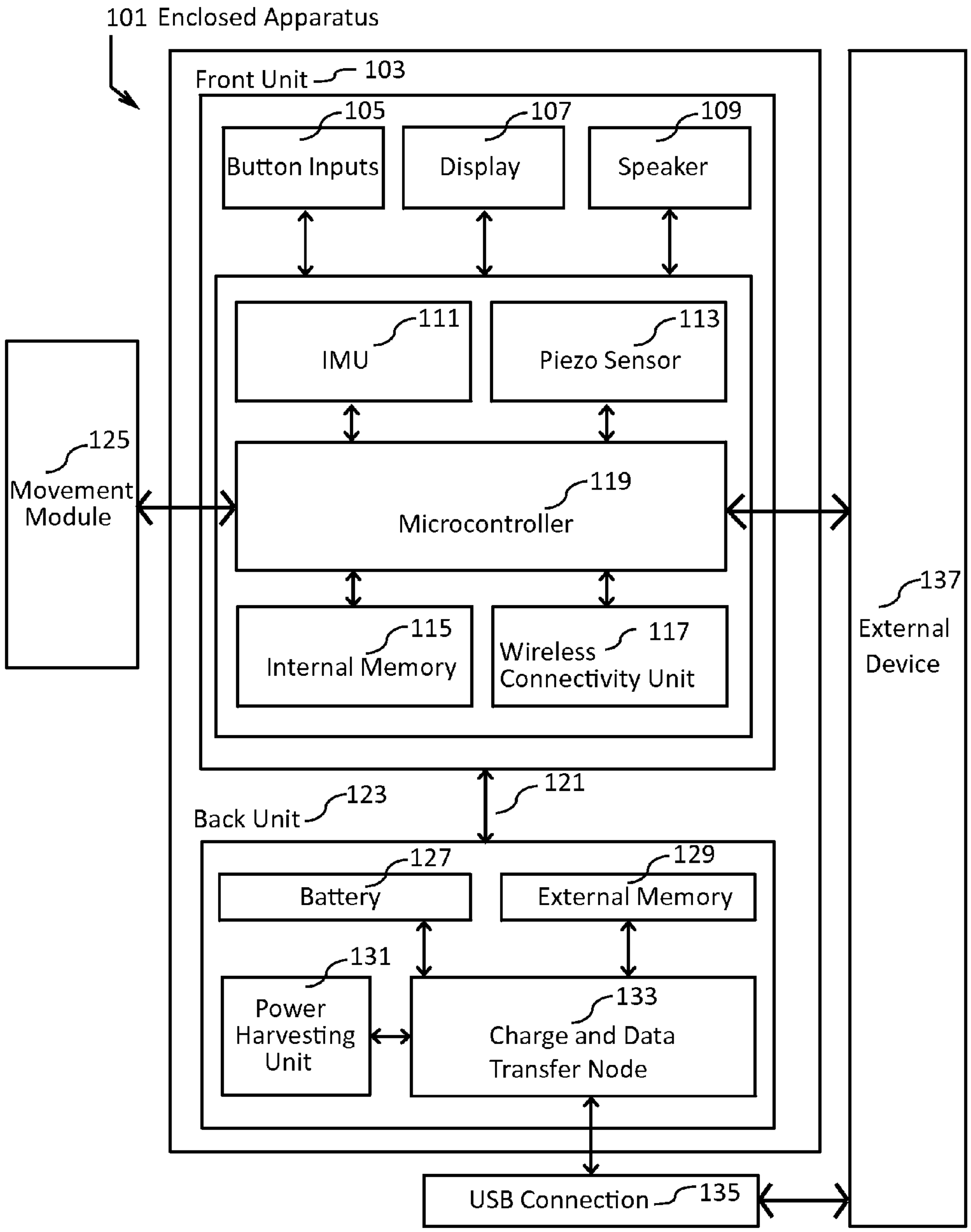

101 Enclosed Apparatus
Front Unit 103
105
Button Inputs
107
Display
109
Speaker
111
IMU
113
Piezo Sensor
125
Movement Module
119
Microcontroller
137
External Device
115
Internal Memory
117
Wireless Connectivity Unit
121
Back Unit 123
127
Battery
129
External Memory
131
Power Harvesting Unit
133
Charge and Data Transfer Node
USB Connection 135

Fig. 1

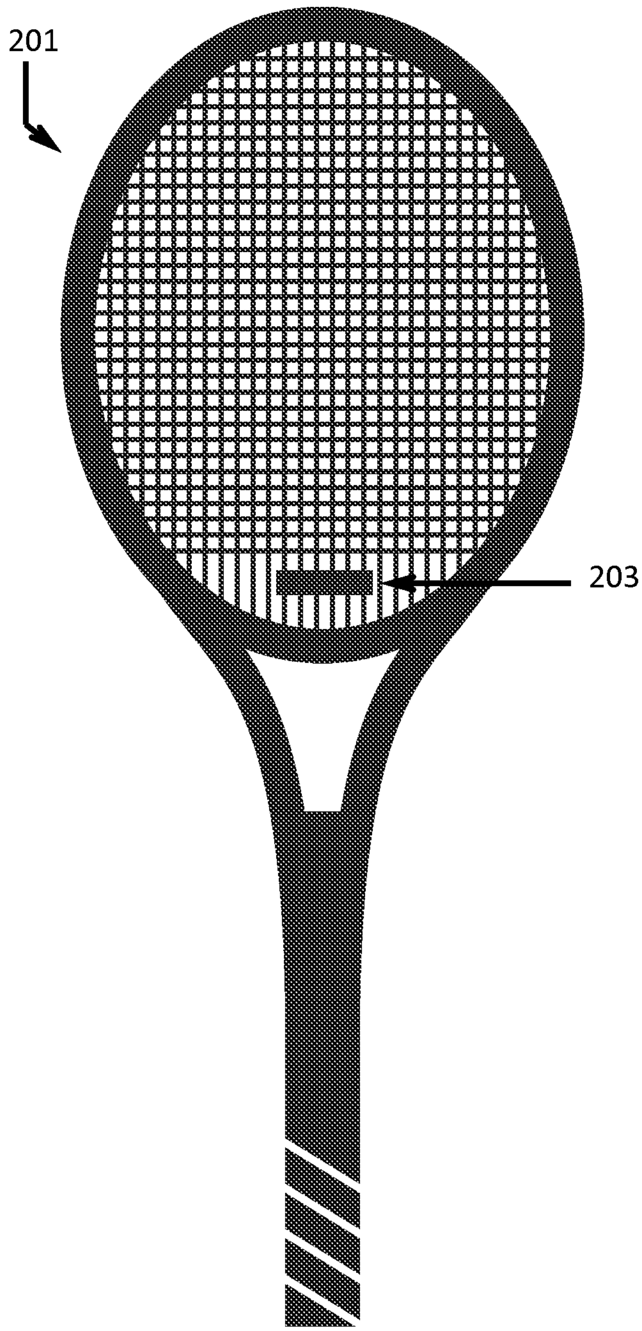


Fig. 2

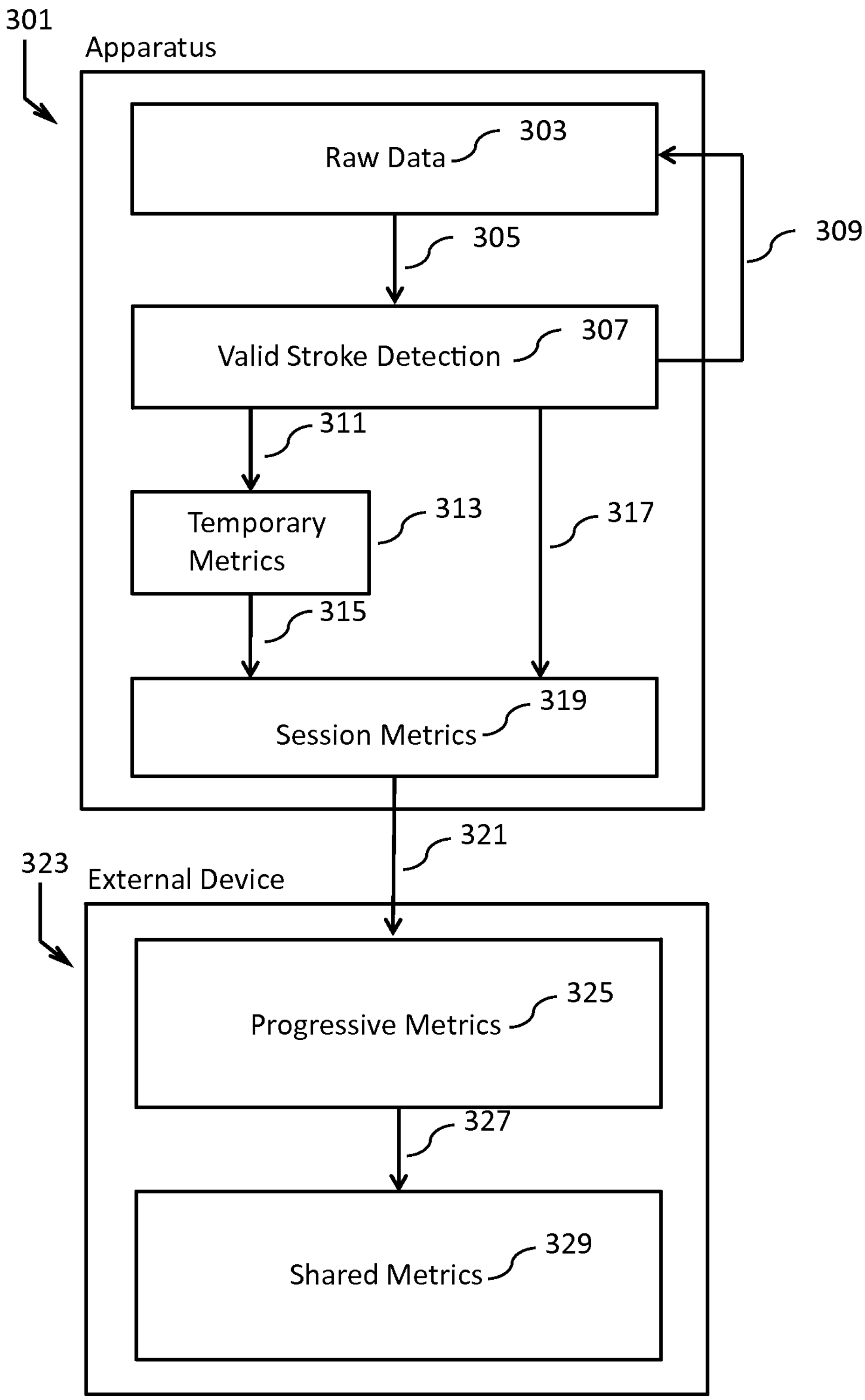

301
Apparatus
Raw Data
303
305
309
Valid Stroke Detection
307
311
Temporary Metrics
313
317
315
Session Metrics
319
321
323
External Device
Progressive Metrics
325
327
Shared Metrics
329

Fig. 3

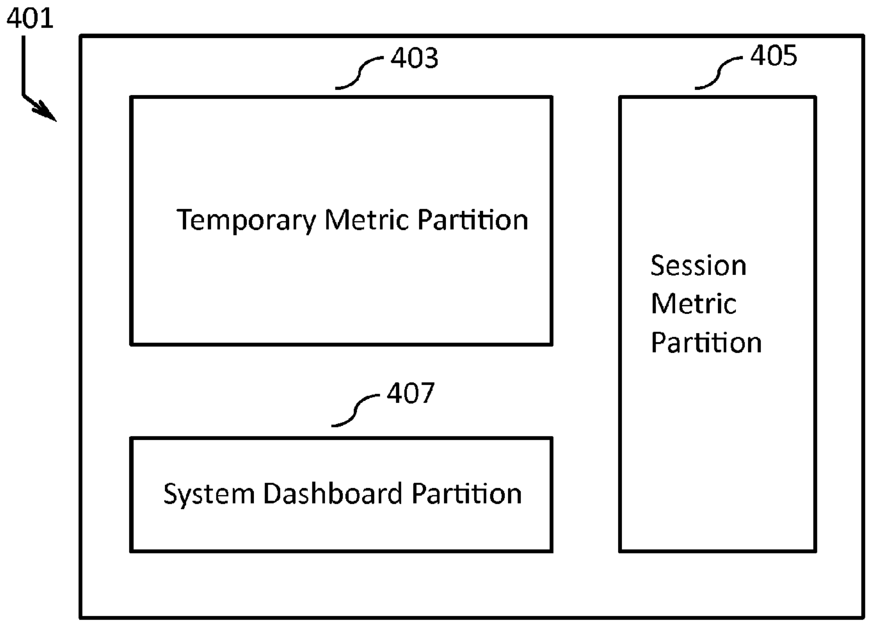

401
403
405
Temporary Metric Partition
Session
Metric
Partition
407
System Dashboard Partition

Fig. 4A

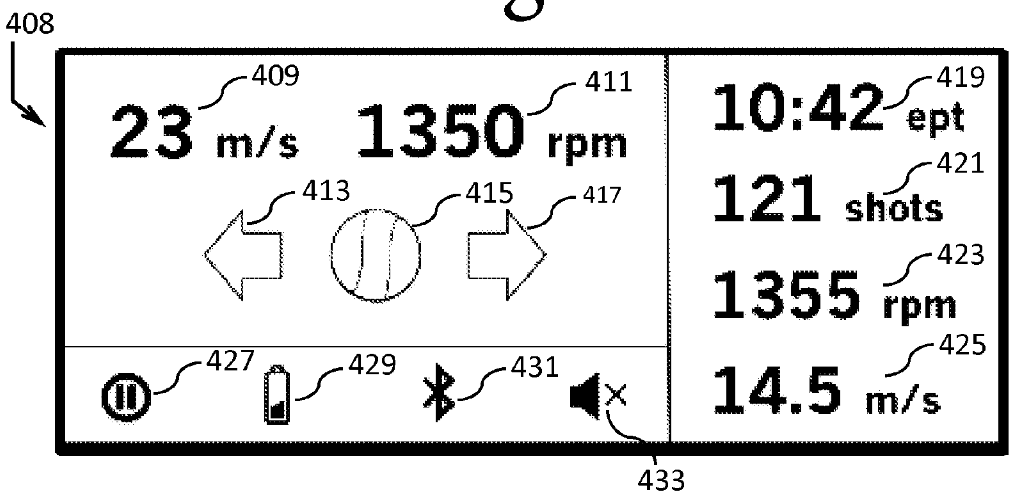

408
409
411
23 m/s
1350 rpm
413
415
417
419
10:42 ept
421
121 shots
423
1355 rpm
425
14.5 m/s
427
429
431
433

Fig. 4B

SWING WITH IMU FEEDBACK OF BACK SWING, CONTACT POINT, AND FOLLOW THROUGH

CROSS-REFERENCE TO RELATED APPLICATIONS; BENEFIT CLAIM

[0001] This application claims the benefit of Provisional Appln. 61/959,320, filed Aug. 21, 2013, the entire contents of which is hereby incorporated by reference as if fully set forth herein, under 35 U.S.C. §119(e).

FIELD OF THE INVENTION

[0002] The present invention relates to inertial measurement feedback techniques for sports equipment and, more specifically, to improving a swing with IMU feedback of back swing, lead up, and follow through.

BACKGROUND

[0003] Given that MEMS devices are becoming more precise and accurate, new devices are needed to help sports equipment users increase the quality of their game. Existing devices are designed to examine one quantitative metric associated with a swing, and these devices are extremely over inclusive as to what motions count as a valid shot. For example, a MEMS device may be attached to the shaft of a golf club to record a speed associated with a golf swing. After a person moves the club, the device may record a speed, but there is no indication of whether that speed was actually associated with a swing for hitting a golf ball or simply a practice swing. A swing may be recorded even when a user taps their sports equipment on their shoe or bounces a ball on the sports equipment with no intention of hitting the ball as if they were in a game.

[0004] Determining whether a set of recordings of the MEMS device can be associated with a swing is called stroke validation. Stroke validation is usually confined to the quantitative scope of the metric being measured. Thus, a threshold value of speed may define a valid stroke for the golf club, but the speed is actually the speed of the club at the shaft location, and has no connection to direction or ball impact. The metric defines the max speed of a location on the shaft of the golf club, not whether the speed was used to effect a quality stroke.

[0005] To add some qualitative analysis, the user may set up video equipment to record each swing. The video is later analyzed by choosing specific swings in the video, slowing down those parts, and overlaying the video with videos of other players or professional models. These features allow both a player and coach to see visual information that can facilitate learning.

[0006] Unfortunately, much of the benefit of practice involves muscle memory. Connecting the after practice analysis of whether a swing was a quality swing with the muscle memory associated with making the swing is very difficult. Developing muscle memory often requires repetition immediately after a quality swing has been made.

[0007] Additional setbacks with the above described approaches include setup time and bulkiness of having multiple apparatus necessary to complete the task. A user trying to use these devices may actually be thrown off their game because the equipment adds weight and offsets balance of the sports equipment. A user is less likely to swing naturally if the user has to set up the apparatus in a particular manner, start a recording, swing, transfer the data to a computer, and then analyze the data on a computer. The time associated with setup makes the user less relaxed and ready to perform a natural, effective swing.

[0008] Other setbacks associated with the above described approaches include hardware implementation. Due to the nature of a MEMs device being used with sports equipment, the device must be housed mechanically in a housing that won't fall off the sports equipment, slide around the equipment, or rattle around while using the sports equipment. To combat these problems, the devices often require connection to a computer to gain feedback of a stroke or swing after a significant amount of time has passed.

[0009] The approaches described in this section are approaches that could be pursued, but not necessarily approaches that have been previously conceived or pursued. Therefore, unless otherwise indicated, it should not be assumed that any of the approaches described in this section qualify as prior art merely by virtue of their inclusion in this section.

BRIEF DESCRIPTION OF THE DRAWINGS

[0010] In the drawings:

[0011] FIG. **1** is a block diagram illustrating a system architecture of an IMU device.

[0012] FIG. **2** is a schematic diagram illustrating an IMU device performing as a dampener on a tennis racket.

[0013] FIG. **3** is a flowchart illustrating steps for transforming raw data of a swing into valid, qualitative feedback.

[0014] FIG. **4**A is schematic template illustrating a user display on an IMU device.

[0015] FIG. **4**B comprises a display interface as an example for explaining embodiments of the present invention.

DETAILED DESCRIPTION

[0016] In the following description, for the purposes of explanation, numerous specific details are set forth in order to provide a thorough understanding of the present invention. It will be apparent, however, that the present invention may be practiced without these specific details. In other instances, well-known structures and devices are shown in block diagram form in order to avoid unnecessarily obscuring the present invention.

[0017] Embodiments are described herein according to the following outline:

[0018] 1.0 General Overview

[0019] 2.0 Mechanical Hardware

[0020] 3.0 Electrical Hardware

[0021] 4.0 Stroke Analysis

[0022] 5.0 User Interface

[0023] 6.0 External Networking

[0024] 1.0 General Overview

[0025] In some embodiments, an IMU is used to detect a quality swing by detecting three phases of a swing: the backswing, the lead up, and the follow through. By associating expected values for metrics associated with each phase of the swing, false positives are significantly reduced. A swing is identified by recognition of a sequence of quantitative metrics associated with the three phases.

[0026] For example, after a threshold velocity is reached, the preceding accelerometer data is reviewed to determine if the threshold velocity was preceded by a slower velocity in the opposite direction to detect a back swing. The angle of the backswing at its farthest point back (a zero velocity in one direction) is then compared with an acceleration that varies with the change in angle to an expected ball contact point to detect a lead up. The angle at this point is then compared with a deceleration that varies with the change in angle to detect a follow through.

[0027] In some embodiments, the vertical centerline of the body is associated with the vertical orientation of the sports equipment mounted with an IMU, and a horizontal plane through the shoulder is associated with the horizontal orientation of the sports equipment mounted with an IMU. Thus, a lead up can be further validated by detecting whether the swing passes through the vertical centerline of the body, and a follow through can be further validated by detecting whether the swing ends above the shoulder.

[0028] In some embodiments, instant feedback is provided as to whether the actual point of impact coincides with the expected point of impact. The actual point of impact may be behind the expected point of impact in the lead up phase. The actual point of impact may be after the expected point of impact in the follow through phase. Comparison of this expected point of impact with the actual point of impact provides quality analysis to a swing or stroke.

[0029] 2.0 Mechanical Hardware

[0030] In some embodiments, mechanical hardware for the IMU device includes housing and a hinge mechanism. In some embodiments, the housing comprises two pieces surrounding the IMU device. The housing is preferably constructed of aluminum because of its high strength to weight ratio. Thus, the walls of the housing may be thin and still provide protection for the inner electronic components. Other embodiments of the two housing pieces include, but are not limited to, plastics, rubbers, composites, and other metals. The two pieces may be attached around a piece of sports equipment, such that some of the electrical components are in one piece and other electrical components are in the other piece. As an example, the two pieces may be attached to each other around the strings of a tennis racket.

[0031] In some embodiments, the two pieces are attached with a hinge mechanism. The hinge mechanism provides for a secure connection on one side of the two pieces, so a mechanical fastener on the other side of the two pieces provides the only separation point. The mechanical faster may include a snap, slide, bolt, rivet, clip, clamp, Velcro, insert or other mechanical fastener type known in the art. There is a clearance around the hinge for a printed circuit board (PCB) cable to pass from one piece to the piece. In this manner, the electrical components of the IMU device may separate onto two or more PCBs.

[0032] In some embodiments, the IMU latches onto sport equipment through either a twist latch or slide latch. The twist latch involves the front piece inserted into the back pieces or vice versa. The front piece rotates until it locks into place, creating a secure physical and electrical connection. The slide latch involves the front piece sliding into the back piece, similar to a camera tripod latching system. The front piece may also have additional inserts or bends to lock into place, creating a secure physical and electrical connection.

[0033] In still other embodiments, the housing comprises a one piece housing with a clamp or grip adapted for attaching to a piece of sports equipment. For example, the housing may have a grip fro stings of a tennis racket.

[0034] In some embodiments, the housing functions as a part of the sports equipment. FIG. **2** is a schematic diagram illustrating an IMU affixed to a tennis racket depicting the location of a combined enclosure apparatus **203** that is latched onto a tennis racket string bed **201**. The apparatus **203** resides within the middle six vertical strings, also known as the "mains" and below (not touching) the bottom most horizontal string, also known as the "cross". This is the same area a vibration dampener is typically affixed. The front unit **103** and the back unit **123**, when operably attached, form the apparatus **203**.

[0035] In some embodiments, the apparatus **203** latches onto the tennis racket string bed **201** through either a twist latch or slide latch. The twist latch involves the front unit **103** inserted into the back unit. The front unit **103** rotates until it locks into place, creating a secure physical and electrical connection. The slide latch involves the front unit **103** sliding into the back unit **123**, similar to a camera tripod latching system. The front unit **103** locks into place, creating a secure physical and electrical connection. The device only powers on when the two components of the IMU housing are locked and connected.

[0036] The dampener may be made of metal, impact-resistant plastic, and a rubber or rubber-like material (i.e. silicone). The dampener may consist of a mixture of these materials to achieve the desired feel, weight, appearance, and durability. The dampener may be a single monolithic piece, or may consist of multiple pieces that attach to one another.

[0037] 3.0 Electrical Hardware

[0038] In some embodiments, electrical systems are provided for computing stroke quality, speed, stroke count, stroke type, ball spin, ball impact, player movement, effective play time with an inertial measurement unit (IMU) device affixed to a piece of sports equipment without encumbering the athlete's equipment by substantially changing the weight, balance, or structure of the equipment.

[0039] In some embodiments, inertial measurement unit (IMU) device comprises a MEMS (microelectromechanical systems) device preferably containing a 3-axis accelerometer, 3-axis gyroscope, and 3-axis magnetometer operably connected to a microcontroller responsible for processing the raw data of the device, onboard memory for storing data, and a battery.

[0040] An inertial measurement unit (IMU) is an electronic component that measures and reports on velocity, orientation, and gravitational forces, using a combination of accelerometers, gyroscopes or angular rate sensors, and magnetometers. These systems are more accurate than single microelectromechanical sensors (MEMS) devices because the sensors may be used in conjunction to correct for bias.

[0041] In some embodiments, the IMU measures vibrations from the string bed and sends this additional data to the microcontroller. Impact data from the IMU provides another level of abstraction that can be used in conjunction with racket head speed at the time of impact, stroke quality metrics, stroke count, stroke type, and ball spin to provide feedback to a user.

[0042] FIG. **1** is an IMU device **101** comprising a front unit **103**, a back unit **123**, an external movement module **125**, and an external device **137**. The front unit **103** houses direct user inputs **105**, a display **107**, and a speaker **109**, an inertial measurement unit **111**, a piezoelectric sensor module **113**, an internal memory unit **115**, a wireless connectivity unit **117**, and a microcontroller **119**. The back unit **123** houses a charge and data transfer node **133**, a battery **127**, an external memory module **129**, and a power harvesting unit **131**. The charge and data transfer node permits a USB connection **135** to an external device **137**, such as a smartphone, computer, or tablet, while also controller the voltage entering into the battery for charging.

[0043] In some embodiments, the two-piece apparatus contains two mechanically and electronically linked components, a front unit **103** and a back unit **123**. The apparatus powers on and operates when both components are operably attached, that is, the two components are securely attached via mechanical means. Both the front unit **103** and back unit **123** contain electronic connection contacts. When the front unit **103** and the back unit **123** are securely attached via mechanical means, there is an electrical connection **121** between the two components. This connection **121** supplies power from the rechargeable battery **127**, within the back unit **123**.

[0044] The rechargeable battery **127** may have a lithium-based chemistry, such as lithium-polymer or lithium iron phosphate. Preferably, it is of a single cell construction with a nominal voltage of approximately 3.7V, and a capacity in the range of 50-800 mAh. It is integrated into the back unit **123** but may be designed to facilitate simple user replacement at end of life. In order to charge the battery **127**, there is charging and protection circuitry within the charge and data transfer node **133**. The function of this circuitry is to provide the correct voltages and currents to the battery **127** during charging to ensure safe operation. This charging and protection circuitry also monitors the battery **127** voltage level and state-of-charge of the battery **127** to prevent an over-charge, over-voltage, or under-voltage condition. This is critical to the safe integration of lithium-based battery technology. The circuitry may report battery voltage and state-of-charge to the microcontroller **119**. This component may accept a charge via a USB connection **135** inserted into the device, via a proprietary or industry-standard power port, and/or via an inductive charging interface. Any of these methodologies may be used in any combination and are not mutually exclusive.

[0045] Embodiments of this component accept charge via a female USB port, a female micro USB port, proprietary or industry-standard power ports, or an inductive charging interface. Embodiments of this component may also be set up to accept charge from multiple sources. Any of these methodologies may be used in any combination and are not mutually exclusive. The rechargeable battery **127** is also charged via the power harvesting unit **131**. The power harvesting unit **131** may use piezoelectric actuators, solar cells, mechanical generators, or any combination of these to generate energy from the motion of the device and/or ambient conditions. This energy is sent to the charge and data transfer node **133** where it is conditioned so that it may be used to charge the battery **127**. This extends the battery life of the device to enable less frequent charging by the user. Another aspect of the current invention resides in a piezoelectric energy harvesting module. To extend the life of the battery before a re-charge is required, the apparatus may contain an energy harvesting module that utilizes the piezoelectric effect. The module leverages an onboard piezoelectric component to harvest energy captured from the vibration of the strings upon any external contact with the racket string bed.

[0046] When piezoelectric actuators are used, the piezoelectric effect is leveraged. The Piezoelectric effect is the ability of certain crystalline materials to generate electricity in response to being physically stressed, such as from deformation or vibration. Multiple layers of piezoelectric materials can be stacked to amplify the voltage and current generated by a given stress. Energy is harvested by using a multi-layered piezoelectric material mounted in a cantilever style (one end is free to move). Upon encountering a shock, as when a player strikes a tennis ball with the racket, part of the energy of the impact is absorbed by the piezoelectric material which undergoes an initial deformation in response to the movement, and afterwards vibrates at its resonant frequency for a short period of time. The material may include a small weight on the end opposite the mounting point. The purpose of this weight is to both amplify the movement of the piezoelectric material and to prolong the period for which it vibrates. This serves to increase the amount of energy that can be harvested after each impact.

[0047] Such vibration of the piezoelectric material generates an AC voltage. This voltage is the input to a specialized component that rectifies and conditions the voltage. The output of this component is a low (approximately 0-5 V) DC voltage that is fed to a capacitor. The purpose of the capacitor is to accumulate energy after each impact until it is of a sufficient amount to be transferred to the battery efficiently. Once the capacitor is full, it is connected to the battery charging circuitry, which transfers this energy from the capacitor to the battery. The capacitor then resumes accumulating energy until the next cycle. Piezoelectric elements used for power harvesting may be the same unit(s) used for data capture purposes.

[0048] In some embodiments, the USB connection **135** allows the external memory **129** to transfer data to and from an external device **137**. Calculated data is sent to an external device **137**, such as a smartphone, tablet, or computer for aggregation, organization, and sharing. The external device **137** can send data in the form of system configuration and firmware updates to the external memory **129**, within the back unit **123**.

[0049] The connection **121** between the front unit **103** and the back unit **123** also allows a two-way data transfer between the external memory **129**, within the back unit **123**, to the microcontroller **119** within the front unit **103**. The data transferred from the microcontroller **119** to the external memory **129** are calculated metrics ready for output to the user. The external memory **129** is distinct from the internal memory **115** in that either the user or the microcontroller **119** can access it, whereas the internal memory **115** is only used for intra-device storage and cannot be directly accessed by the user.

[0050] The external memory **129** may be of an EEPROM, Flash, or other non-volatile memory architecture. It may be used to store data that must be preserved during power cycles or no power conditions, such as user configuration data. It may further be used to store output data from the apparatus that can be accessed by the user, either directly or through an external device **137**. The data may be accessed via any standard wired or wireless communications protocol, including but not limited to USB, Bluetooth, WiFi, Zigbee, ANT, or other protocol. This data access may be performed via the charge and data transfer node **133** or the wireless connectivity unit **117**.

[0051] The internal memory **115** may be EEPROM, Flash, or another volatile or non-volatile memory. The internal memory **115** may consist of more than one discrete component, and may use any combination of memory architectures. It is used to store output data from the device, as well as any initialization code that is required by the device upon startup. It may be accessed directly by the microcontroller **119**, or by an external device **137** via a wired or wireless communications protocol such as USB, Bluetooth, WiFi, Zigbee, ANT, or other protocol. The raw data may also be transmitted to an external device **137** via the wireless connectivity unit **117**, the USB connection **135**, or both in order to be processed, displayed, and/or stored on the external device **137**.

[0052] In some embodiment, the wireless connectivity unit **117** provides an interface to transmit and receive data from an external device **137**. The wireless connectivity unit **117** may use any industry standard wireless communication protocol and/or a proprietary wireless protocol. It may support multiple wireless protocols. This device may contain one or multiple components used for transferring data over wireless protocols. These may include Wireless USB, Bluetooth, WiFi, Zigbee, ANT, RFID, NFC, or a short-range radio link of another type. The device may utilize one or multiple such protocols.

[0053] The data is delivered directly to the user via an onboard display **107** or to an external device **137**. The data is captured from the IMU **111** and a piezoelectric vibration sensor **113**. There is also an optional movement module **125** that can provide a different set of data. The IMU **111**, piezoelectric vibration sensor **113**, and movement module **125** deliver raw data to the microcontroller **119**.

[0054] The IMU **111** is responsible for measuring the movement of the device. It is a MEMS (microelectromechanical systems) device containing a 3-axis accelerometer, 3-axis gyroscope, and 3-axis magnetometer, in any combination. It measures different parameters: acceleration, rotation, and magnetic field strength. It measures each of these parameters on three orthogonal axes. The measurement functions may be done by a single component or by multiple components. Accelerations are measured by the accelerometer and integrated over a period of time to compute velocity, and this may also be integrated over a period of time to compute the path of the device through space. Rotations are measured by the gyroscope and are used to measure the attitude—or orientation—of the racket in 3D space. Magnetic field strength is measured by the magnetometer and is used to supplement gyroscope readings to improve accuracy. All 3 sensors—accelerometer, gyroscope, and magnetometer, may be used in conjunction to correct inaccuracies and noise and provide a more accurate measurement of the movement and orientation of the racket.

[0055] The piezoelectric vibration sensor **113** contains a single piezoelectric element or multiple piezoelectric elements that may be used as a sensor to detect vibration patterns present in the racket or strings for a period of time after an impact. This information may be used to analyze vibration patterns to determine if a valid shot has occurred and/or approximately where on the racket string bed the impact occurred. This sensor may be in the form of a MEMs device package, wherein such a device contains one or multiple piezoelectric elements, or it may consist of one or more discrete piezoelectric elements that are bare (i.e. not contained in a package or integrated with any interface circuitry). Multiple piezoelectric elements may be used to detect vibrations on up to 3 orthogonal axes. Multiple piezoelectric elements with distinct resonance frequencies may also be used to detect different vibration frequencies. Piezoelectric elements used for data capture purposes may be the same unit(s) used for power harvesting **131**. In some embodiments, the IMU replaces the peizoelectric elements in functionality.

[0056] The movement module **125** is an optional accessory that provides a different set of raw data to the microcontroller **119**. This data set, after calculation, creates metrics detailing the movement of a tennis player as opposed to metrics dealing with a tennis player's tennis stroke. The module may contain an IMU and/or a GPS receiver. The GPS receiver may be integrated into the device to allow reception and processing of standard civilian GPS signals. The IMU may be used for "dead reckoning," a method by which motion is tracked over a period of time using no external references. This module is to be used for tracking the movement of the device and player during a session. This data may be merged with any other sensor data or calculated data to provide additional metrics to the end user. The GPS receiver module may contain an integrated antenna, or may be connected to an antenna located elsewhere within the device. All data output by the IMU/GPS module transmits to the microcontroller **119**. GPS module data output may consist of raw GPS signal data or processed GPS data in a standard format. In the former case all processing of raw GPS signal streams is done onboard the microcontroller; in the latter case all such processing is done on the GPS receiver module itself. The transmitted IMU data may be raw unprocessed data, or data processed by an onboard microcontroller inside the movement module **125** in order to reduce the burden on the microcontroller **119**.

[0057] The microcontroller **119** handles the main data processing tasks, intra-device communication, and all user input/output functions. It handles most or all processing and communications-related tasks between components of the device. Specific functions may be handled by specialized components. The microcontroller **119** is optimized for low-power operation. The IMU **111** and the piezoelectric vibration sensor **113** may also perform some data processing functions in order to reduce the burden on the microcontroller. In some embodiments there are a plurality of processors that process data in parallel.

[0058] Another aspect of the current invention resides in user input. Embodiments of the invention comprise buttons, knobs, wheels, slides, joysticks, and switches that the user can use to access various measurements and outputs. These inputs may be external or virtual through a capacitive or resistive touch screen to enable touch-based and/or gesture based input. An inertial measurement unit also detects and recognizes user input such as a "taps" or a motion based gestures. Any of these input methodologies can be used in any combination, and are not mutually exclusive.

[0059] Button inputs **105** may include tactile buttons that the user can push to access various functions, capacitive or resistive touch screen to enable touch-based and/or gesture based input, or a touch screen that is placed directly over the display or directly over the protective display cover. An external device **137**, such as a connected smartphone, tablet, or computer allows for system configuration and firmware updates. The device may also use the IMU to detect and recognize user input such as a tap or a motion based gesture. Any of these input methodologies may be used in any combination and are not mutually exclusive.

[0060] In some embodiments, a display on the IMU device provides instant feedback of quality metrics of a swing. As the device is used mainly outdoors and in the sunlight, the screen needs high contrast and visibility, without glare. The display may comprise and electronic paper display that is low power, durable, and robust, such that it can stand up to the shock and vibration produce by impacts to the string bed.

[0061] In other embodiments, the display comprises an organic light emitting diode (OLED) display, LCD (liquid-crystal display), or PNLC (polymer networked liquid crystal) display. In these embodiments, the miniaturization and manufacturing of this technology provides for ease of replacement and customization.

[0062] Visual output may be in the form of on an onboard display **107** and audible output may be in the form of an onboard speaker **109**. A transparent cover built into the housing protects the display **107**. This cover may be composed of high-strength glass or an impact-resistant plastic, such as polycarbonate. The display **107** may also be encapsulated, or "potted," in a plastic or rubber-like epoxy to protect it from shock and impact. This encapsulation may be complete or partial. The display **107** may also have a backlight or a direct illumination source for viewing under low-light conditions. The speaker **109** may use an electromagnetic actuator or a piezoelectric actuator. The speaker **109** may be voice coil or piezo actuated. It may produce a constant or variable tone upon application of a constant DC voltage, or it may accept an arbitrary waveform to reproduce a full or partial range of audible frequencies.

[0063] In some embodiments, one or more modules or components may be used in different combinations in order to conserve space. For example, the power harvesting unit **131** may not be included in an embodiment to increase room for a battery **127**.

[0064] 4.0 Stroke Analysis

[0065] In some embodiments, analysis of stroke quality requires taking measurements of distance, angle, acceleration, path, and speed of the stroke and identifying the backswing phase, lead up phase, and follow through phases, and then validating each phase. Validation of athlete's backswing requires comparing the associated measurements with the appropriate length, height, and racket angle. Validation of a swing's contact point requires comparing whether the contact point is between 0.5 ft to 2.5 ft (depending on arm length) in front of the athlete's body. Validation of an athlete's follow through requires comparing whether the stroke is continuous and naturally decelerates across the athlete's body.

[0066] Using the above quantitative and qualitative metrics, ball path data may be calculated. For example, identifying top spin shot helps predict a ball with top spin and/or side spin. Top spin causes the ball to follow a trajectory with a smaller radius than a ball with an equivalent velocity, but no spin. It is often utilized to keep a ball in the court, hit sharper angles, and apply pressure to the opponent to hit a higher bouncing ball. Side spin causes the ball trajectory to curve to the left or to the right following impact with the racket. A shot with side spin is used to force the opponent out of position. Identifying a slice shot helps predict a ball with back spin and/or side spin. Back spin causes the ball to follow a flatter trajectory over the net and forces the opponent to hit a lower bouncing ball.

[0067] In addition to the input captured by a user's tennis actions through various sensors, the user may provide direct input to the device via the button inputs, an external device, or via gestures (i.e. tapping, shaking, rotating) that are detected by the IMU. The direct input can notify the IMU device of that a quality shot has been achieved, and the user would like alerts or comparisons of similar data, so the user can try to recreate the shot.

[0068] FIG. **3** is a flow chart of operation steps between nodes in a system, defining the calculations and transmission of data from within the local device **301** and an external device **323**. The raw data **303** is captured, buffered **305**, and compared to determine whether the apparatus movement qualifies as a valid stroke or as "taps" or a motion based gestures, then stored as a valid stroke **307**. If a valid stroke is not detected, raw data capture is repeated **309**. Upon detection of a valid stroke **311**, the raw data **303** is computed into temporary metrics **313**, which are then averaged or totaled **315**, forming session metrics **319**. Additionally, upon valid stroke detection **307**, the raw data **303** can be directly transferred **317** into session metrics **319**. The session metrics **319** are then transmitted **321** to the external device **323** via a USB or wireless connection. The session metrics **319** are stored and aggregated within the external device **323**, forming progressive metrics **325**, i.e. they can be used to interpret a user's progress. The subset of the progressive metrics **325** are then selected **327** by a user for sharing information to other users, forming shared metrics **329**.

[0069] Raw data **303** is captured from the various sensory inputs, that is, the IMU **111**, the piezo sensor **113**, and the movement module **125**. Raw data is acquired continuously, but the data may be retained on the device only for a particular interval of time with a first-in-first-out (FIFO) hierarchy. The data comprising this time interval is known as the buffer **305**. Once the buffer **305** is full, every new data acquisition causes the oldest acquisition in the buffer **305** to be deleted or overwritten. In this manner the buffer **305** always contains the most recent data for a given duration. Physically, the buffer **305** is a block of reserved memory that can be located on any component with sufficient free memory to contain it. This may include the microcontroller **119**, the internal memory **115**, the external memory **129**, or any combination of these components.

[0070] Once a valid stroke is detected **307**, that is when raw data **303** is within an expected threshold velocity, measurements of distance, acceleration, path, and speed associated with the movement of a tennis racket during a typical tennis stroke, and within an expected vibration range after contact between a tennis ball and tennis racket, it may be computed into metrics based on measurements from a piezoelectric sensor. An additional redundancy can be included to eliminate counts made too closely in time by comparing time since the last valid stroke with an expected threshold value. All together, restricting acceptable strokes with in an excepted threshold value allows the device to prevent false positives and produce more accurate metrics. An example of a prevented stroke false positive is a tennis player hitting the racket strings on their feet and hand.

[0071] Upon a valid stroke, raw data **303** is fed into one or a series of software algorithms that are executed on the microcontroller **119**. Different algorithms are used depending on the desired output metric. The outputs of these algorithms are the temporary metrics **313**. Temporary metrics **313** are metrics solely on the most recent valid stroke and are displayed to the user until the next valid stroke metrics are to be displayed. Temporary metrics include, but are not limited to, racket head speed, ball spin, and stroke quality.

[0072] Session metrics **319** are total durations, totals, and averages of temporary metrics. Session metrics include, but are not limited to, effective play time, stroke count, average ball spin, and average racket head speed. Average racket head speed and average ball spin are respective averages of all valid strokes within a session.

[0073] Racket head speed defines the quality of a tennis stroke and its definition is addressed in the background. Racket head speed is computed and outputted by measuring the velocity with the IMU and then adjusting with angular velocities to compute racket head speed. In some embodiments, a racket head speed is calculated for each phase of a stroke: back swing, lead up, and follow through. The comparisons of these values can help with quality analysis of a stroke.

[0074] Ball spin defines the quality of a tennis stroke and its definition is addressed in the background. Ball spin is computed by isolating vertical acceleration component and the angle of the racket head from measurements of distance, angle, acceleration, path, and speed to calculate the expected rotations per minute on the ball struck. This is an absolute metric of the number of rotations per minute of the tennis ball, regardless of the type of spin (top, back, side).

[0075] Effective play time is computed by identifying a time subset of the total active duration of playing session when the player is making dynamic movements to approach an oncoming ball, striking the ball, and recovering (the reaction and player's body's reset after finishing a stroke) from a stroke.

[0076] Stroke count is computed by storing the number of tennis strokes completed. The counter only tracks strokes that are valid tennis strokes, meaning that they have to meet the criteria of a backswing, lead up, and follow through. Additionally, they may be invalidated for shank shots or lack of ball contact. Users have the option to pause and reset the device. Pausing the device triggers the device to not calculate towards effective play time, shot count, average ball spin, and average racket head speed. Resetting the device sets effective play time to 00:00 (hr:min), stroke count to 0 shots, average ball spin to 0 rpm, and average racket head speed to 0 m/s.

[0077] Before the device is turned off or reset the user is given the option to save the current set of session metrics **319**. Additionally, the user can also continually save the session at any time. These saved metrics are used saved onto the external memory **129**. These metrics can be transmitted **321** to an external device **137** via the wireless connectivity unit **117** or a USB connection **135**. Those metrics, when housed and aggregated on an external device, become progressive metrics **325**. Progressive metrics **325** quantitatively present the development of a tennis player's tennis stroke and subsequent performance over time. Progressive metrics **325** include, but are not limited to, average racket head speed, average ball spin, average stroke quality, total and average (per session) effective play time, total and average (per session) stroke count, average ball impact, average stroke type, and player movement.

[0078] Ball impact is computed by comparing expected measurements for on center, off center, and frame/shank hits with actual measurements of distance, angle, acceleration, path, and speed. In particular, the IMU **111** and Piezo sensor **113** detects data on the vibration of the ball on the strings. The frequency components and waveform shape of the vibration can be help to differentiate various types of ball impacts.

[0079] Stroke type is computed by the comparison of expected measurements for types of swings with the IMU **111** data used to calculate the general stroke path. For example, a low backswing to a high follow through or a high backswing to a low follow through results in two different types of swings. Calculation of path with measurements of distance, angle, acceleration, path, and speed along with comparison of expected values defines types of swings, including but not limited to a slice, topspin, a flat shot, a drop shot, and a lob. The angle and direction of the racket head during the back swing and prior to the contact phase of the swing differentiates from a forehand swing and backhand swing.

[0080] Player movement defined as the distance a tennis player has moved during a session whether that player is making dynamic movements to meet, approach, and prepare for an oncoming ball, or simply moving around a court. Movement is calculated through any or all of the module inputs and processed by the microcontroller **119**.

[0081] An aspect of the invention also includes a movement module that tracks the location of the player on the court. The movement module may contain a GPS receiver and an IMU. Player movement may be tracked using GPS position data in conjunction with IMU data. The IMU measures the location of the player with "dead reckoning", a process where in the IMU is used to track absolute motion for a period of time without any external reference point(s). The motion that is tracked includes the distance a tennis player moves during a session whether or not that player is making dynamic movements to meet, approach, or prepare for an oncoming ball.

[0082] Stroke quality is computed and outputted by comparing measurements of distance, angle, acceleration, path, and speed, to identify the phases of the swing or stroke as backswing, contact point, or follow through and validating measurements associated with the identified phase. Validation simply requires comparing actual values with stored expected values for a quality swing. For example, validation of the player's backswing requires comparison of expected measurements to the actual length, height, and racket angle of the athlete's backswing. Validation of the athlete's contact point with the tennis ball requires comparison of expected measurements such that the contact point would be 0.5 ft to 1.5 ft in front of the player's body. Validation of the athlete's follow through requires comparison of expected measurements where the path and deceleration is continuous across the athlete's body.

[0083] Consistent improvement of a swing or stroke requires focusing both on quantitative aspects and qualitative aspects. Overlooked in many systems is an analysis of stroke quality as well as a comprehensive analysis of stroke quantities.

[0084] For example, tennis athletes tend to focus on one quantitative measurement such as racket head speed, stroke count, or ball spin. Racket head speed is the velocity of the racket head upon contact with a tennis ball. The average tennis player's racket head speed is 20-25 m/s. However, optimal racket head speed is around 25-35 m/s. Stroke count is the number of valid tennis strokes completed. A high number of repetitions increase muscle memory, and thus, accuracy and precision of a swing. Ball spin is the rotational speed of the tennis ball in revolutions per minute (RPM) after impacting the racket. The more spin a player imparts to the tennis ball, the more likely the player is to hit the ball into the court, within bounds. The average tennis player's ball spin is about 800 RPM-1,200 RPM, while optimal ball spin is around 1,500 RPM-2,500 RPM. While all three of these measurements are important, many systems only focus on one quantitative measurement. This is an issue because these metrics are inter-related. For example, when the racket head speed is not high enough, a struck ball will not have proper velocity or spin to have an appropriate ball path.

[0085] In some embodiments, the system provides feedback for improving stroke quality by obtaining an optimal starting position, path, and ending position of a swing in each of the three distinct phases of a stroke or swing: the back swing, the lead up, and the follow through. The backswing is the take back of the racket before contact with the ball is made. The lead up is the motion until, a racket connects with a tennis ball at the contact point or expected contact point, and the follow through is the path the racket takes after the point of contact with the ball. The quality of the stroke is affected based on each phases starting and ending position in relation to the athlete's body.

[0086] Effective qualitative analysis illuminates many stroke quality issues. Examples of stroke quality issues include, a backswing being too far past the player's opposite side, or non-playing side; a backswing being not far enough past the player's playing side; a contact point with the tennis ball being too close to the player's body and the arm is either not extended far enough out or too close to the player's body (player side); and a path of a tennis stroke that does not elevate up through a shot after making contact with tennis ball because the player lacks the upward component of a stroke.

[0087] In some embodiments, quality analysis feedback is tailored towards a serve. The serve is the most important tennis stroke and is used to begin each point in a tennis match. It is also the most easily manipulated stroke, where the tennis player is in full control of the stroke, as there is no incoming ball struck by an opponent, but rather the tennis player tosses the tennis ball. The stroke quality components (backswing, contact point, and follow through) of a serve are more complex and have more variations than other tennis strokes. However, because the serve is consistent, an athlete may give feedback to the device, when an optimal server is performed. Then the device can give indicators about whether the phases of other serves match the phases of the optimally defined server.

[0088] Another qualitative aspect of swing analysis is keeping track of each ball impact. The contact point between a ball and racket can be classified as on center, off center, or on the frame of the racket. An on center ball impact is a shot that is struck within the "sweet spot" of the racket. The sweet spot is defined as the area of the string bed where a ball is struck with relative assurance that the ball responds in a controlled and deliberate manner, while producing the least strain on an athlete's body. This area is slightly below the very center of the string bed. An off center impact occurs when the ball is struck outside the "sweet spot" of the racket, but without contact to the tennis racket frame. Finally, a frame or shank shot, is where the ball impact occurs between the frame of the racket and a tennis ball. To a tennis player, it is often obvious when the player has any one of these impact types on an individual stroke. However, improvement would follow from understanding the number of balls, in total, that fall within each impact classification after an entire session.

[0089] Although tennis is highly illustrative, IMU device may be adapted for many specific types of sports equipment, such as the core of a bowling ball or baseball bat, the head or shaft of a golf club or hockey stick, or the frame of other pieces of sports equipment including rackets. Additionally, the unit can be adapted for a helmet or vehicle attachment in various motorsports such as Formula One, NASCAR, Rally Racing, Motocross, and Water Surface Racing. The unit may also be adapted for board sports such as skate boarding, surfing, snowboarding, wind surfing, skiing, water skiing, paddle boarding, or kayaking. The unit may also be adapted for various roller sports such as roller skating, mountain biking, cycling. The unit may also be adapted for various Olympic sports such as archery, athletics, badminton, basketball, beach volleyball, boxing, canoe slalom, canoe sprint, cycling BMX, cycling mountain bike, cycling road, cycling track, diving, equestrian/dressage, equestrian/eventing, equestrian/jumping, fencing, football, golf, gymnastics artistic, gymnastics rhythmic, handball, hockey, judo, modern pentathlon, rowing, rugby, sailing, shooting, swimming, synchronized swimming, table tennis, taekwondo, tennis, trampoline, triathlon, volleyball, water polo, weightlifting, wrestling freestyle, wrestling Greco-Roman, Alpine skiing, biathlon, bobsleigh, cross country skiing, curling, figure skating, freestyle skiing, ice hockey, luge, Nordic combined, short track speed skating, skeleton, ski jumping, snowboard, and speed skating. This is not meant to be an exhaustive list, merely an attempt to give the versatility of the unit.

[0090] 5.0 User Interface

[0091] FIG. **4**A is sample digital display partitioning **4**A and a sample digital display **4**B, defining the total screen area **401**, the temporary metric display partition **403**, the session metric display partition **405**, and the system dashboard display partition **407**. The temporary metric display partition **403** houses the racket head speed **409** (m/s), the ball spin **411** (rpm), and the stroke quality, in the form whether ball impact occurred in the lead up **413**, at the expected contact point **415**, or during the follow through **417**. The session metric display partition **405** houses the effective play time **419** (ept, hours: minutes), the stroke count **421** (shots), the average ball spin **423** (rpm), and the average racket head speed **425** (m/s). Other metrics, such as, but not limited to ball impact, stroke type, and player movement, may be later placed within this display **401** or displayed solely on the display of an external device **137**.

[0092] The system dashboard display partition houses the pause state **4427**, the battery level **429**, the connectivity state **431**, and the audible feedback state **433**. The pause state **427** (on/off), when on, triggers the device to not calculate and save towards effective play time, shot count, average ball spin, and average racket head speed. When off, the device calculates these metrics as normal. The battery level **429** icon displays the amount of batter life remaining. It has three states: 1/3, 2/3 and full capacity. The connectivity state **432** (on/off), when on, toggles an active connection between the wireless connectivity unit **117** and the external device **137**. When off, no wireless connection is made. The volume (on/off), when on, enables the onboard speaker **109**. When off, the onboard speaker **109** is disabled.

[0093] 6.0 External Networking

[0094] In some embodiments, the analysis determined using one or more of the above described techniques may be uploaded to a computer and then imported to an application. The data may then be analyzed through isolating specific swings and comparing/overlaying the data with other swings of other players or professional models. These features allow both a player and coach to see undisputable visual information that can facilitate learning.

[0095] Another aspect of some embodiments is the capability to sync and transfer data with an external device via Bluetooth or a standard wireless protocol connection. This connection can be configured to specifically connect to a smartphone, tablet, or computer.

[0096] An embodiment resides in a system of collecting data through an apparatus and aggregating said data for analyses by an application on a smartphone, tablet, or a computer. The analyzed data can be stored across a network with multiple nodes for storage and access. Nodes can be configured for an integrated display showing multiple metrics, that is, racket head speed, stroke quality, stroke count, stroke type, ball spin, ball impact, player movement, effective play time.

[0097] In some embodiments, the system comprises the ability to log and share metrics and their analyses to parents, other players, and other coaches, via the Internet (email, cloud applications, and social media). The data analysis, including annotations and comments, can be saved to provide a progression over time.

[0098] The user, via various social media avenues or other online distribution means can share progressive metrics **325**. Additionally, the user has the ability to specify certain subsets of the progressive metrics **325** to share. These shared metrics **329** include, but are not limited to, average racket head speed, average ball spin, average stroke quality, total and average (per session) effective play time, total and average (per session) stroke count, average ball impact, average stroke type, and player movement.

What is claimed:

1. An apparatus comprising,

at least one inertial measurement unit, wherein the inertial measurement unit comprises an accelerometer, a gyroscope, and a magnetometer;

a microcontroller operably coupled to the inertial measurement unit;

memory operably coupled to the microcontroller;

wherein the inertial measurement unit, microcontroller, and memory are operably coupled to identify a backswing, lead up, and follow through to validate a complete stroke.

2. The apparatus of claim **1**, further comprising a housing adapted for attachment on a tennis racket with a string bed with a proximal end and a distal end with mains strings oriented from the proximal end to the distal end and cross strings oriented transverse to the mains strings, the housing adapted to attach to the proximal end of said string bed between the proximal end of the string bed and a first cross string.

3. The apparatus of claim **2**, wherein the housing attaches to at least two mains strings to dampen vibrations of the tennis racket.

4. The apparatus of claim **1**, further comprising a battery and a battery charging and protection component operably coupled to the microcontroller.

5. The apparatus of claim **4**, further comprising a piezoelectric module operably connected to the battery charging and protection component.

6. The apparatus of claim **1**, further comprising an output display operably coupled to the microcontroller to indicate a ball impact occurred within the lead up, follow through, or in between the lead up and follow through.

7. The apparatus of claim **6**, wherein the output display comprises an electronic paper display.

8. The apparatus of claim **6**, wherein the output display comprises a touch screen for user input.

9. The apparatus of claim **1**, further comprising an output speaker operably coupled to the microcontroller to make sounds regarding a threshold metric relating to backswing, lead up, or follow through.

10. The apparatus of claim **1**, further comprising an interface operably coupled to the microcontroller for coupling to an external portable electronic device.

11. The apparatus of claim **10** wherein the interface comprises a wireless interface.

12. The apparatus of claim **1**, further comprising an input operably coupled to the microcontroller for indicating that a previous set of raw data comprised a calibrating swing.

13. The apparatus of claim **12**, wherein the microcontroller compares data associated with backswing, lead up, and follow through with data of the calibrating swing.

14. The apparatus of claim **1** further comprising a movement module operably coupled to the microcontroller in order to compute player movement and estimate body position.

15. A method of improving an athlete's stroke, comprising steps of:

using an inertial memory unit, collecting raw data of distance, angle, acceleration, and speed;

using a microcontroller, identifying backswing, lead up, ball impact, and follow through by processing the raw data;

using an output, indicating the ball impact occurred within the lead up, follow through, or in between the lead up and follow through;

wherein the method is performed by one or more computing devices.

16. The method of claim **15**, comprising an additional step of comparing backswing, lead up, and follow through with a calibrated stroke.

17. The method of claim **16**, further comprising validating ball impact by removing acceleration raw data below a threshold value associated with taps.

18. The method of claim **15**, comprising an additional step of transmitting values to an external device.

19. The method of claim **15**, wherein identifying a backswing comprises identifying a change in direction before a threshold increase in acceleration.

20. The method of claim **19**, wherein the threshold increase in acceleration varies with a change in angle from the change in direction.

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