Wearable Training-Monitoring Technology: Applications, Challenges, and Opportunities

Marco Cardinale and Matthew C. Varley

The need to quantify aspects of training to improve training prescription has been the holy grail of sport scientists and coaches for many years. Recently, there has been an increase in scientific interest, possibly due to technological advancements and better equipment to quantify training activities. Over the last few years there has been an increase in the number of studies assessing training load in various athletic cohorts with a bias toward subjective reports and/or quantifications of external load. There is an evident lack of extensive longitudinal studies employing objective internal-load measurements, possibly due to the cost-effectiveness and invasiveness of measures necessary to quantify objective internal loads. Advances in technology might help in developing better wearable tools able to ease the difficulties and costs associated with conducting longitudinal observational studies in athletic cohorts and possibly provide better information on the biological implications of specific external-load patterns. Considering the recent technological developments for monitoring training load and the extensive use of various tools for research and applied work, the aim of this work was to review applications, challenges, and opportunities of various wearable technologies.

**Keywords**: internal load, training technology, wearable technology, external load, GPS

Training-load monitoring has recently gained momentum in sport science, possibly due to technological advancements and better equipment to quantify training activities. The reason for such interest resides in the need to improve and individualize the design of training and exercise programs to maximize the improvements in athletic performance and avoid overtraining and overreaching. Training prescriptions have been notionally based on the concept of progressive overload since humans embarked in structured sport and physical activity. Early examples of training prescription gave clear indications that a scientific approach to training was important not only to identify appropriate progression strategies but also to individualize the training dose and maximize performance. Training activities and/or exercise programs are designed with the aim of producing stimuli capable of triggering various physiological responses leading to improvements in the form and function of various biological systems. Early research by Selye on stress shaped the thinking of modern approaches to training and exercise prescription and laid the foundations for a systematic approach to quantify and describe adaptive responses to various exercise and training paradigms. It is a well-accepted notion that training activities can alter homeostasis and affect various physiological structures which respond to the training “stress” by trying to restore homeostasis. The net result of a well-designed progressive training program is an improvement in the structure and function of the target physiological systems which leads to improvements in human performance. However, the outcome of a poorly designed and/or inappropriate progression in training can result in impaired health and maladaptation, immunosuppression, and alterations in the hormonal profile and typically in underperformance. The optimization of the training program resides in managing what the athlete does and how they respond to the training activities performed. This can be quantified by the athlete training load. A framework proposed by Impellizzeri et al. differentiated between internal and external aspects of training load. The internal load refers to the more physiological aspects while the external load represents the activities (work) performed by the athlete. Adaptation is the consequence of the internal training load which is primarily determined by the external training load imposed on the athlete.

Over the last few years, numerous studies have been conducted to improve our understanding of the implications of various training-load paradigms in various athletic cohorts, however despite the growing evidence in the usefulness of monitoring training activities, resistance is still perceived in some sporting communities. A recent review indicated, that the reasons for the resistance to conduct systematic training-monitoring activities can reside in financial constraints, manpower limitations, lack of knowledge and/or experience in specific training-monitoring activities, resistance from the coaching staff and most of all the lack of guarantee that training-monitoring interventions can improve the quality of training prescriptions. A recent PubMed Search (July 2016) identified 488 papers with the keywords training load monitoring. A more precise analysis using keywords associated with various methods of training-load monitoring showed that a research bias exists toward methods which are easily accessible/low cost (such as the session RPE and similar methods) or with historical methods (lactate training load). Recent research is mostly dominated by external load studies thanks to the accessibility of inertial measurement systems (IMUs) which can be worn by athletes in training and/or competition. There is a lack of longitudinal studies employing internal-load measurements other than sRPE, possibly due to the cost-effectiveness and the invasiveness of measures necessary to quantify internal-load aspects. Considering the recent advances in wearable technologies for training-load monitoring and the extensive array of commercially available tools, it is
important to understand the challenges and opportunities associated with the various technologies. Therefore, the aims of this review are to discuss the most-used wearable technologies and practices, provide some indications for new promising technologies, and provide simple evidence-based guidelines.

Internal-Load Monitoring

The internal load experienced by an athlete can be defined as the summation of the physiological and psychological stimulation/stress imposed during training activities. Every form of exercise/training is characterized by specific physiological and psychological demands which vary not only with the “dose” of the activity (sets, repetitions, duration, etc) but also with the type (eg, strength training vs sport-specific training) of training performed. For this reason, it cannot be quantified with a single modality of assessment but should be approached holistically. While this is theoretically sound, a comprehensive quantification of internal training load is impractical due to the limitation of current technology. In fact, a holistic assessment would require athletes to wear multiple monitoring devices while training as well as to undergo invasive and subjective measurements (see Figure 1). The implementation of too many devices/measurements may interfere with the athlete’s training activities and create challenges with regard to data collection.

The ability to quantify internal load is of fundamental importance as it allows practitioners and coaches to quantify the implications of the external load and training prescriptions on various physiological systems. It also allows the personalization of training activities, as well as the identification of potential health risks and maladaptations. Data should be analyzed for individual athletes to establish

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**Figure 1** — Schematic diagram summarizing technologies to monitor internal training load.

<table>
<thead>
<tr>
<th>Cardiorespiratory Parameters</th>
<th>Humoral Parameters</th>
<th>Neuromuscular and muscle metabolism Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heart Rate: H,$$$</td>
<td>Venous Blood: L,$$$</td>
<td>Electromyography: M,$$$</td>
</tr>
<tr>
<td>Heart Rate Variability: L,$$$</td>
<td>Capillary Blood: M,$$$</td>
<td>Electroencephalography: L,$$$</td>
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<tr>
<td>Breathing related Parameters: L,$$$</td>
<td>Sweat: L,$$$,$$$</td>
<td>Galvanic Skin Response: M,$$$</td>
</tr>
<tr>
<td>Oxygen Uptake and derived parameters: L,$$$</td>
<td>Saliva: M,$$$,$$$</td>
<td>Near Infrared Spectroscopy (NIRS): L,$$$</td>
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<tr>
<td></td>
<td>Urinary Markers: M,$$$</td>
<td>Brain NIRS: L,$$$,$$$</td>
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**Practicality:** High, Medium, Low; Cost: $5,$,$5,$,$5,$,$5,$,$5,$,$5,
meaningful changes in the observed parameters and their biological implications to provide meaningful feedback to the coaching staff.

**Cardiovascular and Respiratory Measurements**

The quantification of heart-rate responses to training is possibly the earliest example of quantification of internal load. After the invention of electrocardiography at the start of the 20th century, heart rate has been able to be detected while exercising since the 1980s thanks to the development of wrist-worn heart-rate monitors (HRMs) communicating with chest bands. Over the years, numerous studies have been conducted to assess the validity and reliability of these devices and the overall conclusion is that HRMs using chest electrodes can be both valid and reliable during physically and mentally challenging tasks (for a review see Achten and Jeukendrup). The use of HRMs has allowed the development of the various training-load indices to quantify the cardiovascular load experienced by the athletes in training and competition. Most of the training-load indices used make assumptions related to the linear relationship identified between heart rate and VO₂ during incremental tests and identify intensity zones and time spent in each zone expressed as a percentage of maximum heart rate and various possibilities exist to quantify training load using such approaches. Recently, further developments in technology has seen promising alternatives to chest belts. Lightweight wrist photoplethysmography is gathering momentum, albeit with mixed results with regards to accuracy/validity, and it could become a valid alternative provided that specific algorithms are implemented to account for motion artifacts so as to reduce the mean error of detection below 3%. Smart textiles also offer promising solutions with textile sensors capable of high accuracy in various activities. This shows that more and possibly better options will be available soon for assessing the implications of training on cardiorespiratory parameters.

Near-infrared spectroscopy (NIRS) is nowadays a well-accepted technology to assess muscle oxygenation in vivo, and our previous research together with studies conducted by others (for a review of this methodology see Ferrari et al) suggest that this technology could be implemented successfully in most sports, including aquatic sports. While the market seems to be showing an increase in portable NIRS devices, only few present some form of validation to date. Recent developments in miniaturizing and embedding the devices in sporting garments suggest that this modality of internal training-load quantification not only has merit but also could have extended applications in the near future.

**Humoral Parameters**

A large amount of research has been conducted examining a range of biochemical, hormonal, and immunological markers able to characterize the acute and chronic responses to various exercise and training paradigms. It is beyond the scope of this article to conduct a comprehensive review of the literature in this area; however, it is important to state that it would represent a dangerous reductionist approach to identify only 1 marker able to quantify some aspects of internal training load. Recent reviews have looked at different approaches and they all conclude that more research is needed. However, the limitations of implementing such measurements reside in the invasiveness of the measurements, the cost-effectiveness of determining humoral responses to training and the difficulty in performing some meaningful longitudinal monitoring. For this reason, we believe that hopefully with further technological developments making such measurements cheaper, more accessible, and less invasive, as well as providing opportunities for rapid feedback, could be an area of research and application which might shed more light on the implications of various training regimens on adaptation. Recent advancements in various “omics” suggest the possibility of gathering more information on biological responses to exercise activities from relatively small blood, sweat, and/or urine samples. However, such methods are still impractical in the applied setting due to the laboratory equipment and expertise necessary to process the samples. Future implementations of such techniques will become reality in sport when simple analytical processes and accessible equipment are extensively available. Wearable solutions are also developing at a very fast rate. The feasibility of equipping human skin with ultrathin devices has been recently demonstrated by the pioneering work of a few laboratories. Recent validation work has shown promising results of epidermal sensors in quantifying biological parameters in vivo while performing exercise activities suggesting that it is not far-fetched to imagine a future of wearable sensing capable of improving our understanding of how the body reacts to various exercise stimuli. In general, until cheaper and less invasive technologies and methods become available, our understanding of the biological responses to training will remain limited with fewer chances to affect day-to-day activities of sport scientists and coaches. Therefore, at the moment, practitioners should use biochemical markers of training-load monitoring with caution taking into account the limitations, the biological and individual variability and the fact that many parameters currently quantified in the field can be affected by many variables.

**Neuromuscular Parameters**

The assessment of neuromuscular parameters of training load has been somewhat limited by the available technology. Recent developments include sporting garments with embedded electromyographic (EMG) sensors capable of quantifying muscle activity during exercise. Furthermore, epidermal solutions suggest that muscle activity of athletes in training could be monitored routinely and accurately. Surface EMG data of athletes and nonathletes in competition or training have been recently published, but to the author’s knowledge there is no longitudinal study presenting internal load assessments using this technique. The same holds true for electroencephalographic measurements and galvanic skin responses observed during training. This is mostly due to the impractical use of such technologies in the sporting setting due to the bulky equipment, as well as the prohibitive costs. For this reason, despite the fact that in many coaching communities there are common references to “neuromuscular load” it is virtually impossible at this moment to quantify this aspect. However, it is possible to assess the effect of training acutely and chronically using various tests which assess the function of the neuromuscular system such as dynamometric measurements, reaction time, electroencephalography (EEG) responses, vertical jumps, and other proxy measures of neuromuscular function. As for humoral parameters, technology in this domain is developing very quickly, and we have examples of EEG measurements during static sporting activities like shooting. Consider the potential for EEG to provide more information about the implications of training activities on the brain, it is hoped that better wearable devices and more accurate signal filtering approaches will be developed to be able to quantify neuromuscular load in different sports.
External-Load Monitoring

External training load can be defined as the work completed by the athlete, measured independently of their internal characteristics. External-load measures can include duration, speed, distance covered, body load, acceleration, metabolic power, and sport-specific movements such as balls thrown or tackles performed. The ability to objectively quantify external training load is essential in athlete monitoring as it allows practitioners to evaluate the effectiveness of a training program or intervention, minimize the risk of athlete injury,33 design individual training programs that reflect competition demands,34 and allow the athlete to maintain and optimize performance.35

Athlete monitoring should be conducted at an individual level to identify meaningful changes in external load. Therefore, it is important to understand the accuracy and reliability of the devices used to measure external load as this will allow practitioners to determine the athlete’s day-to-day variation in these measures and confidently determine meaningful changes in load.

Global Positioning Systems

In elite sport, wearable technology such as global positioning system (GPS) devices and inertial sensors such as accelerometers, magnetometers, and gyroscopes are commonly used to monitor the external load of the athletes during training and competition.35 GPS devices measure position, velocity, and acceleration, the data of which are processed using various algorithms and filters to provide a range of metrics that can be used to quantify external load.36 Accelerometers have been used to quantify movement for over a decade, with accelerometers now commonplace in technology such as smartphones, wearable fitness devices, and individual inertial sensors. Accelerometers provide a measure of acceleration which can be used to estimate overall external load imposed on the body.37 This may provide a more representative value of overall muscular peripheral load than velocity and distance based metrics as it incorporates external load from collisions, foot impact, and other movements that are not accounted for when using GPS. Almost all GPS devices used in sport contain a triaxial accelerometer. Devices may also contain a magnetometer and/or gyroscope which measure direction and orientation, and angular movement respectively.38 Data from these additional sensors can be integrated to calculate advanced movement patterns and be used to quantify load in indoor sports.

Distance and Velocity Measures

Total distance is the most common measure of external load using wearable technology. This measure is provided using GPS data and can be calculated either by positional differentiation or as the integral of Doppler-shift velocity. Although not all manufacturers disclose their chosen method, 2 prominent GPS manufacturers (Catapult Sports and GPSports) use positional differentiation to calculate distance. Often the distance covered is reported according to specific speed thresholds and it is common to see a threshold for low-speed running, high-speed running, and sprinting.6 The GPS device calculates velocity either derived from the change in distance (determined by positional differentiation) over time or using the Doppler-shift method. As Doppler-shift appears to provide greater precision and less error,40 this method is commonly used by manufacturers. Raw GPS velocity data may be further processed using filtering techniques (eg, median or exponential filters), which will vary based on the manufacturer. Different filtering techniques can substantially change the velocity output and are not reported by all manufacturers. External-load metrics arising from distance and velocity data include the distance covered within specific speed thresholds and/or the number of discrete efforts that occur within a specific speed threshold (ie, number of sprints). Researchers and practitioners often focus on total distance and the distance covered at high speeds as this is thought to be the most demanding and important movement undertaken by the athlete. However, high-speed running should not be interpreted as high-intensity activity as this is not a complete reflection of the external load imposed on the athlete.50 High-intensity activities can also include jumps, accelerations, decelerations, changes of direction, and tackles.41

Acceleration

Acceleration is more energetically demanding than constant-velocity movement.41,42 During a maximal 5-second sprint from a static start 50% of the total work is achieved within the first 1.5 seconds and a peak power output 40% greater than the average output is obtained after only ~0.5 second.52 Thus, from a standing start the hardest work is likely performed before the sprint threshold is reached. Further, performing an acceleration from a low velocity can match or even exceed the power output required to maintain a higher constant velocity.41 Thus accelerating is not only a metabolically demanding task, but one that does not need to occur at a high velocity to be challenging. This suggests that if external load is quantified based only on distance and speed measures it is likely that the true high-intensity work undertaken by athletes will be underestimated.

Acceleration is derived from GPS velocity data. There are two primary levels of data processing when calculating acceleration. The first is the time interval over which acceleration is derived from the velocity data. Using a longer time interval will result in average acceleration which has a smoothing effect on the acceleration data. The second level of processing applies smoothing filters to the already calculated acceleration data. Any errors in velocity data are magnified when acceleration is derived therefore, acceleration data can often be substantially filtered. As with velocity data, the filter techniques vary depending on the manufacturer. As acceleration filters are applied to previously filtered velocity, data differences in filtering techniques can substantially affect the acceleration measures reported. This has been observed when GPS data were processed before and after a software update resulting in a substantial reduction in the number of accelerations detected following the update.43 Although filtering techniques were not reported, it is likely that changes in the data-filtering techniques contributed to these differences. Typically, the number of acceleration efforts or the distance covered in specific acceleration thresholds are used as external load measures. However, caution is needed when interpreting this data given the limitations of current technology.44

Accelerometer-Derived Measures

Accelerometers can provide an external load measure of physical activity that may overcome the limitations of GPS based metrics. This measure quantifies the overall load on the body indicating the total stress resulting from acceleration, deceleration, change of direction, collisions and foot impacts.35 Manufacturers may have slight variations in how this load is calculated; however, it is typically the sum of acceleration in all 3 planes of movement measured using a triaxial accelerometer. An example is the metric PlayerLoad used by Catapult, which is the square root of the sum of the squared
instantaneous rate of change in acceleration in the x, y, and z axes divided by 100. These load measures are described in arbitrary units therefore, reliability is more easily determined than validity. While GPS measures are reliant on the quality of the satellite signal, these load measures are calculated purely from accelerometer data and can therefore be collected indoors or in areas with poor signal quality (eg, indoor or high-walled stadiums). Research that has used PlayerLoad measures to quantify external load during training has found it to have a strong relationship with total distance covered. It has been suggested that practitioners could use PlayerLoad measures as a surrogate for measures of total distance when GPS is not available (ie, indoors). Accelerometer external-load values are of an individual nature; therefore, when monitoring athletes practitioners should compare within-athlete changes rather than between.

Validity and Reliability

Given the expanding number of wearable devices available for sports, understanding their reliability and validity is essential to inform training practice. Decisions around athlete training may be based on small fluctuations in training load; thus, precision is extremely important to differentiate between real change and measurement error. As manufacturer validation is rarely performed, external validation is necessary for each device and device metric to understand the error so that correct assumptions can be made regarding changes in load variables. A substantial number of studies have assessed the validity and reliability of wearable technology for their use in sport. This has been extensively reviewed elsewhere, so this section will summarize the findings.

The validity of GPS devices for measuring distance and velocity appear to improve with a higher sampling frequency. Improvements may also be due to advances in chipset technology and signal processing algorithms. Regardless of the sampling frequency, accuracy has been shown to be reduced at higher velocities. However, validation studies have often used protocols that involve running trials commencing from a static start when assessing high velocity. In studies that have isolated the acceleration and high-velocity-running phases, GPS accuracy is reduced as the rate of acceleration (change in velocity) increases. For example, GPS was found to have a lower coefficient of variation for measuring running at constant high speeds (5–8 m/s) compared with low constant speeds (1–3 m/s), 3% versus 8%, respectively. Similarly, validity is shown to improve over trials of longer distances, where the acceleration phase is relatively diminished over the trial. This would explain the increased errors for movements that require rapid changes in velocity such as change-of-direction movement and short explosive actions. As distance and velocity are calculated independently and are subject to filtering it is important that each measure and the associated analysis technique from the GPS is validated appropriately. For example, velocity calculated via Doppler shift has shown a higher level of accuracy and lower error than velocity calculated via positional differentiation.

Of primary importance when monitoring athlete load is the reliability of the monitoring device as this will allow practitioners to identify meaningful changes in external load. Individuals may respond differently to a given training load; therefore, an individualized approach to athlete monitoring is important. Higher sampling frequencies and improvements in technology have been found to improve reliability in a similar way to validity. The intraunit reliability of velocity and distance at any given velocity is difficult to accurately determine as it requires participants to perform multiple trials at the exact same speed. Intraunit reliability is also difficult as it is unclear how wearing multiple devices may affect GPS signal quality and accelerometer results may vary when placed in different locations. While interunit reliability appears to have improved it is recommended that the same device be used on a given athlete when monitoring training load to minimize intraunit variability.

The validation of the accelerometers measure of Player Load is problematic as it represents an arbitrary unit, however its reliability has been assessed under laboratory and field conditions. When using a hydraulic universal testing machine to oscillate devices at specified acceleration ranges, devices showed strong interunit and intraunit reliability (CV of <1.10%) for Player Load. Similarly in field conditions (Australian Football match), devices were shown to have strong interunit reliability (CV of 1.94%) for Player Load.

Validity and reliability of wearable technology are improving with technological developments. As validation research is often conducted externally after the release of new technology, practitioners are likely to be using the devices before this information is available. Unfortunately, validation is required with each new device release or upgrade, and following any changes to data processing which may occur after firmware or software updates. The ability to monitor athletes requires identifying changes within athlete load measures over time. Thus practitioners are recommended to ensure consistency in data collection, processing, and analysis where possible. For this reason, practitioners may wish to delay device and system upgrades until the end of the season. If retrospective data can be reprocessed this can provide comparable data for each new season. This consistency will enhance the reliability of external-load metrics used to assess athletes.

Use of Load Monitoring in Sport Settings

A large amount of the external-load research is descriptive, detailing and comparing external load in different circumstances (eg, during training and competition). The benefit of these studies is that they provide methods to quantify and analyze external load; however, there is limited ability to generalize or compare results as they are dependent on the training program and athletes/team participating in the research.

Practitioners have a variety of external-load metrics at their disposal when monitoring athletes. The way in which these metrics can assist practitioners in optimizing their training plan can vary with each metric. Information regarding the body load of an athlete can provide a holistic representation of the stress imposed on the athlete, however, it is difficult to design specific training drills based on this metric. External-load measures relating to distances covered at specific speeds may be more appropriate as they provide practitioners with tangible metrics that can be used to plan what the athletes will actually do in the training program. Similarly, when using external load to indicate fatigue, velocity and distance based measures are unlikely to completely represent the stress on the body, so body load and/or acceleration metrics should also be included. It is impractical to suggest that practitioners use all metrics for each component of the training plan and their decision should be based on their understanding of the metric and if it can be used in a practical way to support their training goals.

A number of studies have explored the relationship between training and injury (for review see Drew et al). External-load metrics are often quantified as both acute (7 d) and chronic (eg, last 4 wk) and as a ratio of the 2. The actual load metric used varies between studies however, total distance appears to be the most common. Both high and low external loads are associated
with injury risk, with suggestions that there may be an optimum load threshold for individual athletes.\textsuperscript{3,51} It may be that a low external load results in athletes being underprepared for the training or competition demands whereas chronically high loads may impose too much stress on the body. There is a strong theory that in some sports the interplay between acute and chronic external load may be the most important consideration for athlete monitoring with spikes in acute load associated with a higher injury risk.\textsuperscript{54} Regardless of the method used, external load should be monitored from an individual perspective as there are many other factors that may contribute to the risk of injury.\textsuperscript{1,52}

**Summary and Conclusions**

Despite the increased interest in training-load quantification, research and practice seem to focus mostly on what is easy to measure rather than developing a holistic approach to the quantification of workloads experienced by athletes with particular reference to the biological responses. Current findings suggest that many internal- and external-load parameters can be measured using wearable technology with relative accuracy and in a reliable manner. However, it is important to stress that many manufacturers do not provide information about the accuracy, validity, and reliability of their equipment nor give access to the raw data for further analysis. For this reason, generalizations on the accuracy and validity of any technology or method should not be made, and conclusions of research studies should be always specific to the hardware and software versions employed and the sporting context. Better wearable solutions could possibly be available in the future using epidermal electronics providing the basis for body-sensor networks to assess training loads in sporting activities. Inertial measurement units (IMUs) will ideally become smaller with better software providing the modern sport scientist and coach access to numerous datasets to make better-informed decisions on training prescriptions and recovery. However, such fast-paced changes do not come without risks. The lack of quality assurance and standards of manufacturing processes and the lack of transparency by manufacturers do not guarantee that the data gathered are/will be accurate/valid and reliable, so due diligence will be always required. Needless to say that with more data comes the need to develop user friendly, accessible, well-designed databases and athlete-management systems capable of safely managing and storing data. Furthermore, such systems should be able to generate rapid and meaningful reports, as well as supporting data-modeling activities to improve the decision-making progress in the field.

**Final Recommendations and Practical Applications**

- Sport scientists and coaches should be aware of the limitations of every device/method used.
- Industry standards need to be developed to make sure that the quality of data generated by measurement devices is of high enough quality to be able to make training decisions.
- Research studies should report details of hardware and software versions used and limit the significance of the findings to the versions used in the data-collection activities.
- More longitudinal observational studies are needed to provide coaches and sport scientists with terms of reference with regard to internal and external training loads in different athletic cohorts.
- Although a wide range of metrics are available, practitioners should limit their use to those that they understand and that can affect their training program.

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