Wearable and telemedicine innovations for Olympic events and elite sport

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Abstract

Rapid advances in wearable technologies and real-time monitoring have resulted in major inroads in the world of recreational and elite sport. One such innovation is the application of real-time monitoring, which comprises a smartwatch application and ecosystem, designed to collect, process and transmit a wide range of physiological, biomechanical, bioenergetic and environmental data using cloud-based services. We plan to assess the impact of this wireless technology during Tokyo 2020, where this technology could help characterize the physiological and thermal strain experienced by an athlete, as well as determine future management of athletes during a medical emergency as a result of a more timely and accurate diagnosis. Here we describe some of the innovative technologies developed for numerous sports at Tokyo 2020 ranging from race walking (20 km and 50 km events), marathon, triathlon, road cycling (including the time trial event), mountain biking, to potentially team sports played outdoors. A more symbiotic relationship between sport, health and technology needs to be encouraged that harnesses the unique demands of elite sport (e.g., the need for unobtrusive devices that provide real-time feedback) and serves as medical and preventive support for the athlete's care. The implementation of such applications would be particularly welcome in the field of medicine and the workplace (with particular relevance to emergency services, the military and generally workers under extreme environmental conditions). Laboratory and field-based studies are required in simulated scenarios to validate such emerging technologies, with the field of sport serving as an excellent model to understand and impact disease.

Key words: ecosystem, wearables, technology, sensors, biodata

Background

Elite sport places enormous physical, cognitive and emotional demands on athletes during their sporting careers[1–4], posing a risk for their physical and mental health[5,6]. Characterising the physiological responses of the athletes *in situ* is essential to effectively protect athlete health. However, this characterisation requires the assessment of precise physiological, biochemical and biomechanical responses of an individual athlete during their specific sporting activity, ideally in real competitive scenarios. Traditionally, a comprehensive assessment of the individual athlete during real sporting situations was neither technically possible nor permitted under competition regulations. Instead, this assessment would typically involve simulating the general demands of the sport either in a laboratory and/or during simulation training performed in the field but with low ecological validity[7]. However, recent advances in wearable technology have accelerated the development of more unobtrusive, precise and affordable devices that can be used to monitor a wide range of parameters in the exercising athlete. For example, Roe and colleagues studied the use of accelerometery to quantify collisions and running demands in professional rugby players[8], thereby representing a reasonable characterisation of the physiological and biomechanical demands during a competitive match. Further research also assessed the concussion risk in American Football players using helmet-mounted accelerometers[9] or eye tracking technology as a method to screen and monitor sport-related concussion[10]. Wearable technology also allows for physiological monitoring through glove-type biometric sensors during Formula 1 races, with these gloves equipped with a pulse oximetry sensor to measure heart rate and blood oxygenation during races. Data are transmitted remotely to the technical/medical team allowing the monitoring during a race, evaluating levels of stress, and providing access to life-saving information in the case of any accident[11]. This rapid evolution and development of wearable technology has been previously predicted, with the arrival of a new generation of affordable technology offering coaches, athletes and teams an unheralded opportunity to use either performance-metrics (e.g., number of accelerations) and/or bio-metrics (e.g., core temperature monitoring) to improve performance[12]. As a result, wearable technology in sport has become a multi-billion-dollar business[13] with an overwhelming production of technologies worn close to the body (e.g., infrared cameras, radar), on the body (e.g., heart rate monitors, smart clothing, sweat-sensing wearables) or even in the body (e.g., ingestible telemetric core temperature sensors, hypodermic needles). The wide variety of sensors are in part due to the varying demands and characteristics of each sport, as well as any sub-disciplines, such as the exercise mode, intensity and duration, rules, individual and team, indoors and outdoors, and clothing. These will also vary for the same sport depending on the terrain, the environment and perceived importance of the event (national competition versus Olympic final).

To date, most attempts to quantify performance *in situ* have been restricted to the use of high-speed cameras. Quantitative 2D video analysis is the simplest approach of motion analysis and has a number of practical advantages to sport scientists and coaches[14,15]. However, complex sporting activities involving movements in more than one plane (e.g., the discus throw in athletics) require the recording of motion with two or more cameras simultaneously (3D motion analysis)[16]. The implementation of this technology has helped researchers to examine foot biomechanics during an official marathon[17], and to analyse the throwing mechanics of the world record in the javelin throw[18]. Despite the practical and technical difficulties in quantifying the various demands of large-scale sporting events in real-life competitions, there have been numerous successes in this regard. For example, during both the 2017 World Athletics Championships in London and the 2018 World Athletics Indoor Championships in Birmingham, two large-scale biomechanics studies took place[19]. In London, forty-nine high-speed cameras were placed in the Olympic Stadium and a number of biomechanical reports were produced for different running, jumping and throwing disciplines[19].

The monitoring of core temperature during competition is also now a reality. For example, the core temperature of 40 cyclists was monitored during the 2016 Road Cycling World Championships in Doha[20], which revealed that both male and female cyclists reached a higher core temperature during a 40-min time-trial than during a road race of several hours (Figure 1, Panel A). Our group has also assessed the core temperature of 56 athletes during the 2019 World Athletics Championships in Doha[21], where extreme environmental conditions occurred (>30ºC and >80% humidity[22]). The core temperature of four male athletes during the marathon is displayed in Figure 1, Panel B.

These studies demonstrate the immense value of core temperature monitoring during competition and have encouraged further applications at other international sporting events such as Dakar Rally, World Rugby 7 Series, a sailing test event for Tokyo 2020 or numerous marathons around the world. For example, core temperature was measured in four elite sailors during a Tokyo 2020 test event in hot environmental conditions (34ºC and 85% relative humidity). The core temperature of these elite athletes during this simulated scenario (taking pre-cooling measures) reached peak values of 38.6°C±0.4°C and 38.9°C±0.4°C, respectively. Notably, the highest individual core temperature response reached 39.4°C, and this case is depicted in Figure 2. We have also successfully evaluated the core temperature of elite marathoners during major marathons (Figure 1; Panel C and D). The use of wearable technologies during these sporting events allows for the better understanding and direct assessment of the physiological and biomechanical demands of real competition.

[Please insert Fig 1 around here]

[Please insert Fig 2 around here]

With the upcoming Summer Olympic Games, we aim to implement these technologies and innovations to different athletes and sports, with the environmental conditions in Tokyo predicted to be extreme. The International Olympic Committee (IOC) proactively created an *"Adverse Weather Impact Expert Working Group"* intended for the Tokyo 2020 Olympic Games. This group has instigated numerous developments to help protect the health of athletes competing in the heat in Tokyo 2020 and beyond. One such development building on the success of the Doha 2019 IAAF World Athletics Championship assessment of core body temperature, and the impact of athletic performance and different cooling strategies on heat distribution (as measured by thermal cameras)[21], is the development of live-transmitting technology that allows the tracking of multisource data within a single application. Specifically, the developed ecosystem provides live feedback of core temperature, heart rate and a range of biomechanical variables facilitated through a Cloud-based portal allowing the athlete support team to view the data in real time anywhere with internet or mobile access[23,24]. This technology could help in the management of athletes during a medical emergency to instantly orient the diagnosis. In particular, combining core and skin temperature monitoring with biomechanical parameters could potentially identify disturbances in gait and therefore identify premature signs of EHS[21].

Given the potential these novel technologies have to protect the health of athletes competing in extreme ambient conditions, we describe here the ecosystem being developed to be implemented in Tokyo 2020 for first time. This technology provides live feedback of ambient, performance and biometric data, and its implementation is envisaged to serve as a guide for subsequent technological applications during major sporting events.

Technological parameters

Dashboard and Connectivity (via the Cloud)

Currently, there are no commercial wearables that can unobtrusively track and assess physiological, biomechanical or biochemical parameters of competing athletes in real time. The live tracking of performance and biometrics data is now possible via an Oracle®-Enabled Cloud solution that has been developed specifically for use at the Tokyo Olympics (Figure 3) to provide a holistic and comprehensive overview of the activity and its impact on the athlete. For this purpose, a number of athletes (specific number still under debate) attending at the Tokyo 2020 and participating in sports exposed to heat stress (race walking, marathon, triathlon, road cycling and mountain biking) will be recruited. The pilot data collected during Tokyo 2020 will serve as a reference to implement this technology in future competitions at a larger scale. The current focus of the dashboard being developed is on the individual athlete and tracking multiple metrics such as distance, speed, pacing, foot mechanics, or estimated oxygen uptake, with the capacity to interconnect numerous sensors (see below). In addition to the metrics received via the connected sensors, the application also provides a live data feed of air and land surface temperature together with relative humidity[24]. Traditionally, air temperature and relative humidity data have been collected from static weather stations, which may fail to reflect the spatial variations of these variables due to sparsity of the network. A unique development has involved the tracking of the actual heat experience of the individual (the SCOUTS model)[25]. The SCOUTS model was designed to minimise heat stress in individuals and urban communities by using "Mobile Crowdsensing", which allows the model to gather data at much finer spatio-temporal granularities compared to traditional methods. This model is in the process of being integrated with the exercising athlete so that individual air temperature and relative humidity can be known for each athlete, no matter his/her spatio-temporal situation. A complimentary solution involves downscaling weather forecast data with satellite data at athlete's location using advanced machine learning algorithms. This is essential in regions where weather station networks are absent. Such a digital approach permits seamless transition to any global location, provision of ambient conditions for each athlete, and endless possibilities to scale up to include more parameters such as forecast of upcoming ambient conditions, UV index and air quality indices. Our technological solution integrates real-time data transmission including ambient conditions from downscaled modelled data via an Application Programming Interface (API) connection in remote areas such as well-known distance training locations in Kenya/Ethiopia (Figure 3). In this scenario, the athlete makes use of the digital infrastructure to have the required information readily available. Given the planned implementation for Tokyo 2020, this application is currently being piloted at numerous athlete training centres (e.g., for Zaragoza, Spain and Antalya, Turkey) in view of final implementation during the Olympic Games (Figure 4).

[Please insert Fig 3 around here]

The ecosystem that has been developed also allows for the remote activation or de-activation of smart devices that collate the information from any activated sensors. In previously conducted trials during major city marathons it was observed that athletes would fail to activate, or in error de-activate the devices under the stress of the event, resulting in lost or uncollected data. A multi-athlete dashboard is also under development to allow a large number of athletes to be monitored simultaneously. This application once available is envisaged to provide useful information for supervising physicians who will be able to access live video feeds alongside the performance and biometrics of individual athletes to inform them any clinical assessments that may be required.

[Please insert Fig 4 around here]

Smartwatch (including Connectivity)

The current ecosystem developed for use in Tokyo requires the athlete to wear a smartwatch, connected to our ecosystem through an application via a mobile network. The mobile application runs on all smartwatches utilising the Android Wear OS [2.0] operating system and standalone connectivity, overcoming the need for the smart watch to be paired to a smartphone (Figure 3). An early version of our ecosystem involved the use smartwatches with nano-sim technology but for Tokyo 2020 this is being replaced with eSIM technology. This technological innovation has bypassed the need for devices to be connecting using Wi-Fi connectivity, as eSIM allows for a more extensive accessibility using mobile data requiring lower memory space for its functions and is less expensive than a traditional SIM card. eSIM technology also allows individuals to modify devices remotely by the use of the cellular phone, negating the need to acquire a different SIM. This would enable to embed numerous profiles in one electronic device, swapping multiple numbers and settings within the device, as well as switch to a preferable profile across different devices they own. For implementation in Tokyo, a number of smartwatches with e-sim connectivity will be distributed for testing. A total of 4 different sensors are able to connect simultaneously with the current generation of smartwatches (with eSIM) and version [2.0] of Android Wear OS. However, if using sensors with their own hub Bluetooth connectivity (e.g., smart wristband, Figure 4), more than 4 sensors can be connected, albeit at the expense of battery life.

Athletes wishing to use the real-time ecosystem for training, preparation for the Games (e.g., acclimation and/or acclimatisation) and for health/performance monitoring at the Games, will need to be familiarised with the technology in their respective countries of origin (see implementation details below). The full use of smartwatch and ecosystem will require the use/subscription to the local mobile network. The use of the smartwatch device in Japan with all activated options will require either connection/subscription to the local Japanese network, or (if out of range) "roaming" use of other cell networks. Roaming may delay smartwatch connectivity to the ecosystem from real time by up to ~20 seconds. Negotiations are at an advanced stage with numerous mobile network providers/distributors in Japan to provide a mobile connection to each athlete free of charge during the duration of their stay in Japan.

Sensors

The rapid development of technology over the last 20 years has seen the rise of unobtrusive small sensors or devices utilised in sport. These devices can be located in numerous places including inside and outside the human body as well as mounted on equipment utilised during physical activity. Given the objective to characterise the real-time demands and responses of athletes during competition at the Games, with particular focus on coping with the extreme heat conditions expected in Japan, we have prioritised those metrics that are valuable indicators of exertional heat stroke (EHS) and exertional heat illness (EHI). With this in mind, the sensors linked to the ecosystem have been assigned "essential", "desirable" and the "future" (summary displayed in Table 1) based on the availability and also the ease of use. However, as part of the future requirements of real-time monitoring, any Bluetooth-compatible sensor can, theoretically, be integrated within the current ecosystem.

Table 1. Summary of the essential, desirable and future sensors to be linked to the ecosystem

Essential Sensors	Desirable Sensors	Future Sensors
Core body temperature ingestible pill sensor	Wireless foot-worn inertial sensors	Electrocardiogram and heart rate variability sensor
Heart rate sensor	Wireless foot insole pressure system	Sweat electrolytes and acidity parameters
	Team sports analytics	Real-time continuous glucose monitoring system

	Swimming analytics	SpO_2 sensor to measure blood oxygen

Essential Sensors

Core body temperature ingestible "pill" sensors: This system adapted for use with our platform and application, is the only acceptable surrogate to rectal temperature[26]. We recently developed a "hub" to aggregate in real time a range of data feeds to assist athletes[23]. The individuals ingest a pill [either CorTemp (HQInc, FL, USA) or eCelsius (BodyCap, Caen, France)] prior to their event, to monitor core temperature (Figure 5). Either pill is easily swallowed and passes through the gastrointestinal tract without affecting bodily functions, typically within 12 to 48 hours. Both systems have been used in training and competition for various sports with no side effects reported (e.g., competitions shown in Figure 1). Data collection begins once the pill is activated and core temperature is recorded until the completion of the event or, if applicable, of the medical and/or recovery intervention (e.g., cold-water immersion). The timing of the pill ingestion prior to the competition is a crucial consideration, as previous research has stated that ingesting the pill before overnight sleep (for morning competitions) and allowing for at least 10 h before core temperature measurement appears to offer the best possibility of the pill being unaffected by subsequent fluid ingestion[27]. There will be an option for all data to be transmitted either after the event or in real-time using the multivariable dashboard. Real-time core temperature monitoring will be possible given the radio signal from the telemetric pill being received by a wrist/ankle band, which is connected via Bluetooth to the smartwatch (the characteristics that allows the smartwatch to transmit in real time are explained in detail in the previous section "smartwatch"). This connectivity allows for the real-time transmission of core-temperature, as shown in the dashboard (Fig 3).

[Please insert Fig 5 around here]

Heart rate sensors: A telemetric heart rate monitor chest strap (Polar, Kempele, FI) will be used by each athlete to measure heart rate. The reason for selecting chest strap-based monitors rather than wrist-worn monitors is based on the greater accuracy of chest strap-based sensors[28]. Wrist-worn monitors' sensors allow for heart rate and blood oxygenation monitoring by using a photoplethymography sensor. These devices normally use green light reflection for its greater absorptivity of haemoglobin compared to other lights (e.g., red light), which is crucial given wrists have comparably low concentration of blood flow[29]. The accuracy of these wearables has been shown to be sufficient during rest, but diminishes during exercise[28]. Nevertheless, there may be some individuals opting for a more comfortable wrist-worn monitor, who should be advised according to their specific sporting demands and the need to accurately measure heart rate (e.g., marathon runner vs. spectator).

Heart Rate Variability (HRV): The evaluation of HRV is among the most promising tools to monitor fatigue and stress levels by providing an indirect evaluation of the heart control, especially by the autonomic nervous system[30]. In fact, previous research has reported that a well-managed and periodised training program in elite swimmers maintained HRV parameters at the baseline levels, whereas international competitions led to depressed HRV[31]. The monitoring of this variable could also alert to different levels of stress in athletes, and potentially of insufficient recovery[32,33]. Additionally, international sporting events are characterised by many athletes suffering from *jet lag* and travel fatigue, which could potentially impair athletic performance[34]. HRV monitoring could further aid in the potential identification of an unrecovered athlete following a long flight.

Desirable Sensors

Wireless foot-worn inertial sensors (FWIS): A foot-worn inertial sensor (Physilog, GaitUp, CH) will be placed on both shoes of the athlete in order to measure stride and foot mechanics, including contact time of each foot (sec), cadence (steps/min), strike angles of each foot (degrees), and their variability [24,35–38]. FWIS and wireless Foot Insole Pressure System (FIPS) along with a dedicated signal processing algorithm will be used for the evaluation of foot mechanics and pressure as well as force impact data and gait patterns during walking and running conditions (Figure 6)[35]. Another kinematic parameter of interest for monitoring and processing is stride variability (SV). The variability of biomechanical characteristics in human locomotion is reflective of noise performed during mechanical repeated tasks that the human body requires in order to be functional in everyday life activities (stability, walking, running, cycling, resting or even sleeping)[36–38]. The SV signal is an interesting exploratory parameter that could provide useful, and until now unidentified insights into locomotion[39–41]. For running, specific algorithms have been developed that process triaxial accelerometer, gyroscope and barometric pressure data to calculate contact, flight, swing, and step times. These sensors have enabled our team to obtain unique kinematics data in elite distance runners (Figure 7)[24], and have the potential to prevent overuse injuries (e.g., kinematic asymmetries during repeated actions) and also aid in the early identification of EHS (e.g., abnormal evolution of foot mechanics patterns across a marathon).

[Please insert Fig 6 around here]

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Wireless foot insole pressure system (FIPS): Insole force (Loadsol, Evalu/Novel, DE) and pressure (SCIENCE, Moticon, DE)[42–45] sensor systems will be used to measure foot dynamics and ground reaction forces, by assessing total impact and distributed forces of lower extremities, as well as foot pressure distribution and variability across different sports and shoe conditions (Figure 6). This technology has been previously used for injury prevention in walking[46], and can potentially identify injury risk or excess of fatigue during sport-specific actions in sport.

Team sports analytics: A hybrid Global Navigation Satellite System (GNSS) [FieldWiz, Advanced Sport Instrument, CH, (Hardware)] and an Inertial sensor [Gait Up, CH, (Software)] will be used for the integration and monitoring of sprint force-velocity-power profile, jumps and impacts of each athlete. Accelerometers and gyroscopes placed on the upper back of the athlete are commonly used in team sports, as these allow for load monitoring during training and competition, providing the coaching and medical personnel with a wide variety of data in real-time[47]. Specifically, parameters such as the total distance covered by an athlete, the speed of the athlete during each acceleration or the impact of forces exerted during intense physical contact can be monitored and transmitted[47].

Swimming analytics: An inertial sensor in the head cap or swimsuit and a developed algorithm (Gait Up, CH) will be used for each athlete to quantify total distance, total duration, lap duration, lap count, stroke count per lap, total strokes count, SWOLF Score (Score combining: Pool length, Strokes, Lap Duration) and swim style (Auto-detect style: crawl, breaststroke, butterfly). Dedicated swimming sensors with similar features exist such as "Phlex"[48], "Form"[49], or "TritonWear"[50], which are accelerometer-based devices with integrated heart rate sensors capable of identifying and monitoring swimming kinematics in real time. These devices allow the coach to get instant data on a mobile/tablet/computer, which permits the coach to provide accurate individual feedback to his/her swimmers.

Future Sensors

Electrocardiogram (ECG) and heart rate variability sensors: Wireless ECG (Channels: 3, SR: 500 Hz, Holter, Customed GmbH, Germany) will be used for the heart rate variability (HRV) assessment during real-life conditions and physical activities across different ambient conditions. The evaluation of HRV is among the most promising tools to monitor fatigue and stress levels by providing an indirect evaluation of the heart control, especially by the autonomic nervous system[30]. In fact, previous research has reported that a well-managed and periodised training program in elite swimmers maintained HRV parameters at the baseline levels, whereas international competitions led to depressed HRV[31]. The real-time monitoring of this variable during training and competition could also alert to different levels of stress in athletes, and potentially of insufficient recovery[32,33]. Additionally, international sporting events are characterised by many athletes suffering from *jet lag* and travel fatigue, which could potentially impair athletic performance[34]. HRV monitoring could further aid in the potential identification of an unrecovered athlete following a long flight. The aim here is to identify and compare whether HRV could be affected by running and environmental conditions, as well as to determine the correlation between HRV and the kinetic and kinematic mechanisms of lower limbs across assessed conditions. These measures could possibly help to safely interpret how the heat strain mechanism affects HRV and SV and whether HRV and SV could be used as indicators of heatstroke during high intensity running activities to protect athletes and individuals from heat illnesses.

Sweat electrolytes and acidity parameters: A miniaturized sensing chip (Energy-harvesting "Lab-on-Skin™" sensor, Xsensio) will be used for real-time monitoring of biochemical data at the skin surface or just below the skin, by assessing varying indices such as sweat electrolytes and sodium concentration in a direct and non-invasive method. Such microchips are capable of detecting and quantifying a broad range of biomarkers on the attomolar centralisation[51,52]. Compared to technologies such as the Abbott Freestyle[53], Xsensio plans to track multiple parameters simultaneously. This function can be used by sports clubs and their medical personnel as a tool for better designing of training programmes, as well as a method for injury prevention, and accelerate recovery and rehabilitation[52].

Real-time continuous glucose monitoring (CGM) system: This technology primarily emerged as an innovative solution to detect hyperglycaemic and hypoglycaemic excursions in a wide range of patients with diabetes mellitus[54], including research of these patient population in response to exercise[55–57]. However, concerns have been raised about the validity of using these devices during high-intensity exercise in healthy individuals[58], including CGM models such as the Guardian Real-Time (Medtronic MiniMed Inc., Northridge, CA, USA)[59–62] or the CGMS (Medtronic MiniMed Inc., Northridge, CA, USA)[56,57]. A recent comprehensive review on the use of CGM monitoring in diabetic populations in response to exercise has identified more than 2000 CGM samples collected in soccer, skiing, golf, continuous cyclometer, HIIE cyclometer and intermittent cycling[58]. This review stated that the majority of studies showed important CGM errors during periods of exercise[58], which questions its use in an exercising athlete. It is worth noting that the validity of the most novel models of the aforementioned sensors has not been tested. In light of the above, the integration of the latest real-time CGM sensors would depend upon accuracy and validity testing but, if proven effective, its implementation to the field of sport would be of invaluable impact. CGM (and in the near future lactate and other metabolites) is expected to gain popularity amongst elite athletes given their unique capacity to unobtrusively measure markers of fatigue and assess fuel utilization at any time of the day, during training or competition. Application of this technology is destined to become commonplace in sport and exercise science/medicine and to revolutionise training and performance motoring in both elite sport and clinical conditions[63].

SpO_2 sensor to measure blood oxygen: Earlobe probes with Bluetooth connectivity are reliable proxies of measured oxygen saturation, although some of these devices have a poor validity[64]. Bluetooth connectivity will allow the connection to our smart watch ecosystem and the implementation of valid/reliable pulse oximeters would not only be invaluable for clinical use, but also during exercise testing in the laboratory, where elite athletes can desaturate during maximal tests[65]. A further practical application would be for the assessment of the athletes' response to altitude exposure[66]. In short, an accurate measure of real-time blood oxygen saturation in elite athletes is generally more useful as a

clinical/medical tool (except for altitude exposure). An example of this technology is the "MyOxy" wearable device, which is able to connect to a cloud-based portal and transmit blood oxygenation in real-time[67].

Need for Validation

While the use of the technologies described above are becoming increasingly prevalent for physicians and sport scientists within international sports and medical federations, at rehabilitation centres, sports clubs, there is an urgent need to better understand the functionality, utility and applicability of these technologies in order to optimise their effectiveness. Some of the aforementioned sensors (especially those included in the "future" category) lack of validity data, which illustrates the need for a certification system (like CE mark for performance) that regulates the use of wearable sensors during competition according to their validity and availability to all athletes/technical teams. With this rationale in mind, concerted efforts of our research team in collaboration with the International Federation of Sports Medicine (FIMS) have already proceeded in order to establish a Guiding Reference Standard (GRS) for wearable devices[68,69]. The main objective of this GRS is to provide high-quality, external, and non-profit validity testing for wearable technology. The effectiveness of a given wearable will be tested and certified, so its validity data will be publicly available. As stated in a recent review developed by our group[69], this validity and certification process would be necessary so that both the athlete's physical integrity and sports integrity prevail.

Conclusions

The aforementioned integrative solution represents the first real-time, integrated, and remote system that can monitor and analyse both health- and performance-related information, obtaining data from the body and the environment and providing instantaneous feedback to the athlete/coach/scientist. Following its pioneering implementation at Tokyo 2020 and a post-event survey of the participants for feedback, we aim to furtherly develop and refine this real-time technology to serve as a “hub” to aggregate a much larger range of data feeds to protect the health of athletes, help characterise and understand performance at an individual level as well as to enhance the broadcast of sporting events with the relay of interesting performance-metrics and bio-metrics to the spectator.

This focus on technology during major competition is intended to encourage further innovations enabling future monitoring of a much wider spectrum of data in real-time. This implementation aims to better understand exercise performance and to allow for a preventative telemedicine tool to inform on the health of athletes during competition and potentially the wider population in the future. The utilization of such technology along with other wearable technology transmitting data in real time will undoubtedly become the norm at major sporting events as international sporting federations seek to make their sport more interesting and accessible to wider audiences.

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Figure 1. Core temperature monitoring during the Individual Time Trial (ITT) and Road Race (RR) at the 2016 Road Cycling World Championships in Doha (Panel A) and during the women's marathon at the 2019 IAAF World Athletics Championships in Doha (Panel B). Panels C and D show the core temperature of an elite runner during the 2016 New York City Marathon, and the core temperature of two elite runners (top 15) during the 2016 Amsterdam marathon, respectively.

Figure 2. Individual core temperature (solid line) and heart rate (dotted line) in an elite female sailor during a Tokyo 2020 test event.

Figure 3. The bespoke ecosystem for live tracking of performance and biometrics data.

Figure 4. Integration and connectivity for live tracking of numerous metrics to enhance safety during sporting events with particular reference to athletes at increased risk of exertional heat stroke (EHS) and exertional heat illness (EHI).

Figure 5. Core temperature monitoring by HQInc (image on the left) and BodyCap (image on the right).

Figure 6. Application of wireless foot-worn inertial sensors and foot insole pressure/force systems into the running shoe for physiological and biomechanical assessment.

Figure 7. Strike angle and ground contact time while running on a treadmill and outdoors comparing two different commercially available running shoes.