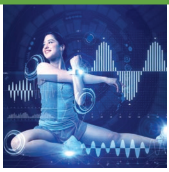

Anytime, anywhere! Inertial sensors monitor sports performance

Hugo G. Espinosa, Jonathan B. Shepherd, David V. Thiel, and Matthew T.O. Worsey

Humans move continuously as part of normal living, even when asleep. The health of your heart, lungs, and digestive system—and even your mental health—are greatly improved through exercise. In modern times, technical aids have significantly reduced opportunities for physical activity; e.g., jobs are more sedentary, household chores require less physical effort, and commuting usually involves sitting in a vehicle. The result is increased obesity and ill health in the population, with the extreme case of type 2 diabetes becoming far too common in youth and younger adults. Individuals, governments, and corporations (particularly in the fitness industries) attempt to counter this through various exercise schemes, and, given the human motivation to win, sports are thought to play a leading role.

In an age of quantification, what can we use to measure human movement on the sports field and in everyday living? A unique answer is wearable movement sensors. A small,

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noninvasive body-worn sensor can record the movement of different parts of the body. The advent of low-cost electronics, small battery size and cost, and wireless data logging and data streaming to a smartphone makes the "now" generation of sports monitoring equipment available to the population around the world at a reasonable cost.

Measurement systems that are large and require continuous power are geographically restricted and have limited use in remote locations (in the forest, in the water, and on the ski slope, among others) without major additional infrastructure (e.g., cameras, timing gates, and lots of software smarts). Inertial systems circumvent many of these barriers.

The most direct measure of movement is through an inertial sensing system. A measurement of inertia is achieved through the movement of a weight attached to a spring via Newton's first law of motion: an object will continue to move at constant velocity unless acted on by a force. Furthermore, as a force is the product of the mass by the acceleration, an inertial sensing system [inertial measurement unit (IMU)] is based on the measurement of acceleration: an accelerometer responds to linear acceleration, and a gyroscope responds to centrifugal acceleration during rotation. Of course, it is not trivial to interpret movement (distance and velocity) from acceleration and angular rotation. Take acceleration for example: on Earth we contend with the planet's gravitational acceleration. While the direction and magnitude are constant ($g = 9.8$ m/s^2), an acceleration-based sensor on the body is in a changing reference frame, and so a 3-axis accelerometer will have parts of g in all three acceleration components. The Earth's gravitational acceleration is a static constant addition to the measured acceleration, which can confuse the measurements obtained from IMUs.

Inside a magnetic IMU

The development of microelectromechanical systems (MEMS) technology has paved the way for the production of small devices that use mechanical and electrical components in combination. MEMS-based IMUs incorporate miniaturized accelerometers and gyroscopes, which can detect and record 6-axis acceleration and rotation at relatively high sampling speeds (more than 100 samples/s), while not hindering biomechanical processes involved in movement. Often magnetometers are combined within IMUs to measure and detect 3-axis orientation, resulting in a 9-axis unit known as a *magnetic IMU* (*MIMU*).

Accelerometers

An accelerometer is a device used to measure the acceleration of a body in its own instantaneous rest frame. Two important properties of an accelerometer are its operating range and sampling rate. The operating range defines the magnitude of acceleration that can be measured by the device, and the sampling rate represents how many data points per second are recorded. The sampling rate is commonly defined as sampling frequency in hertz (e.g., 100 or 500 Hz, 1 kHz). An accelerometer generally outputs its measurement as a factor of the acceleration of gravity ($g = 9.81$ m/s^2).

Your smartphone is likely to contain an inertial sensor with an acceleration range of ±16 g. However, it is important to note that the acceleration signals generated by different types of movements are diverse, and it is crucial that an accelerometer with appropriate properties is selected for analysis. This also depends on the placement of the device. For example, the analysis of high-impact movements, such as a boxing punch using a wrist-mounted sensor, will require a higher operating range and sampling rate compared with the analysis of walking while employing a sensor located near the center of mass. Currently, some sensors used mostly for research applications can contain acceleration ranges up to ±400 g.

Gyroscopes

A gyroscope is a device that measures angular velocity, generally in degrees per second (°/s), and it can be used to analyze rotational movements. When a gyroscope within a MEMS device is rotated, the change in angular velocity causes a small resonating mass to shift. The kinetic energy is converted into a very low-current electrical signal that can be amplified and read by a microcontroller. A typical range of commercial fitness devices is ±2,000°/s.

Gyroscope technology has many applications, a main one being in the aviation industry. Gyroscopes are used in aircraft instruments, such as an attitude indicator and a turn coordinator. When an aircraft turns, a force is applied to the gyroscope that, due to precession, translates to a perpendicular force applied on a gimbal, providing the pilot with bank information and the rate of turn. Based on a similar principle and with the advent of wearable IMUs, a gyroscope can now be used to describe human movement. Gyroscope data have proven effective for feature detection in gait analysis. In elite activites such as figure skating and ballet, where the ability to rotate controllably at a high velocity is fundamental, gyroscopic data can be used to identify defects in an athlete's biomechanical processes. This can assist coaches with the development of focused training programs tailored to an athlete's specific needs.

Magnetometers

A magnetometer is a sensor capable of measuring the strength and direction of surrounding magnetic fields. A magnetometer measures magnetic field magnitude in units of gauss (commonly of the order of ±7 G). Incorporating a magnetometer into an inertial sensor means that it is always known what direction the inertial sensor is facing relative to the Earth's magnetic field, acting just like a digital compass.

Regarding sports applications, research is being conducted into using magnetometer data to measure the spin rate of instrumented cricket balls. Upon a full revolution of a sensor inside the cricket ball, the magnetometer reading will return to its initial value from which the speed of revolution can be deduced. The accuracy of a magnetometer is hindered when used in an environment consisting of other magnetic fields, including moving conductors, such as those generated by stadium flood lights or underground power lines.

Sensor fusion

When a 3D accurate position and orientation of a body is required, magnetic sensors are embedded and combined within the IMU; this process is widely known as *sensor fusion*. Combined data from multiple sensors are used to obtain more insightful measurements, such as an accurate estimation of orientation angles under static and dynamic conditions. One such algorithm that achieves this is Madgwick's attitude heading reference system (AHRS). The algorithm incorporates magnetic angular rate and gravity sensor arrays, including tri-axis magnetometers, to compensate for magnetic distortion.

Sensor orientation can be presented as quaternions or Euler angles (roll, pitch, and yaw). Figure 1 shows an example of Euler angles on a typical wrist-worn wearable sensor. The AHRS algorithm replaces a traditionally used Kalman filter or extended Kalman filter, reducing implementation and computational complexity and satisfying the requirement of high sampling rates. With the orientation of the sensor known at all times, more accurate measurements can be calculated and more reliable metrics extracted.

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Error sources on MIMU raw signals

Raw MIMU signals are inherently noisy. Typical sources of error are documented in Fig. 2. It is important to perform baseline testing to understand and classify the effects of these common errors on the designated sporting system because it will affect the repeatability and precision of the sensor to detect human motion.

After error identification, correct calibration and filtering of the data can be powerful tools for removing erroneous measurements (noise) and enhancing the ability to extract meaning from the signal. Although powerful, filtering an IMU signal is not without risk. With the advent of programming-based filtering libraries and tools, users can easily smooth a signal; however, this process often removes valuable information, altering the peaks of events and the time when these events occur. An understanding of the processing algorithms and the

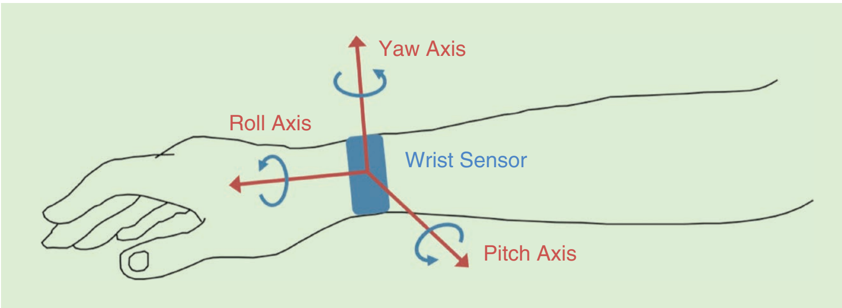

FIG1 A representation of the pitch, roll, and yaw angles on a wrist-worn wearable sensor.

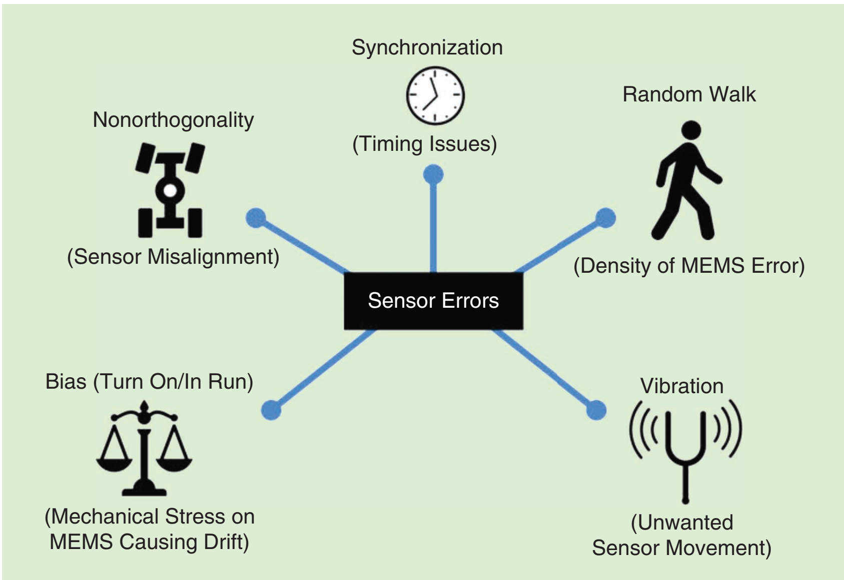

FIG2 The common error sources on raw MIMU signals.

An understanding of the processing algorithms and the characteristics of the data you are aiming to measure prior to implementation can maintain the integrity of your sports tracking system.

characteristics of the data you are aiming to measure prior to implementation can maintain the integrity of your sports tracking system.

Sports applications and a case study: Swimming

The data measured by MIMUs can be used for a multitude of applications in sports. Commercial devices, such as fitness watches, wristbands, and smartphones, have embedded MIMUs that output such metrics as steps taken, standing hours, walking and running distance, number of floors climbed, active energy, resting energy, and burned calories, which help promote physical activity within the general public. These devices tend to have a daily step goal, which encourages the user to engage in physical activity on a day-to-day basis.

The use of MIMUs is transitioning into elite sport training and competition. There is a vast amount of research surrounding the development of algorithms that use MIMU data to produce insightful metrics for the tracking and measurement of an athlete's performance, fatigue, injury prevention, and rehabilitation. Some sports applications include swimming, soccer, boxing, netball, athletics, tennis, and wheelchair basketball.

The selection of the fitness device for elite training and competition is crucial. The device should be unobtrusive, small, light, easy to attach, and power efficient, and it should have both an appropriate range and sampling frequency based on the targeted sport. In swimming, the device must be waterproof and have internal data storage because wireless radio transmission is not possible under water.

Figure 3 shows an example of front crawl (freestyle) swimming raw acceleration data (in m/s^2) from an elite swimmer during the 2016 Grand Prix event in preparation for the 2016 Olympic Games in Rio de Janeiro, Brazil. The sensor was placed on the swimmer's lower spine. The data are plotted in a time series and show an approximate of 18 strokes/lap in a 50-m pool with three tumble turns, making a total swim of 200 m in four laps. In interpreting the data, some axes may be more dominant and relevant than others. In this case, the body's mediolateral axis (*x*-axis, the blue line) clearly shows the stroke count (a zoom of five strokes shows the stroke feature in detail), and the anterior-posterior axis (*z*-axis, the red line) clearly shows the tumble turns. Commercial software, such as MATLAB, is commonly used for the data analysis, processing, and visualization of results.

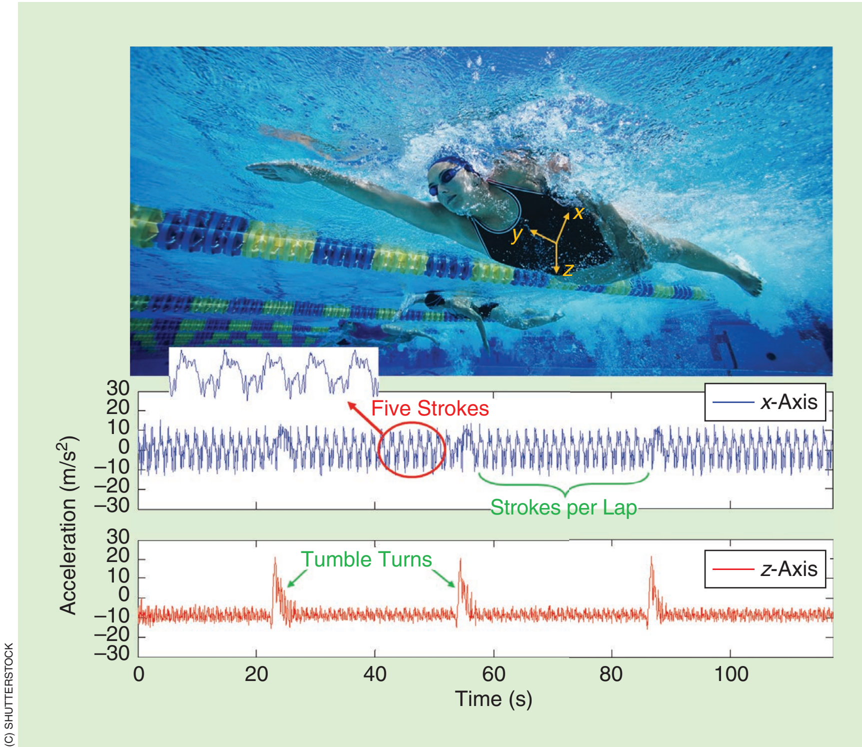

FIG3 An example of front crawl raw acceleration data from an elite swimmer. Also shown is the identification of strokes and tumble turns in a four-lap swim.

Commercial product and environment

Wearable sensors for sporting applications have unique commercialization challenges. To reduce the risk profile of your wearable product, there are several considerations. The lean launch method is one framework for understanding how to bring your sports sensor to market. The core concept of lean is to be agile by iteratively learning, building, and measuring (Fig. 4).

Learn

Deeply understand your product and where your product will fit in the sports technology landscape. Tools to identify business models, outline possible consumers and their current pains, and identify stakeholders and potential investors as well as understanding the potential growth and scalability of your product will aid the product design. An initial search of prior art (e.g., patents and publications) in the context of your idea should be performed. The importance of this step cannot be stressed enough as litigation cases in the space of wearable technology are common and costly. Be vigilant when checking other sensor types and sporting applications because the interfering art could be from a different sport.

The governing of the adoption and uptake of technology by sporting bodies' regulations is unique to the field of sports, so it would be wise to understand the rules surrounding the specific sports you are targeting. If no prior art is found, starting the process of internationally protecting your idea is important. Furthermore, as you will be capturing human performance data, it is crucial to consider the legal ramifications of the data you're capturing and create data-handling and protection policies.

Build

From your assumptions about what sporting problems could be solved with your IMU sports sensor, create and launch a minimal viable product. The steps may involve designing the hardware, manufacturing the printed circuit board, creating firmware, developing software, creating a user interface, and managing distributed databases.

Measure

Review your minimum viable product and your consumers' reactions to it. Understanding how they adopt your IMU should lead to enhanced insights about your product and to iterations to improve it.

The cyclical nature of these three steps is designed to assist you to develop a solution that meets a real problem that is matched with a consumer who wants to purchase the product. Understanding that sports are built on relationships and competitive edge can help you launch your product and gain publicity. An example is contracting an elite athlete to use your product. If the athlete performs well, this could be a great launching pad. However, there are many top athletes striving for marginal gains, so be realistic about the athlete's chance of performing at a top level, because if he or she does not excel, that could negatively impact the perception of your product.

The data measured by MIMUs can be used for a multitude of applications in sports.

Conclusion

Monitoring an athlete's performance in his or her natural training environment has become a necessity; wearable technology meets this need and has proven to be as effective as laboratory testing. Using small portable wearable devices, an athlete's movements can be captured, stored, analyzed, and presented. Such technology relates to MIMUs. The data collected by accelerometers, gyroscopes, and magnetometers can be used to monitor athletes' performances, their recovery from injuries, their improvement over time, their assessment of fatigue, and other relevant metrics. In combination with physiology sensors, for example, pulse oximeters that measure heart rate, such metrics as low- and high-intensity periods can be calculated. These data can be used by a coaching team to make informed tactical decisions, such as substitutions during a competitive game.

In recreational sports, fitness, and weight loss, care must be taken when using wearable devices. Excessive reliance on step count and stairs climbed should not be taken as absolute goals at the expense of all other parameters, such as diet and other forms of exercise, not readily interpreted by a wrist-mounted MIMU. The outputs of MIMUs and long-term trends in achievement must be part of the solution to weight loss and obesity and not used as a sole measure. For many, increasing their daily step count and other achievements has had positive motivational benefits in increasing exercise. The adage that you must be able to quantify to note improvement certainly holds true, and this is what MIMUs can do.

In a similar manner, elite sports performance can be improved using the feedback from MIMUs, but the effect remains limited as there are many other parameters not possible to measure using MIMUs, such as awareness, intent, motivation, and team play strategies, among others. MIMUs can measure some types of movement, and this is invaluable in calculating parameters such as steps, running distance, velocity, body orientation, and position in the field. However, these measures are only part of the complete picture for athletes and those looking to improve their cardiovascular fitness and lose weight.

Depending on the sports application, a particular device may be more suitable and effective than others, so keep that in mind next time you go shopping for a fitness device. It is also important to note that, although the application fields presented in this article are focused on sports, MIMUs can be used in different areas where human monitoring is required, including health, defense, law enforcement, education, construction, and forensics.

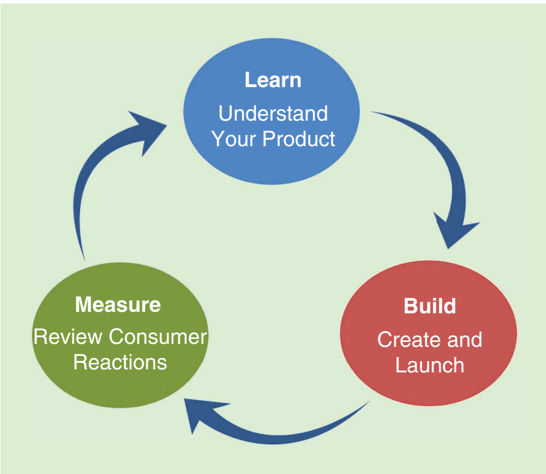

FIG4 The lean launch framework for product risk reduction.

Understanding that sports are built on relationships and competitive edge can help you launch your product and gain publicity.

Read more about it

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