Sports Sensing: An Olympic Challenge for Computing

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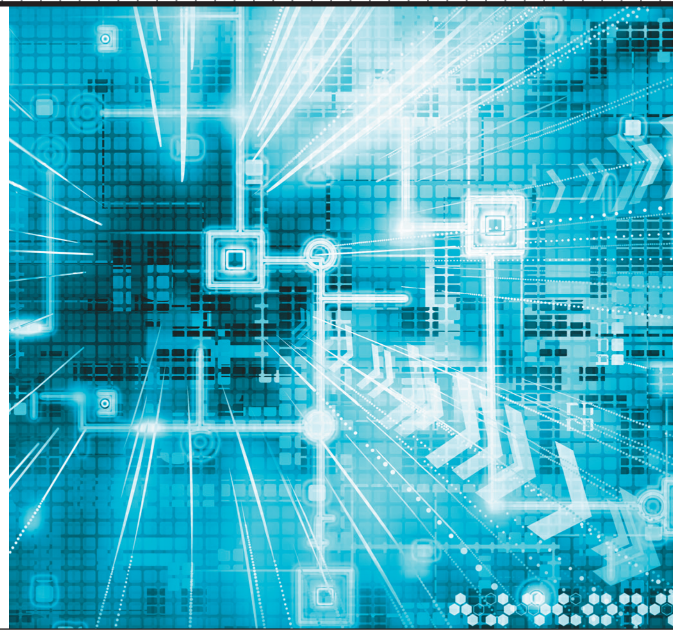

Sensor nodes are becoming small and light enough for athletes to wear imperceptibly, yielding new types of data that can be used to enhance performance.

The motto of the Olympic Games—Citius, Altius, Fortius (faster, higher, stronger)—rings out every two years as we sit back to observe the titans of the sporting world clash. Technology plays an increasingly visible role in these international competitions as experts use computers to dissect, benchmark, and analyze the superhuman performances on display. But technology is also playing a less noticeable, but increasingly important, role in the training behind the performances.

Athletes have long benefited from computing technology through the design of better surfaces, equipment, and clothing. However, using such technology during training to improve performance has been hampered by the *observer effect*: the athlete's awareness of the system impacts performance and hence devalues any measurements the system makes.

Nowhere is this effect more pronounced than in sports science labs, which are filled with expensive devices that can assess elite athletes' biomechanical and physiological functions. However, these labs take athletes out of their regular training environment, and the use of invasive sensors and treadmills or similar stationary equipment does little more than simulate their regimen.

There's little doubt that the data derived from such testing has revolutionized sport but, ideally, technology should facilitate rather than dictate training. Scaling the science lab to encompass the training venue isn't a realistic option for sports unbounded by walls, nor is it likely to be justifiable in terms of cost. However, sensor nodes are becoming small and light enough to blend into the training environment and, more importantly, for athletes to wear inconspicuously.

SENSING ON THE ATHLETE

Putting sensors on athletes isn't completely new. Wireless heart-rate monitors and other kinds of physiological sensors that attach to convenient body sites such as the torso or ear are prevalent at all levels of sport. However, it has been more challenging to develop wearable technology capable of replacing the bulky machines that researchers currently use to analyze complex body movements in order to maximize athletic performance while minimizing injury risk.

Although there's a long way to go, commercial ventures are already emerging in this space. Numerous biomechanics-related body sensors (see, for example, www.sensixa.com) have recently come to market following the success of the original Nike+ sensor—a simple accelerometer in the shoe that counted jogging steps and used heuristics to estimate the distance travelled (http://nikeplus.nike.com).

In fact, all of today's off-the-shelf systems work in a similar way, eschewing the accuracy needed for true biomechanical analysis to provide broad estimates of quantities attractive to the hobbyist. In contrast, our research has focused on how to produce quantitative measures of

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performance that are acceptable to amateur and elite athletes as well as sports scientists.

RESEARCH CHALLENGES

For this goal to be achievable, sensors must be undetectable. They must be more than invisible—from painful experience we know that athletes will discard on-body nodes with noticeable inertia or uncomfortable attachments at the first opportunity.

This problem is magnified by the fact that the best body sites for capturing biomechanical signals are often the extremities, which experience intense accelerations that necessitate firm sensor attachment. (To see why this is a problem, try pumping your arms back and forth as though running while wearing a slightly loose watch.)

Attaching sensors to footwear is a popular solution. This is simpler than fixing sensors directly to the body, and athletes are naturally tolerant of additional weight at this site. However, this tolerance has limits—an elite athlete's shoes can weigh as little as a few hundred grams, leaving little leeway for the sensor designer. In addition, the feet experience surprisingly large forces; researchers routinely recommend the use of 5g or higher accelerometers. Shoes can also experience multiple conditions from which electronics must be shielded including heat, mud, water, and sweat.

More traditional sensing challenges are less problematic in the sports science domain. For example, battery life, the bane of many wireless sensor networks, is far less of an issue since training sessions are measured in small multiples of hours and are often punctuated by breaks during which batteries can be replaced or recharged if necessary.

In addition, the communications range is limited to body length in wearable sensors for athletes; off-body communication, when needed, is usually performed by a specialist processing node that aggregates and forwards data to the network.

Finally, athletes and coaches alike prefer to concentrate directly on the performances, negating the need for real-time feedback from sensing systems. Sensor data is collected and processed for review shortly after a specific performance or even after the entire training session.

Figure 1. Sprinting shoe augmented with the Imperceptible On-body sensor Node (ION).

ION PLATFORM

At the Cambridge University Computer Laboratory, we've developed the Imperceptible On-body sensor Node (ION) specifically with athletes in mind.

At 25 × 35 × 8 mm and 4 grams, the ION board has minimal inertia even after adding a 4-g, 200-mAh Lithium-ion battery that has a similar size and supports numerous hours of continuous sensing. Multiple IONs self-synchronize using the 2.4-GHz ISM channel and can sample up to 12 analog signals at 1 kHz each. In recognition of the one-shot nature of sports performances, the sensor uses flash memory to ensure data persistence no matter what happens to the power supply.

Although multiple IONs can sense at many body sites simultaneously, we've initially deployed it on shoes for the reasons previously mentioned. Our trials so far have involved sprinting, a fundamental skill for many sports with physical movements at the extremes of human ability and for which there has been surprisingly little quantitative measurement.

As Figure 1 illustrates, augmenting a sprinting shoe with the ION produces a minimal observer effect.

SENSOR SELECTION

To demonstrate the utility of our system, we set out to establish the link between a sprinter's speed and ground contact time. Correlation of these two quantities had long been hypothesized but not proven to satisfaction.

The traditional measurement technique for contact time uses force plates, a series of load cells connected to a false running surface that must be physically installed in the track. However, few facilities install force plates, and those that do use only one or two to minimize surface damage. Thus, capturing every ground contact in a sprint isn't feasible using this approach.

We first estimated contact time using foot accelerometry. When the foot strikes the ground, this generates a few sharp acceleration peaks that can serve as event triggers. However, the lift of the foot, signifying the end of the contact, is much harder

Figure 2. Shoe insoles outfitted with four force-sensing resistors (FSRs) and an associated ION.

to measure—instead of lifting their feet, sprinters peel them from the ground, pushing from their toes. The lack of a clear signal for the lift-off event introduces significant error in contact time estimation. Such ambiguity is unacceptable in the sporting domain, where significant differences in contact times are on the order of milliseconds.

We thus concentrated on developing a custom insole capable of sensing pressure. Because the load cells or strain gauges underlying force plates are too bulky and rigid to be worn comfortably in a shoe and thus wouldn't meet our undetectability goal, we experimented with thin, flexible materials that change electrical properties when deformed, including polyvinylidene diflouride (PVDF) films and force-sensing resistors (FSRs). Figure 2 shows a configuration with four FSRs attached to the base of a thin insole.

The PVDF films produced accurate force measurements but fared badly in the field, where the high pressures and torsions typically tore the material. The FSRs were far more durable but are infamous for low precision—outputs reportedly vary by 10 percent, and many researchers have deemed them suitable only for qualitative measurements.

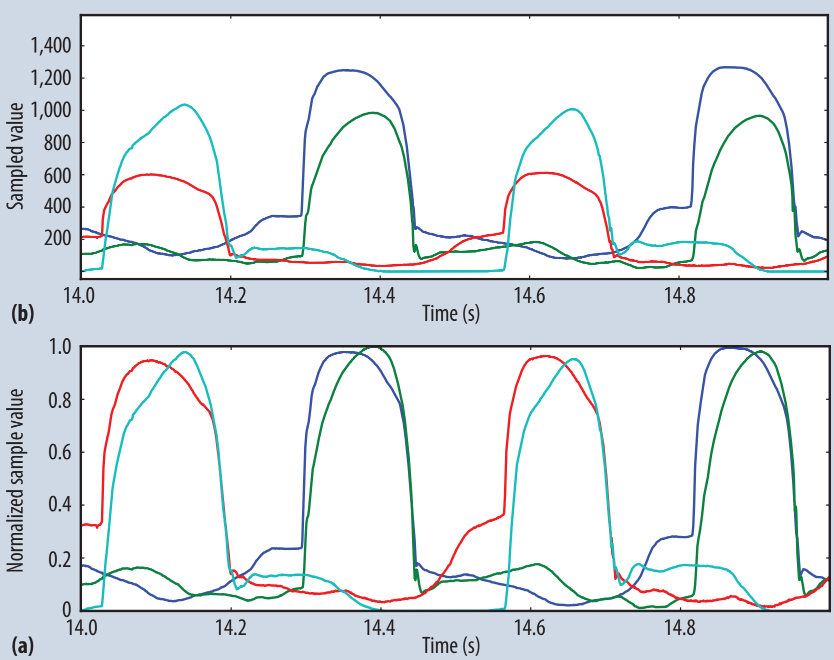

Figure 3. FSR signal samples taken from two sensors on each foot during four sprint steps: (a) raw and (b) normalized.

However, the forces applied during the gait cycle vary by many orders of magnitude, and measurement precision ceases to be an issue when deriving event *timings*. As Figure 3a shows, even the raw sensor output for two FSRs at the toe and midfoot easily captures the gait cycle and the salient events within it. After normalizing the signals, as Figure 3b shows, we used careful signal processing to estimate ground contact times within 1 ms (R. Harle et al., "Towards Real-Time Profiling of Sprints Using Wearable Pressure Sensors," *Computer Comm.*, Mar. 2012, pp. 650-660).

The weakest part of the system is the ION-to-sensor connection. To retain kinesthetic imperceptibility, the in-shoe wiring must be highly flexible and have a low profile. However, this generally results in poor durability, and sprinting soon breaks the contacts.

We investigated the use of flexible, printed circuit boards, but the thickness required to prevent tearing during sprinting resulted in a rigidity that caused discomfort. We now use thin (28 AWG), flexible wires with factory-crimped 1.25-mm Molex connectors and apply heat shrink to minimize bending.

SYSTEM OPERATION

The current ION system is undetectable and can easily capture information about entire sprint repetitions. This has enabled us to explore the relationship between speed and ground contact time. We've looked at a mix of elite and amateur sprinters over a series of sprints and, as Figure 4a shows, discerned a strong exponential link between the two quantities.

In addition, analyzing the contact times across specific runs has revealed interesting anomalies. For example, in Figure 4b, which shows the contact times for five 60-m sprints, there's an unusually long trio of contacts starting at the 15th step of the first run that could be

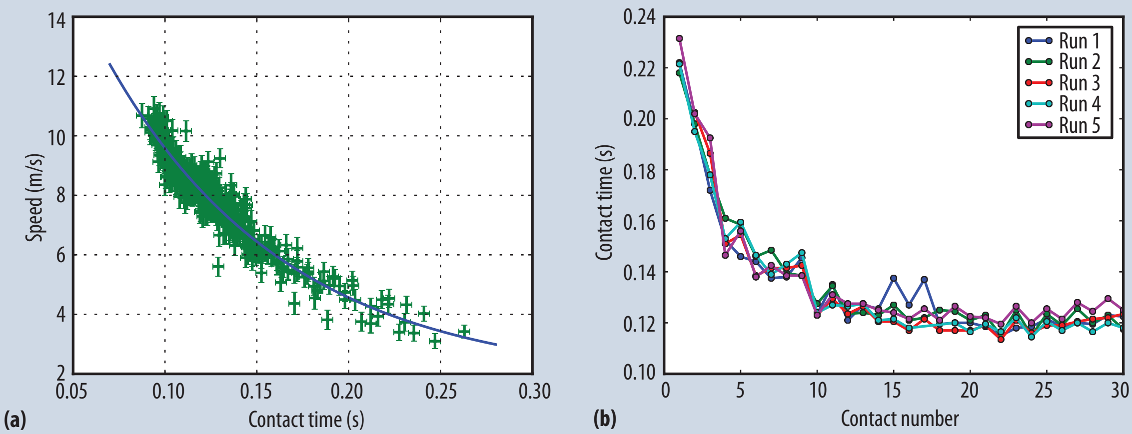

Figure 4. ION system operation: (a) speed versus ground contact time and (b) contact time progression for five sprints.

attributable to many causes—the onset of an injury, a small stumble, or a momentary lapse in concentration. The ION system can thus draw the attention of athletes and coaches to phenomena most training sessions miss.

GOING FOR GOLD

The more data we collect, the more we're convinced that sensing in the shoe is both viable and scalable. Even using low-fidelity sensors such as FSRs, we can derive high-fidelity results that provide unique insights into athletes' mobility patterns.

Ultimately, we envision this technology filtering down to the general market. There's no reason why everyday shoes couldn't continually monitor and analyze our movements, highlighting everything from changes in gait (hinting at a need for orthopaedic evaluation) to the impact forces of hard falls (which could help diagnose potential injuries).

At the same time, we're exploring other on-body sensing locations. We're hoping to decompose the signals from wearable sensors into more meaningful biomechanical data and to find other interesting uses for collected data. Imagine, for example, being able to compare your athletic performance to that of your role model, to record your progression (or decline) on the field, or even to monitor your recovery from injury to establish when you've returned to full fitness.

We've only scratched the surface of what the ION platform, and body sensor networks in general, can do for sports science. As you enjoy the London 2012 Olympics this summer, remember that behind every medal lie months of blood, sweat, tears, and—increasingly—computing.

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