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Master's Degree in Biomedical Engineering

Engineering of Medical Devices

WEARABLE DEVICES IN SPORT:
Technical and Clinical Evaluation

Supervisor:

Dr.ssa Agnese Sbrollini

Candidate:

Irene Falaschetti

Co-Supervisor:

Prof.ssa Laura Burattini

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Abstract

The integration of wearable technology in sports has redefined how athletes monitor their performance and health. This study investigates the transformative role of wearable devices in sports, focusing on their ability to measure physiological parameters in real time.

The first section reviews the types, structures, and market trends of wearable sensors, emphasizing their growing relevance in enhancing athletic performance. A systematic literature review identifies key studies validating wearable devices for sports applications, highlighting the characteristics and the potential of these technologies. Subsequently, five commercial devices—KardiaMobile 6L, Polar M400 with Polar H7 sensor, Garmin Forerunner 245, BioHarness 3.0 Zephyr, and Frontier X2—are analyzed for their technical characteristics, usability, and application in sports settings. In the experimental section, these devices are validated against medical-grade tools like Holter monitor on an athlete at laboratory, and then showcasing their accuracy and practical utility in monitoring 5 athletes during 3 different sports: running, speed skating and cycling.

The findings demonstrate how wearable technology bridges the gap between laboratory-grade precision and real-world usability, paving the way for more precise, personalized, and accessible training methodologies.

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Introduction

Sport biomechanics and training have traditionally been tested under laboratory conditions, requiring specific settings and expensive equipment. The novel use of wearable devices addresses the lack of ecological validity in such measures and offers an affordable, user-friendly option for biomechanical assessments. Recently, wearable sensors have enabled the quantification of performance and workload by providing mechanical and physiological parameters, leading to their exponential growth in popularity. Many wearable sensors are now commercially available and capable of delivering both kinetic and kinematic data, thus improving the feasibility and efficiency of assessments and making them a viable alternative for sports practitioners and researchers. Additionally, wearable devices allow for real-time monitoring and biofeedback [1]. Technological advancements have enabled athletes, coaches, and physicians to track functional movements, workload, biomechanical and bio-vital markers utilizing wearable sensors to maximize performance and minimize the potential for injury. Wearable monitoring systems can provide continuous physiological data thus permitting the development of accurate treatment plans and athlete-specific training programs to potentially mitigate and alleviate injuries [2].

1 Wearable sensors in sport

Over the last decade, wearable and portable devices for cardiac monitoring have become increasingly popular, as they are relatively inexpensive and user-friendly. Miniaturized technologies and powerful signal processing applications make them a noninvasive, cheap, and time-efficient tool for cardiac monitoring while playing sport outside a clinically controlled environment.

Wearable devices are designed to be worn on different body locations for noninvasive sensing of an individual's parameters without interrupting or restricting the user's movements. Portable devices are designed to monitor cardiac conditions more easily than traditional monitors, being small and lightweight. On a sport field, portable devices may be useful in documenting and contributing to diagnosis of exercise-induced arrhythmias [3].

Wearable device is defined as a sensor or sensor suite unencumbered by wires for the continuous and non-invasive detection of biosignals, analytes, or biomechanical and impact forces for monitoring human health and performance. Over the past two decades, the wearables field has moved from a *device* to a *systems* viewpoint, where the system combines the device with analytics. While previous literature has reviewed specific technical domains of the wearables field, such as sensors, materials, and soft interfacesor focused on the fabrication and application of such devices to address a specific medical condition, such as atrial fibrillation, cystic fibrosis, or diabetes, there remains an unmet medical need to assess, develop, and validate this technology specifically for sports medicine. Given the heightened attention to athlete safety and performance, it necessary to evaluate the translational utility of wearable devices to detect key metrics pertinent to human performance assessment (Fig.1) [2].

Figure 1. Four areas of focus as it relates to assessing human performance [2].

1.1 Anatomical perspective of wearable sensors

Anatomy is the study of the structure and organization of living organisms and their parts. Wearable Technology (WT) is the term for devices or materials that can be worn on the body and provide some functionality, such as sensing, computing, communication, or entertainment. The relationship between anatomy and the physical structure of WT is important for several reasons:

- It affects the comfort, fit, and usability of the WT or material.
- It influences the accuracy, reliability, and validity of the data collected by the WT or material.
- It determines the potential benefits, risks, and limitations of the WT or material for different applications and users.

Sleeves, shirts, trousers, vests, jerseys, and gloves allow real-time monitoring of various internal and external training loads related to athletes. For this purpose, WT structures are designed to be placed on different anatomical regions according to the type of training and sport. The human anatomical regions are shown in Fig.2. Some of the anatomical concepts that are relevant for WT are:

- Anatomical regions: The body can be divided into different regions based on location, function, or structure. For example, the head, neck, torso, arm, hand, leg, and foot are anatomical regions that can wear different devices or materials.
- Physical movement: The body can perform different types of movement based on the joints, muscles, and bones involved. For example, flexion, extension, abduction, adduction, rotation, and circumduction are types of movement that can affect the fit, function, and comfort of WTs or materials.
- Perspiration-comfort: The body can produce sweat as a way of cooling down and regulating body temperature. Sweat can affect the skin condition, moisture level, and friction of the body part that wears the device or material. For example, sweat can cause skin irritation, infection, or corrosion if not properly managed by the WT or material.
- Ergonomics: The body can interact with the environment and the device or material in different ways based on its posture, position, and orientation. Ergonomics is the study of how to design devices or materials that fit the human body and its activities. For example, ergonomics can improve the usability, efficiency, and safety of WTs or materials.

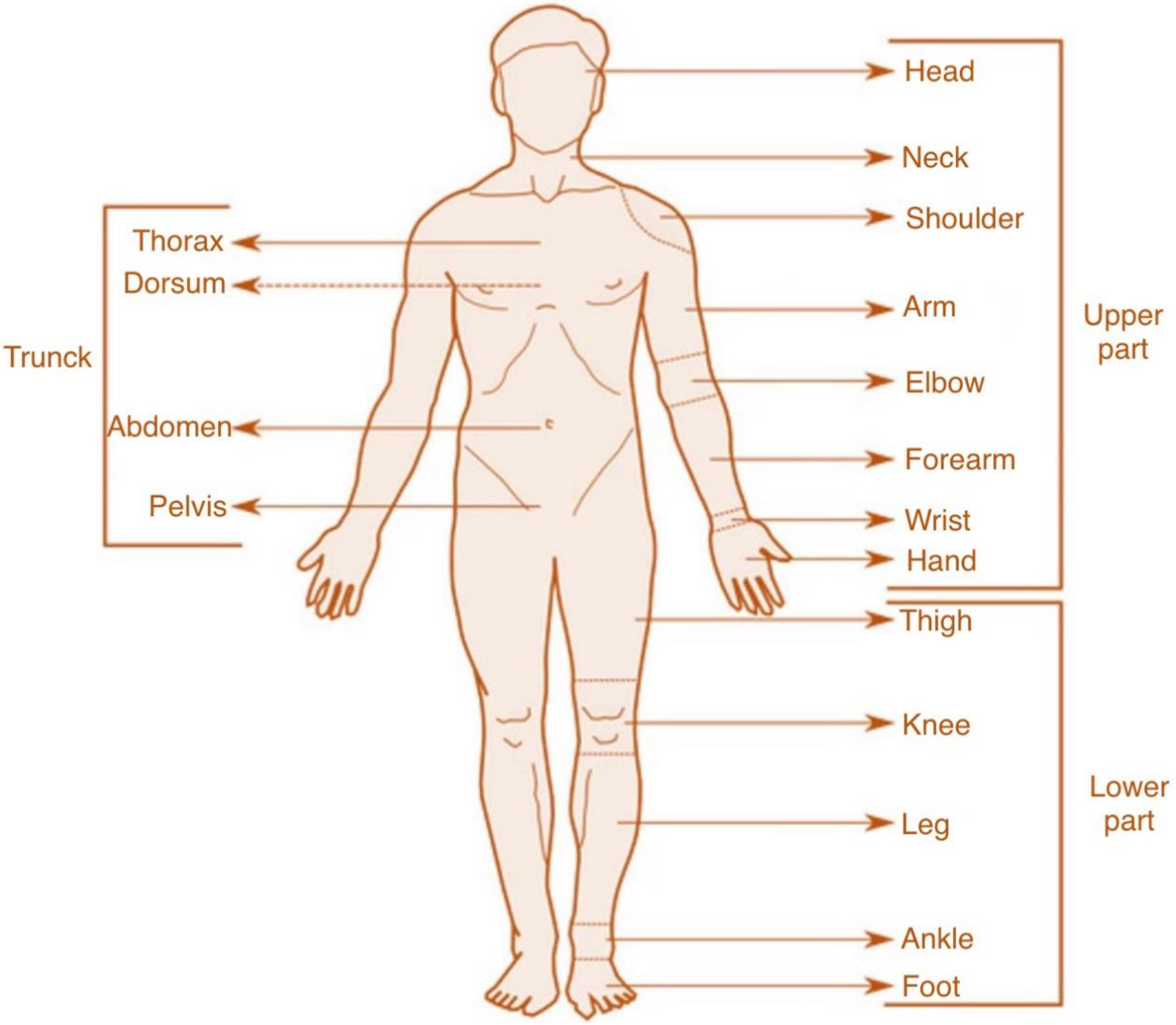


Figure 2. Anatomical parts of the human body. [4]

In the process of devising WT, it becomes imperative to consider a multitude of anatomical factors. These considerations encompass the size, shape, and relative proportions of the specific body part destined to bear the device or material. Additionally, an assessment of the range of motion, flexibility, and strength exhibited by the targeted body part assumes significance. Factors such as skin sensitivity, temperature, moisture levels, and blood flow in the chosen anatomical region warrant meticulous evaluation. Furthermore, scrutiny should extend to the location, function, and potential interplay with other adjacent body parts or organs that might be influenced by the deployment of the device or material. Lastly, an indispensable facet of this comprehensive analysis lies in recognizing and accommodating the individual preferences, needs, and expectations of the end user. Wearable technologies used in the sports field vary depending on the sport(s) and anatomical region they are used for. The main regions where commercial wearables are placed in the sports field are the thorax, arm, forearm, wrist, hand, thigh, leg, and head. It is observed that these wearables are concentrated on the thorax and wrist regions in terms of anatomical regions. From this perspective, the thorax is an advantageous region for monitoring body movements due to its proximity to the physiological aspects of breathing and heart function, as well as its proximity to the body's center of gravity. The wrist, arm, and forearm regions, on the other hand, are areas that can provide information about arm strength, posture angle, or the correct execution of movements in sports that heavily involve hand and arm usage. Additionally, since the veins are close to the skin in these regions, information about heart rate and oxygen levels in the blood can also be obtained [4].

1.2 Physical structure of wearable sensors

From an anatomical perspective, the physical structure of the WT to be used varies depending on whether certain regions are mobile, semi-mobile, or fixed. The materials used in WT production in the sports field are primarily divided into three subcategories: rigid, soft, and textile-based [4].

1.2.1 Rigid structures

Rigid WT structures are mechanically rigid systems. Many WTs in this field are designed to be rigid due to the likelihood of actions such as impacts, falls, and crushing occurring during sports activities. In rigid sensor structures, a large part of the body that makes up the sensor is primarily intended to protect the system from mechanical impacts and ensure proper attachment of the sensor in the correct position.

1.2.2 Soft structures

Soft WT refers to sensor systems that can be produced by injecting conductive alloys into soft, silicone-like materials. In these types, molds are prepared according to the areas where measurements will be taken, and the soft material is poured into the prepared molds. The flexibility and coating capability of soft WT allows for precise measurements. The sensor position is more stable compared to rigid WT. In soft wearable technologies, the measurement method relies on the deformation of the surface. Soft sensors are more suitable for continuous motion tracking, human-machine interfaces, and measuring physiological parameters of the human body compared to their traditional, more rigid counterparts.

1.2.3. Textile structures

Textile-based WT (shown in Fig.3) is typically created by embedding conductors, sensors, special fibers, and other electronic components into the fabric using techniques such as weaving, embroidery, or knitting. Among these systems, the most common and straightforward method is to add sensors to the textile surface. This can be achieved by directly sewing or gluing a typical sensor onto the fabric surface. Transmission lines required for the sensors to function are applied to the textile using conductive threads or a cable-drawing method. Another method in textile-based sensor applications is to impart sensor properties to the textile surface through various modifications. These modifications can be executed internally or externally. Internal modification involves chemically or mechanically modifying the textile surface during the production of cationic yarn or fibers, making the textile surface sensitive to external factors. This way, the textile fiber or thread itself becomes a sensor. External modification refers to post-production processes such as dyeing, various coating methods, or lamination, which transform the textile surface into a sensor.

Internal and external modifications can be applied during production, but internal modifications encounter difficulties in interacting with electronic circuits and have lower sensitivity. In this regard, external modifications are more functional and practical. Internal modifications result in a more homogeneous structure since they are applied to the entire textile surface, and factors such as sliding, bending, and stretching behave uniformly across the surface. On the other hand, external modifications do not exhibit similar homogeneous behavior on the textile surface as they cause local changes. Additionally, discomfort can occur more easily when there is a stiffer structure in that area when worn. Both internal and external modifications result in a change in the performance of the sensor surface when their properties deteriorate over time due to washing.

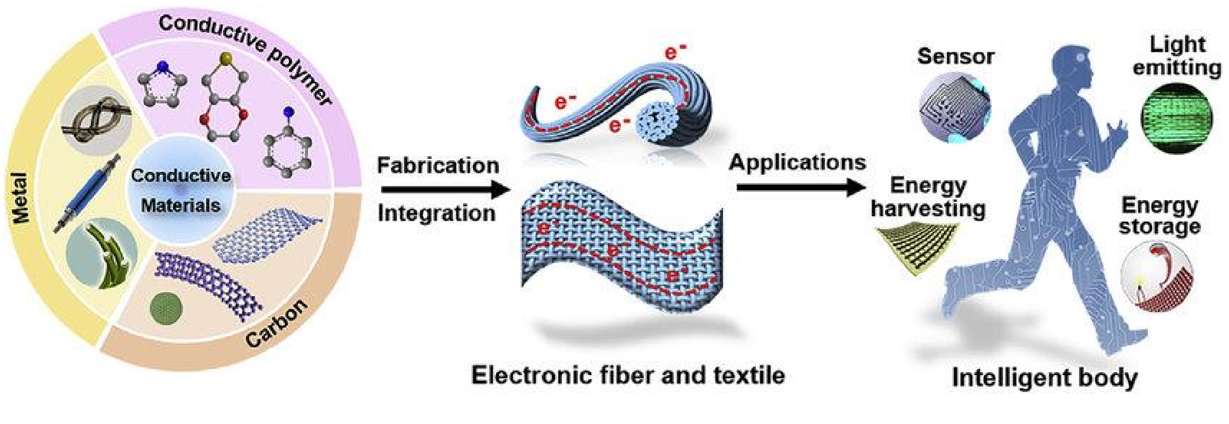


Figure 3. Textile structure.

1.3 Types of wearable sensors

There are a lot of different types of wearable sensors in sport. In particular, the major categories are four: Physiological Sensors, Biomechanics Sensors, Location Sensors and Environmental Condition Sensors [4].

1.3.1 Physiological sensors

Physiological data encompasses information derived from the biological processes occurring within the human body, serving as a valuable source of insights into an individual's health, performance, or overall condition. Prominent among the sensors used for capturing physiological data are well-recognized devices such as Electromyography (EMG), Electrocardiography (ECG), and Electroencephalography (EEG). Furthermore, physiological data acquisition extends to include an array of sensors such as functional Near-Infrared Spectroscopy (fNIRS), Oximeter, Blood Pressure Sensors (BPS), Galvanic Skin Response (GSR), and respiratory monitoring sensors.

- EMG system (shown in Fig.4) measures the electrical activity of muscles. By providing data such as muscle contractions and muscle strength, they can provide information about muscle activity and performance. EMG electrodes are placed to detect the electrical signals originating from the muscles. During muscle contraction and relaxation, neurons in the muscle fibers produce electrical signals. This electrical activity is associated with the movement of muscles or changes in muscle tone. EMG electrodes detect and record the electrical activity of muscles by capturing this electrical activity. The obtained EMG signals are processed and recorded through amplifiers and data recorders. EMG signals reflect the magnitude, duration, timing, and coordination of muscle contractions.

Figure 4. EMG sensors.

- ECG (shown in Fig. 5) is a technique that records cardiac electrical activity and provides information on heart rate variability (HRV), cardiac arrhythmias, and cardiovascular health. ECG is a valuable tool for evaluating the health and performance of athletes, as it can reflect the autonomic nervous system regulation, the metabolic demand, and the cardiac adaptation to exercise. ECG is an important tool for monitoring athletes' health and performance, optimizing exercise programs, and assessing heart health. ECG electrodes are placed on specific locations of the torso and limbs to capture the signals generated by the cardiac depolarization and repolarization. Some commercial WT, such as smartwatches and wristbands, claim to have ECG detection capabilities, but they usually measure a single-lead ECG that is more suitable for detecting training load or cardiac disorders than for providing a comprehensive ECG analysis. The conventional ECG acquisition is often inconvenient and intrusive, as it requires multiple electrodes and wires that may interfere with the natural movement of the athletes.

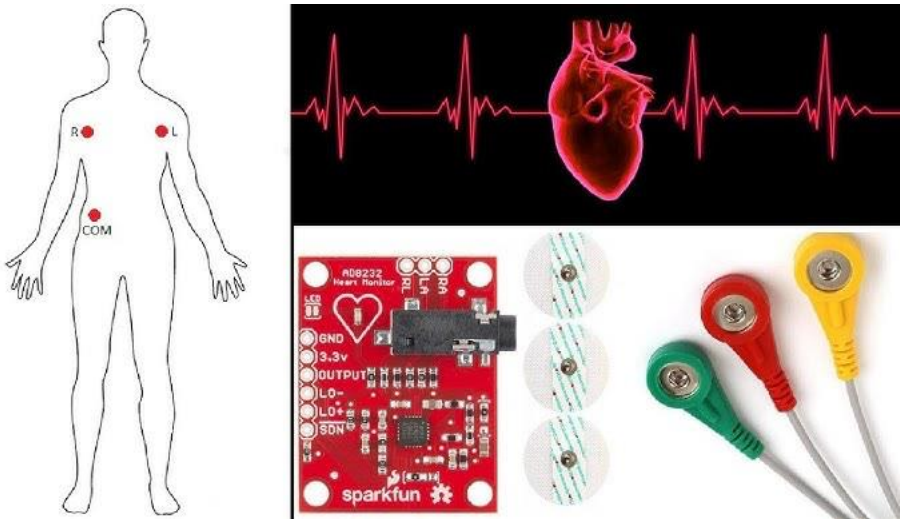


Figure 5. ECG sensors.

- EEG sensors (shown in Fig.6) measure brain waves using electrical methods and provide data related to brain activity. These data can provide information about an athlete's brain activity, sleep quality, concentration, and other factors. The working principle of EEG involves the placement of metal plates called electrodes or sensors on the scalp. These electrodes are used to detect electrical activity in the brain. The electrodes are typically placed at specific points on the scalp to capture electrical signals from different regions of the brain.

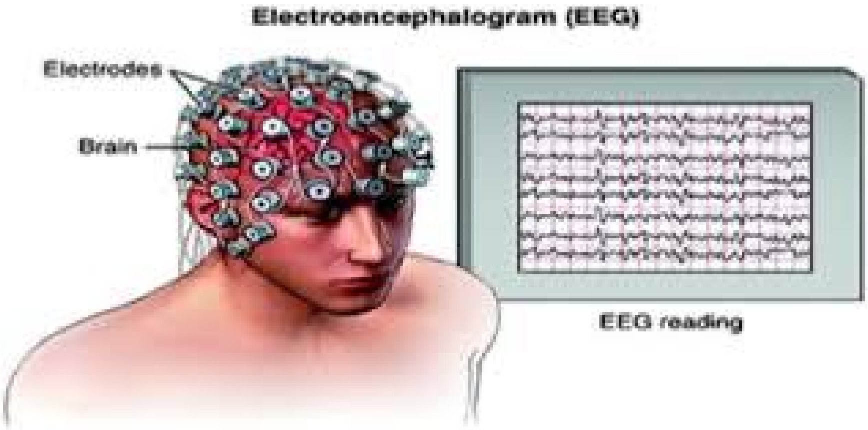


Figure 6. EEG sensors.

Brain cells or neurons are the cells that generate and transmit electrical signals. This electrical activity is due to the potential differences created as neurons communicate with each other. EEG electrodes detect and record these electrical activities to obtain brain wave patterns. EEG signals consist of different components known as low-frequency (slow) and high-frequency (fast) brain waves. Brain waves can reflect different aspects of brain activity such as sleep, wakefulness, focus, or different mental states.

- Athlete brain activity monitoring applications are also measured with functional near-infrared spectroscopy (fNIRS) sensors. Neuronal activity in the brain causes changes in oxygenation. fNIRS uses near-infrared light emitted by a light source, which is absorbed by hemoglobin in the tissue. When the oxygenation of hemoglobin changes, its absorption properties also change. When the fNIRS detector detects the reflected or scattered light from the brain, it measures the changes in oxygenation and collects this information as a data set.
- Pulse oximeter sensors are used by placing them on the fingertip or near blood vessels to provide data such as peripheral oxygen saturation (SpO2), heart rate (HR), and photoplethysmography (PPG). Oximeters operate by using two different light sources: red and infrared. Oxygenated blood absorbs more red light, while deoxygenated blood absorbs more infrared light. The oximeter measures the amount of light passing through the skin or tissues using these two light sources. This data provides information about athletes' oxygen levels, heart rate, and exercise performance.
- BPS facilitates the assessment of athletes' blood pressure levels and cardiovascular well-being through blood pressure measurement. Typically, the BPS is designed as either a cuff

or a wristband. This WT employs a mechanism in which the cuff is inflated using air until arterial blood flow is occluded. The pressure reading corresponding to the cessation of arterial blood flow indicates the Systolic blood pressure value. After this occlusion, the applied pressure is gradually released. During this process, oscillations in pressure occur due to cardiac contractions, and the pulse rate is determined by quantifying these oscillations and the time intervals between them. The minimal pressure threshold required for pulse detection designates the Diastolic blood pressure value. Consequently, this methodology enables the determination of both systolic (maximum) and diastolic (minimum) blood pressure values, expressed in pulse per minute and millimeters of mercury (mmHg) units.

- The GSR sensor is based on the principle that the skin's electrical conductivity can vary due to sweating. Sweating increases the moisture level on the skin, thereby increasing electrical conductivity. Therefore, when a person experiences an emotional response or exerts physical effort, the amount of sweating and, consequently, the electrical conductivity change.
- Respiratory sensors measure data such as respiratory rate, respiratory depth, and respiratory pattern. These data provide information about athletes' respiratory performance, exercise capacity, and energy expenditure. These sensors typically work by measuring respiratory movements using various types of sensors, including optical, mechanical, or electromagnetic sensors, which are usually placed on the chest area. Smart masks are WT capable of monitoring an athlete's respiratory and metabolic parameters during exercises or other activities. There are many commercial examples such as Calibre, K5, and Cortex–Metamax 3B. These devices exhibit the characteristic of becoming the gold standard, particularly in terms of energy expenditure and performance measurements. Wearable smart masks comprise a multitude of sensors such as gas sensors, flow sensors, heart rate sensors, temperature sensors, and humidity sensors. However, the primary sensors consist of oxygen and carbon dioxide gas sensors along with a flow measurement sensor. Other sensors serve auxiliary roles, and in some commercial products, they are positioned in a manner that could be more effective outside the mask, incorporating additional systems such as ECG. Wearable smart masks hold considerable potential applications within sports science and medicine. They enable accurate and continuous measurements of fundamental parameters, namely, respiratory gas exchange and metabolic rate, for evaluating aerobic capacity, anaerobic threshold, energy expenditure, substrate

utilization, respiratory efficiency, lung function, and more. These parameters can aid in assessing and optimizing physical performance, including monitoring training intensity and duration, recovery, and adaptation processes, as well as identifying health issues or risks. Wearable smart masks also have the capability to offer personalized feedback and guidance tailored to users' goals and preferences.

1.3.2 Biomechanics sensors

Biomechanics is the application of mechanical engineering principles to living organisms, and it encompasses studies at the tissue and joint levels. Biomechanics involves applying forces to biological systems and specifically includes the effects of forces applied to the human body. Within this scope, motion data refers to the use of sensors to monitor athletes' skeletal movements and muscle activities. In sports, the primary sensor used for motion sensing is the IMU and other sensors such as force sensors and EMG sensors are also utilized.

- IMU (shown in Fig. 7) is a type of microelectromechanical system (MEMS) sensor consisting of multiple sensors combined. An IMU sensor can include an accelerometer, gyroscope, and magnetometer sensors. The accelerometer is used to measure changes in acceleration resulting from applied forces. The gyroscope is used to determine the amount of angular rotation. The compass is used to measure the orientation of the sensor based on Earth's magnetic field. The compass is mainly used as a supporting sensor for sensor fusion with the accelerometer and gyroscope to determine the direction and magnitude of motion. IMU sensors can be used for various purposes such as swimming, posture analysis, and exercise tracking.

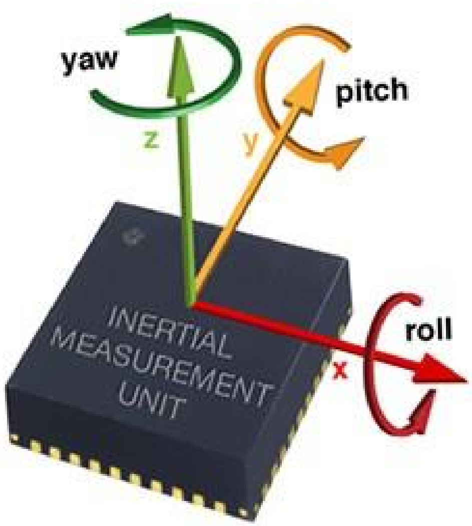


Figure 7. IMU sensor.

- Various sensors are used for force and motion detection in the field of sports. Some of these are sandwich-type sensors consisting of piezoelectric, resistor, capacitor and magnetic elements. These sensors convert mechanical energy into electrical energy to form triboelectric nanogenerator (TENG) systems. TENGs can be integrated with textile-based systems as wearable sensors in the field of sports. Piezoelectric sensors are inexpensive, sensitive, and capable of measuring quickly, but piezo crystals have a fragile structure and are not suitable for highly flexing surfaces. Resistive sensors, on the other hand, measure the deformation of the tissues obtained by knitting conductive threads as a change in resistance. These sensors are affected in situations such as liquid contact and perspiration, and coated systems must be used. The Strain gauge sensor is a coated resistive sensor and must be attached to the surface to detect hand movements. These sensors are custom-made and expensive. Applications for the use of conductive liquid in silicon are resistive sensors with high performance but difficult to manufacture and design. If these sensors are punctured or ruptured, the leaking liquid may harm human health. Capacitive sensors are passive circuit elements that measure the capacitance change of the dielectric material between two conductive plates. These sensors are preferred because of the insulator of biological materials and offer new horizons in the measurement of biopotential energy in humans. Capacitive sensors do not require electrodes to contact the skin, use conductive liquid/gel, or fixation, and can measure as precisely and stable as other methods.

1.3.3 Location sensors

Location sensors are used to track athletes' position changes and movements. The most fundamental wearable positioning systems include Global Navigation Satellite System (GNSS), Ultra-wideband (UWB) positioning systems, Wi-Fi, Bluetooth, RFID, and wearable marker positioning systems. The most used methods among these are GNSS, UWB, and camera-based wearable marker positioning systems.

- GNSS refers to satellite-based navigation systems, with the Global Positioning System (GPS) being the most widely used. A GNSS receiver receives satellite signals, analyzes the timing and location of the signals, and determines the user's position accordingly. GNSS is suitable for open-field applications, but it may not work or may be misleading in indoor environments due to signal weakening and reflections. In sports, it is used for position determination, speed and distance measurement, and activity analysis studies.

- The UWB positioning system consists of a transmitter and one or more UWB receivers. The UWB transmitter generates short-duration pulse signals and transmits them over a wide frequency band. UWB receivers receive the signals from the UWB transmitter and analyze their arrival time, power, and frequency spectrum. Through this analysis, the position of the user wearing UWB can be determined based on the time, path, and obstacles through which the signals propagate. UWB positioning provides high accuracy and precision and is also inexpensive and easily portable. UWB modules combined with IMUs are used for applications such as motion capture, biomechanics, and action recognition.
- Camera-based wearable marker positioning systems involve tracking multiple wearable markers with multiple cameras to monitor the user’s position and movements. These systems allow real-world movements to be reflected in virtual environments. While these systems are designed for positioning purposes, they are primarily used in biomechanical analysis and motion recognition due to their high precision and accuracy.

1.3.4 Environmental condition sensors

Environmental condition sensors on the WT are sensors that measure environmental effects such as air quality, humidity, temperature, air pressure, and UV light level. These sensors are used to monitor the condition of the environment where athletes are present. Air quality sensors assess the impact of factors such as air pollution and allergens by monitoring athletes’ respiratory conditions during exercise. Humidity sensors track the humidity levels in the surroundings, while temperature sensors monitor environmental temperature changes. Air pressure sensors track atmospheric pressure variations and are used for altitude calculations. UV light sensors measure athletes’ exposure levels to sunlight.

1.4 Physiological status of the athlete measured by wearable sensors

1.4.1 Heart rate and electrocardiogram detection

Modern HRMs most commonly record heart signals by means of one of two methods, electrical or optical. The electrical approach is utilized by electrocardiography (ECG) sensors, which gauge the bio-potential generated by electrical signals in the body, whereas the optical approach is implemented by photoplethysmography (PPG) sensors, which use light-based technology to gauge the blood volume being moved by the pumping heart. Electrical HRMs consist of two elements: a monitor/transmitter, predominantly worn as a chest strap, and a receiver. When the monitor detects a heartbeat, it transmits a radio signal, which is then used by the receiver to determine and display the current HR. This signal sent by the chest strap can be a simple radio pulse or be uniquely coded. More recent optical HR-measuring devices, in turn, use a light-emitting diode to emit light through the skin and measure how it scatters off blood vessels. Some such devices are able to monitor HR while simultaneously measuring oxygen saturation and other parameters.

In recent years, smartwatches have increasingly come to include HRM functionality, vastly boosting their popularity. Such smartwatches, as well as smart bands and cell phones, often use optical PPG sensors. Currently, many vendors sell products with fitness and HR measurement technologies, predominantly using their own proprietary HR algorithms. Moreover, devices with ECG recording capabilities are becoming increasingly popular among physically active people, both with on-demand (e.g., Apple Watch) and continuous recording options (e.g., Frontier X2). Heart rate variability (HRV), shown in Fig. 8, is a function available in devices using both the ECG and PPG techniques. For instance, HRV data collection functionality was introduced to Apple Watch devices in 2018.

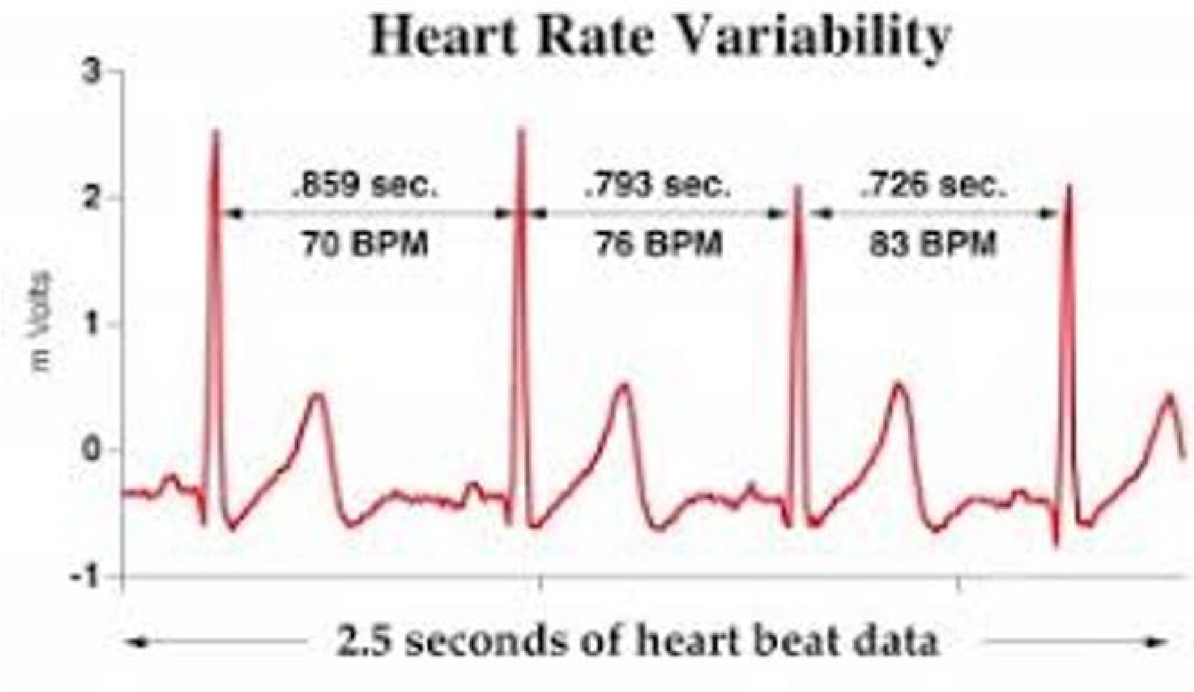


Figure 8. Heart Rate Variability (HRV).

At present, there are various types and a large number of portable medical devices for HR monitoring used by athletes, leisure-time exercisers, and cardiac patients. However, only a few are certified for use as medical devices. Almost all currently used HRMs are capable of "catching" arrhythmias. The main function of an HRM device is to monitor sports training, distance covered during practice, and pace. A high degree of accuracy and reliability is expected by endurance athletes. This requires not only GPS functionality but convenient control of these parameters as well, which should not interfere with or interrupt training. Heart rate rhythm monitoring is largely seen as an extra functionality by (presumably) healthy semiprofessional and professional endurance athletes, but it is perhaps considered the most important from the point of view of athletic club doctors [5].

Detection of arrythmias

Photoplethysmography technology, the technique of shining light through the skin and measuring the amount that is scattered by the blood flow, is used in optical HRMs. In practice, these devices can only determine the HR without having the ability to record the ECG curve. Numerous algorithms created by individual companies producing optical HRMs allow for the diagnosis of atrial fibrillation (AF), as Fig. 9, with a high probability, based on HRV analysis; however, it is always necessary to confirm such a diagnosis with a standard ECG.

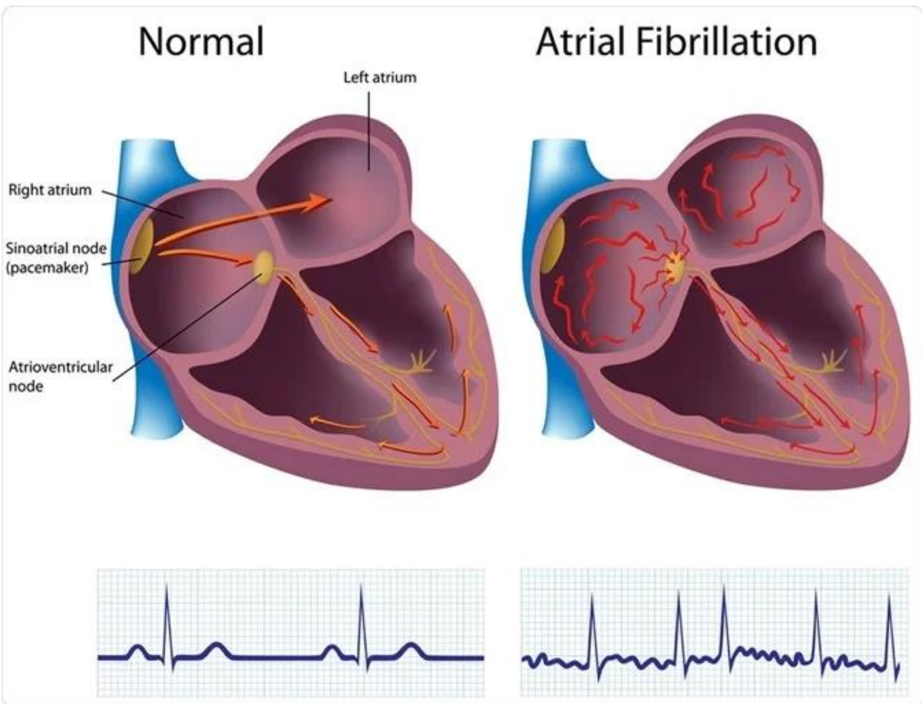


Figure 9. Difference between normal ECG and atrial fibrillation.

An HR recorder based on PPG can be placed almost anywhere on the body, keeping in mind the limitations of the device itself. This has resulted in a plethora of different HR monitoring devices placed in watches, rings, wristbands, caps, other garments, earphones, and many other types. Data from these sensors are then sent to devices that collect and display them (e.g., smartwatches, smartphones, and PCs).

For devices based on ECG technology, in contrast, data are obtained from electrodes that exhibit a difference in potential. Recording devices read the main electric field associated with the contraction of the ventricles (in most devices for athletes) and ultimately interpret this phenomenon of the beat-to-beat periods in the form of HR. If they have the function of measuring HRV (the variation in the beat-to-beat periods or variation in R-R intervals of the ECG curve), they become a helpful diagnostic tool in conduction disorders (measurement of pathologically long R-R intervals). In high-tech sports HRMs, a single- or multiple-lead ECG curve is recorded. However, the electrode positions in standard ECGs are different from those used by wearable sensors, which moreover provide a reduced number of ECG leads that do not necessarily match a subset of the 12 standard ECG leads. This aspect influences the interpretation of ECG features acquired through wearable sensors. When this electrical phenomenon is used by HRMs (main electric field registration) without ECG curve recording, the HR, which represents the peripheral effect of the heart pulse resulting from the frequency of contraction of the heart chambers, can be accurately determined without being able to assess the heart rhythm (sinus rhythm, AF, ventricular tachycardia [VT], or other).

Athletes are not immune to any of the types of arrhythmias found in untrained healthy people or cardiac patients. Single ventricular or supraventricular beats are undetectable by most sports HRMs and are mostly non-threatening for athletes. It is more important to recognize the rapid rhythms that often occur at high physical loads. Fast supraventricular and VT or rapid ventricular rhythms during paroxysmal AF in an athlete with pre-excitation syndrome can be dangerous. Rapid supraventricular rhythms during training, such as recurrent atrioventricular nodal re-entrant tachycardia, are most often those that force the athlete to stop an exercise and are rarely the cause of syncope. Paroxysms of AF or atrial flutter occur in athletes, both at rest and during exercise, but they have different mechanisms. When they occur during exercise, it is impossible for the athlete to continue the effort, or they are at least forced to significantly reduce exercise intensity. Individuals with AF and a rapid ventricular rate, or the need for long-term anticoagulation therapy, should be excluded from competitive sports. An AF attack during the pre-excitation syndrome (Wolff–Parkinson–White syndrome) may be equal to hemodynamic cardiac arrest and, rarely

(< 0.6% incidence), lead to sudden cardiac death. A deadly danger is a VT, which can result not only in unconsciousness because of the heart's hemodynamic dysfunction but also in an athlete's sudden cardiac death. A feature of all sports HRMs is that they can detect arrhythmia during training, which is the most important aspect. It is advisable for their morphology (supraventricular or ventricular) to be determined upon their occurrence. In practice, the use of digital devices for VT detection has lagged far behind their use for detecting AF, mostly because VT discriminators still require improvement. A sudden increase in pulse rate detected by a digital device is suggestive of possible paroxysmal tachycardias; however, most electrical and PPG HRMs are not able to discern the origins of tachyarrhythmia. Moreover, digital devices using ECGs need to be activated through an active process, which might not be possible to perform in non-tolerated VT cases. Electrocardiography patches, which provide continuous recording with good quality records, are a specific exception in this respect; however, these are not typical sports HRM medical devices. Future developments in wearable technologies may be expected to help diagnose symptomatic VTs, thereby aiding in clinical decision making.

1.4.2 Muscle oxygen saturation

Physiological quantification of how muscles respond to physical exercise is gaining interest in elite-level athletes to improve their overall performance. In the past, athletes have relied upon measurements, such as blood lactate concentration, HR, or maximum oxygen uptake (VO_{2max}) to assess the intensity at which they should be exerting themselves. While quantification of these parameters has helped craft athlete-specific workout regimens to improve performance, these measurements are indicative of systemic changes in the body, with no detailed information about the working muscle groups.

Muscle oxygen saturation, which refers to the amount of oxygen in the blood of muscles, is a measurement that has emerged as a useful parameter to help athletes optimize their performance. The technology behind SmO_2 monitors was developed several decades ago; however, it remains an emerging area for wearable device fabrication in scientific literature today.

1.4.3 Sleep quality detection

Sleep quality and duration (Fig.10) is an important measure of health and is known to directly affect the performance and recovery of an athlete. Wearable devices have been developed to evaluate sleep quality and have focused on monitoring body movement patterns as a measure of sleep restfulness. Examples of wearable devices currently in the market which monitor, and track sleep quality are the Fitbit sensors, Jawbone UP, Misfit Shine, Komodo AIO Smart Sleeve, Polar watches, and WHOOP band.

Studies certificated that and higher resting HR and lower HRV were associated with an increase in percentage of time spent in a slow wave sleep. The data suggested that when the physiological restorative demand was higher, the percentage of time in slow wave sleep was increased to ensure recovery. The study demonstrated that monitoring sleep using devices like the WHOOP band enabled the implementation of sleep hygiene strategies to promote adequate slow wave sleep when the body needed physiological restoration.

Various studies have shown that a lack of sleep lowered athletic performance, worsened lung function, decreased the time to fatigue, increased injury risk, and increased lactic acid production thereby increasing the likelihood of post-workout muscle fatigue and soreness.

Figure 10. Sleep quality detection.

1.5 Market of wearable sensors

The market gives an idea of what the forecast is for wearable tech in all industries. It can show signs of what trends will arise soon. The big two industries are consumer and defense, hence larger investments are required for them. Figure 11 shows how big these two are in relation to others. IDTech mentioned different waves of wearable technology advancement. The first stage is established wearable sensors such as hearing aids, headset, Global Positioning Systems (GPS), cameras, thermistors, etc. These are wearables that have long been used in different industries and have been able to evolve. The second phase is made-wearables. These are micro-electro-mechanical sensors (MEMS) that have been developed for wearables as technology has advanced and are influenced by the impact of smart phones being used daily, such as GPS or inertial measuring unit (composed of accelerometer, gyroscope, and magnetometer) sensors. This has helped fitness tracking wearables revolve around these sensors exclusively. The third phase is the future phase; these are made for wearables, which use advances in research to make better use out of sensors, thus improvements are made in flexibility, motion, and smart textiles. This is where future investments will be heavy, and even though they may not be commercial yet, it is projected to "experience huge growth". Market research shows how fitness and lifestyle products will grow the most for this sector, but wearable technology advancing in multiple industries should not be neglected [6].

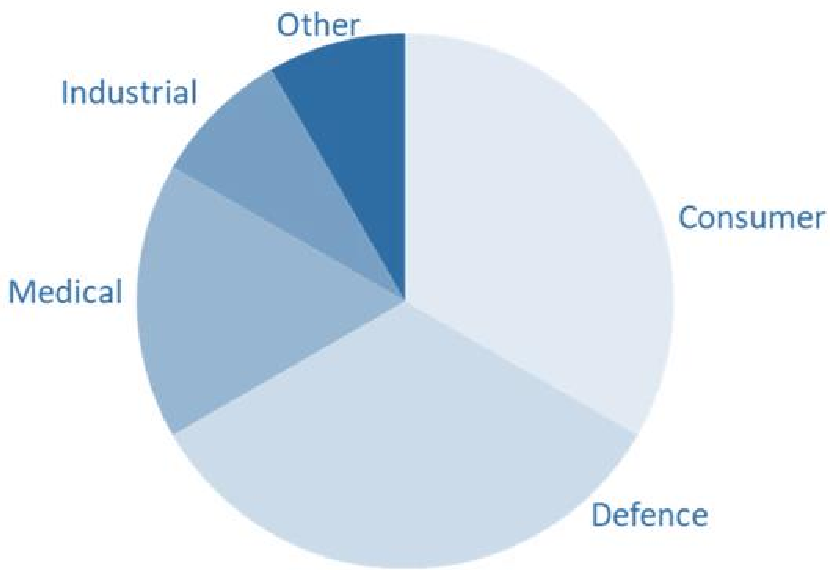


Figure 11. Wearable technology market share [6].

2 Systematic research

The present scoping review investigated the commercial wearable devices acquiring cardiac signals that were/are used in the sport research field.

The aim was to define the trends in wearable and portable devices usage and to identify their application to the sport field.

The literature search and method reporting performed here followed the PRISMA extension for scoping reviews (PRISMA-ScR) [7].

2.1 Literature search strategy

A systematic literature search was conducted on two electronic bibliographic databases: PubMed and Scopus. The roots “athlet” and “sport” were used to search for studies in the sport field. The roots “sensor” and “device” accompanied by the adjectives “wearable” were used to search for studies on wearable monitoring systems. The keyword “heart rate” and the root “electrocardio” were used to search for studies on cardiac signals. The search terms were organized into three concepts:

1. athlet*, sport*;
2. wearable, sensor*, device*;
3. heart rate, electrocardio*.

Terms within the first and third concepts were combined with the Boolean operator “OR”, within the second concept the term “wearable” were combined with the Boolean operator “AND” with the terms “sensor*” and “device” that were combined between them with the Boolean operator “OR”. Then, concepts were combined with the Boolean operator “AND”.

“Title” and “Abstract” were used as limits for the search field, English as limit to filter language, “2014” as maximum limit to filter publication years.

2.2 Selection of studies

Obtained documents were imported into the Zotero reference management system for duplicate removal. Eligibility criteria for title, abstract, and full-text screening and selection were:

1. studies focusing on commercially available wearable devices able to acquire cardiac signals, namely, ECG and HR;

2. studies proposing wearable devices used during sport practice;
3. studies considering populations of athletes, recruited without limits on sport level, from healthy lifestyle subjects to professional athletes.

Documents for which the full text was not available were excluded.

2.3 Data charting and synthesis

A excel table was jointly developed to classify all wearable sensors in sport.

Each device was described in terms of types (wristwatch receiver, smartwatch, smartphone, etc), area of application (chest, wrist, etc), mode of detection (PPG, ECG, etc), cardiac sensor (ECG and/or HR), ECG viewing/remarks (YES or NO), target user (athletes, professional athletes, amateurs, healthy lifestyle, coach, doctor) and signal output format. Specification of wearable devices were retrieved from technical and user manuals or in the manufacturer website.

2.4 Results

Overall, 579 studies were identified in the bibliographic databases. Of these, 92 were duplicates and 3 were withdrawn from publication, so 484 were left for further analysis. After title, abstract and full-text screening based on eligibility criteria, 18 studies were selected. Figure 12 depicts the entire process of the systematic literature search study selection and classification. The selected studies consisted of 17 journal papers and 1 conference proceeding. Their classification provided a table of wearable sensors used in sport.

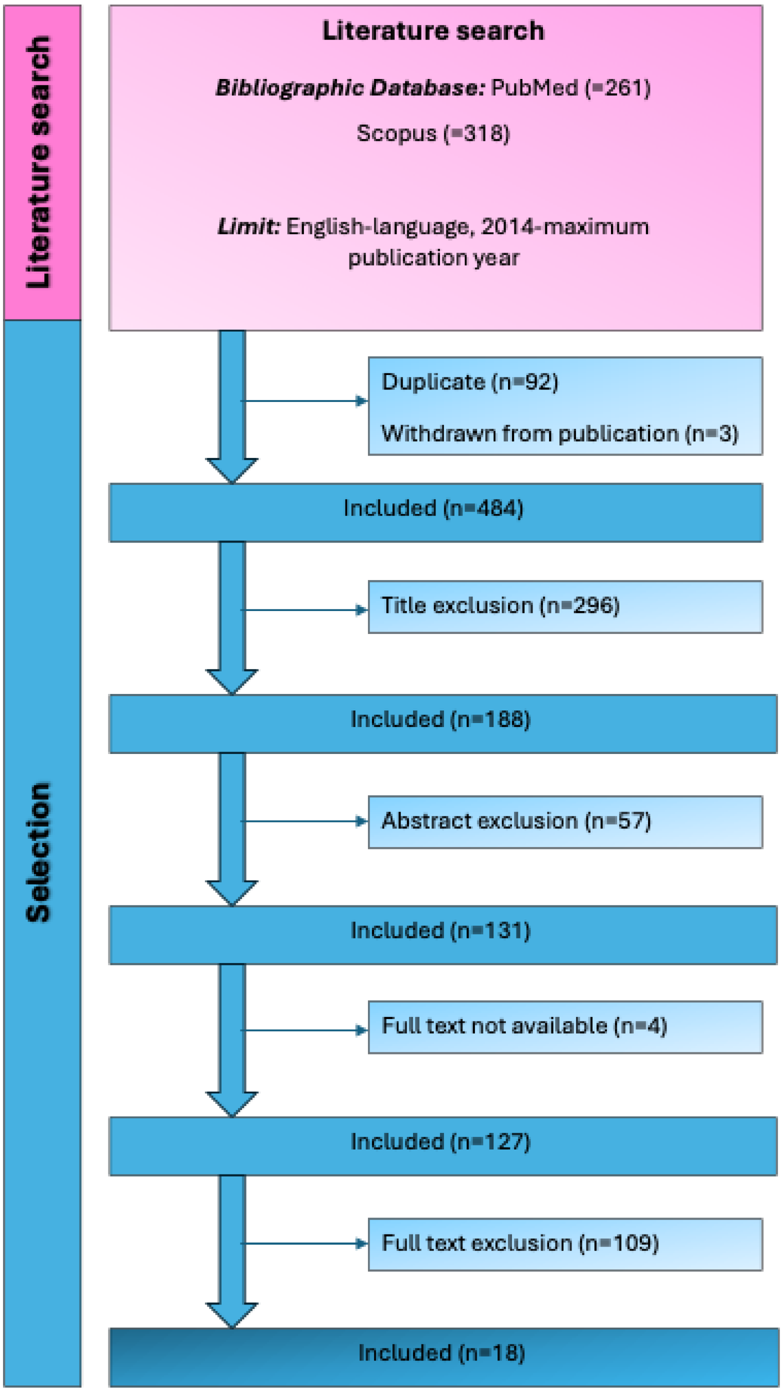


Figure 12. Flowchart of systematic literature search study selection.

2.5 Discussion

In the last few decades, the use of wearable devices that allow real-time acquisition of vital parameters has increased significantly. The purpose of this study was to investigate the commercial wearable devices acquiring cardiac signals, ECG and HR used in sport.

After the literature search and review, 18 studies were included. A systematic literature search was conducted based on the generic terms in the search string without a specific name of device or sport.

Table 1. Commercial wearable devices characterized by type, area of application, mode of detection, cardiac sensor, ECG viewing/remarks, recommended as usable and trustworthy for, signal output format. Information not available is reported as "/".

DEVICE	TYPE	AREA OF APPLICATION	MODE OF DETECTION	CARDIAC SENSOR	ECG VIEWING/ REMARKS	RECOMMENTED AS USABLE AND TRUSTWORTHY FOR:	SIGNAL OUTPUT FORMAT
Garmin Forerunner 910XT [1]	Wristwatch receiver	Chest strap with ECG device 2 E and monitor/transmitter	E-T HR	HR	NO	PA, AM, HL	.csv, .tcx
Polar V800 [1] [4]	Wristwatch receiver	Chest strap with 2 E and a monitor/transmitter	E-T HR (RR interval)	HR and HRV	NO	PA, AM, HL	.csv, .tcx
Polar Vantage V [1] [18]	Wristwatch receiver	Chest strap with 2 E and monitor/transmitter + PPG in wristwatch	E-T and PPG-T HR only	HR	NO	PA, AM, HL	.csv, .tcx
Garmin Fenix 5 wristwatch [1] [3] [4] [18]	Smartwatch	Wrist (option: + chest strap, HRM)	PPG-T HR	HR	NO	AM, HL	.csv, .tcx
Jabra Elite Sport earbuds [1] [3] [4]	Smartphone	Ears	PPG	HR	NO	AM, HL	.csv (only via app)
Motiv ring [1] [4]	Smartphone	Ring on finger	PPG	NO	NO	HL	.csv, .json
Preventicus Heartbeats [1]	Smartphone mApp camera	Fingertip	PPG	HR	NO	N	.csv
Cardiio Rhythm [1]	Smartphone mApp	Fingertip or video facial detection	PPG	HR	NO	N	.csv, .json
MOOV HR [1]	Smartphone mApp with headphone in ear (active training)	Strap with PPG sensor on forehead sweatband (for most activities) or swim cap	PPG	HR	NO	AM, HL (works underwater)	.csv

Table 1. Cont.

DEVICE	TYPE	AREA OF APPLICATION	MODE OF DETECTION	CARDIAC SENSOR	ECG VIEWING/ REMARKS	RECOMMENTED AS USABLE AND TRUSTWORTHY FOR:	SIGNAL OUTPUT FORMAT
Apple Watch [1]	Smartwatch	Wrist-finger	ECG and PPG-T HR	2 E, 1 L ECG	YES (On smartwatch and smartphone)	HL	/
KardiaMobile 6L [1] [4]	Handheld	Fingertips ± leg or chest	ECG	2 or 3 E; 1 L or 6 L ECG	YES (On smartphone, tablet, or PC)	N	.atc,.edf, .pdf (for ECG)
Wellue AI ECG Monitor [1]	ECG recorder	Chest strap or ECG electrodes for connecting with the ECG recorder	ECG	1-L ECG	YES (On tablet or PC)	N	.csv, .pdf
Frontier X2 [1]	Strap with ECG device	Chest strap with ECG device	ECG	1 L ECG	YES (On smartwatch smartphone, tablet, or PC)	PA, AM, HL (Ideal for extreme intensity sports, recommended in water)	.csv
QARDIO MD [1]	Smartphone mAPP	Chest strap with 4 electrodes	ECG	4 E, 3 L	YES (On PC)	Currently clinical use only	.csv, .pdf
Life Signal Biosensor Patch [1]	Patch	Chest, self-adhesive	ECG	4 E; 2 L ECG	YES (ECG on PC in-device, 5-day continuous measurement. Wireless near real-time telemetry and cloud)	Medical device, single use only, CE and FDA validation. Recommended for athletes with suspected arrhythmia during extreme exercises (e.g., competitions)	.csv, .pdf

Table 1. Cont.

DEVICE	TYPE	AREA OF APPLICATION	MODE OF DETECTION	CARDIAC SENSOR	ECG VIEWING/ REMARKS	RECOMMENTED AS USABLE AND TRUSTWORTHY FOR:	SIGNAL OUTPUT FORMAT
Nuubo System-Shirt-Based [1]	Recorder connected to shirt	Strap vest (shirt) on chest with electrodes	ECG	4 E 2 L ECG	YES (Up to 30 days continuous recording, ECG on PC)	PA, AM, HL	.csv, .pdf
Lexin Mio [2]	Wristband wearable device	Wrist (option: + chest strap, Polar H10)	PPG	HR	NO	HL (used for walking and running)	.csv
Suunto Spartan Sport Watch [3] [4]	Sport watch	Wrist (option: + chest strap, HRM)	PPG and ECG (chest strap)	HR	NO (HR on watch)	A, HL (only this device was found valid for Mountain Bike)	.tcx, .csv
Scosche Rhythm + [3] [4]	Armband Heart Rate Monitor	Arm	PPG	HR	NO (HR on the receiving device)	A, HL	.csv
Polar H7 Heart Rate Monitor [3] [4]	Heart rate monitor	Chest strap	ECG	HR	NO (HR on the receiving device)	A, HL	.csv (via app)
Polar A360 Fitness Tracker [3]	Fitness Tracker	Wrist (option: + chest strap, HRM)	PPG	HR	NO	HL	.csv (via app)
Polar S810i [4]	Heart rate monitor	Wrist + elastic strap (wrist+chest)	ECG	HR	NO (HR on watch)	A (used for Speed Skating Marathon)	.csv, .hrm
Polar S810 [4]	Heart rate monitor	Wrist + elastic strap (wrist+chest)	ECG	HR	NO (HR on watch)	PA (used for Badminton)	.csv, .hrm
Polar Team Pro sensor [4] [15]	Monitoring system for team	Uses of Polar Pro Sensor (Chest strap)	ECG	HR	NO	A (used for Basketball, Football, Soccer, Volleyball)	.csv, .hrm
Polar H10 chest strap [4] [6] [13]	Chest strap	Chest	ECG	HR, ECG	NO (HR on the receiving device)	A, HL (used for Running, Basketball, Badminton)	.csv, .hrm

Table 1. Cont.

DEVICE	TYPE	AREA OF APPLICATION	MODE OF DETECTION	CARDIAC SENSOR	ECG VIEWING/ REMARKS	RECOMMENTED AS USABLE AND TRUSTWORTHY FOR:	SIGNAL OUTPUT FORMAT
BioHarness 3.0 Zephyr [4]	Health monitoring device	Chest	ECG	HR, ECG	/	A (used for Running, Soccer, Cycling, Basketball, Fitness, Jogging, Tennis, CrossFit, Aerial skills, Zumba)	.csv, .hed, .dat, .txt
Hexoskin shirt [4]	Smart shirt	Strap vest (shirt) on chest	ECG	1-L ECG; HR	YES (HR and ECG on smartphone)	A (used for Climbing)	.csv, .json
Polar T31 Coded band [4]	Chest strap-based device	Chest	ECG	HR	NO (HR on the receiving device)	PA (used for Swimming)	.hrm
Samsung Galaxy Watch 3 [4]	Smartwatch	Wrist	PPG	HR	NO (HR on watch)	A (used for High intensity workout)	.csv, .tcx, .pdf
Garmin Forerunner 305 [4]	GPS Sports Watch	Wrist, chest	ECG	HR	NO (HR on watch)	A (used for Aerobic activity)	.csv, .tcx
Apple Watch I [4] [11]	Smartwatch	Wrist	PPG	HR	NO (HR on watch)	A	.csv, .xml., .pdf (only some cases)
Apple Watch III [4]	Smartwatch	Wrist	PPG	HR	NO (HR on watch)	A	.csv , .xml, .pdf (only same cases)
Fitbit Blaze [4]	Fitness Tracker	Wrist	PPG	HR	NO (HR on watch)	A	.csv
Fitbit Charge 3 [4]	Fitness Tracker	Wrist	PPG	HR	NO (HR on watch)	A	.csv

Table 1. Cont.

DEVICE	TYPE	AREA OF APPLICATION	MODE OF DETECTION	CARDIAC SENSOR	ECG VIEWING/ REMARKS	RECOMMENTED AS USABLE AND TRUSTWORTHY FOR:	SIGNAL OUTPUT FORMAT
Fitbit Ionic [4]	Smartwatch	Wrist	PPG	HR	NO (HR on watch)	A	.csv (via app)
Garmin Forerunner 235 [4]	GPS Sports Watch	Wrist (option: + chest strap, HRM)	PPG	HR	NO (HR on watch)	A	.csv, .tcx
Garmin Venu Sq [4]	Smartwatch	Wrist	PPG	HR	NO (HR on watch)	A	.csv, .tcx
Garmin Vivosmart HR [4]	Fitness Tracker	Wrist	PPG	HR	NO (HR on watch)	A	.csv, .tcx
Adidas Smart sports bra [4]	Smart Sports Bra	Chest	HR sensing fabric	HR	NO	A	.csv (via app)
PulseOn [4]	Heart Rate Monitor	Wrist	ECG and PPG	HR, ECG	NO (HR on the receiving device)	D	.csv (via app)
Kardia AliveCor [4]	ECG recorder	Fingertip	Dry electrode	HR, ECG	YES (HR and ECG on smartphone)	A, D	.edf, .pdf (for ECG)
Polar OH1 [4] [13]	Heart Rate Sensor	Forearm	PPG	HR	NO (HR on the receiving device)	A	.csv, .hrm
Polar Pro sensor [4]	Heart Rate Sensor	Chest	ECG	HR	NO (HR on the receiving device)	A, C	.csv, .hrm
Polar Vantage M [4]	GPS Sports Watch	Wrist	PPG	HR	NO (HR on watch)	A	.csv, .hrm
Polar Vantage V2 [4]	GPS Sports Watch	Wrist	PPG	HR	NO (HR on watch)	A	.tcx, .csv, .hrm

Table 1. Cont.

DEVICE	TYPE	AREA OF APPLICATION	MODE OF DETECTION	CARDIAC SENSOR	ECG VIEWING/ REMARKS	RECOMMENTED AS USABLE AND TRUSTWORTHY FOR:	SIGNAL OUTPUT FORMAT
Polar Ignite sport watch [4]	Sports Watch	Wrist	PPG	HR	NO (HR on watch)	A	.csv, .hrm
Berlei sports bra [4]	Sports Bra	Chest	ECG	HR	/	A	/
Sensoria fitness sports bra + HRM [4]	Smart Sports Bra	Chest	ECG	HR	NO (HR on smartphone)	A	.csv (via app)
TomTom Spark 3 [4]	GPS Sports Watch	Wrist	PPG	HR	NO (HR on watch)	A	.tcx
TomTom Spark3 Cardio [4]	GPS Sports Watch	Wrist	PPG	HR	NO (HR on watch)	A	.tcx
Omrom M6 Comfort [4]	Blood pressure monitor	Upper arm	Oscillometric method (blood pressure meaurement)	HR	NO	HL	.csv (via app)
Microsoft Band 2 [5]	Fitness Tracker	Wrist	PPG	HR	NO (real time analysis)	HL	.csv (via app)
Huawei Watch [5]	Smartwatch	Wrist	PPG	HR	NO (HR data in real time)	HL	.csv
Google Nexus 6P [5]	Smartphone	Fingertip	PPG	HR	NO	HL	.csv, .xml, .json (it depends on the app used)

Table 1. Cont.

DEVICE	TYPE	AREA OF APPLICATION	MODE OF DETECTION	CARDIAC SENSOR	ECG VIEWING/ REMARKS	RECOMMENTED AS USABLE AND TRUSTWORTHY FOR:	SIGNAL OUTPUT FORMAT
BioStamp nPoint® sensor [6]	FDA 510(k) cleared, electrode-based, wearable, medical grade ECG sensor, with high sampling capabilities	Chest	ECG	HR	NO (HR data in real time)	PA (used for Squash)	.csv, .json
E-skin ECG [7]	ECG monitoring system	Chest (5 E + data recorder)	ECG	3-L ECG	YES (On PC)	HL (used for Full marathon)	.csv, .json
Fitbit Charge 2 [8]	Fitness Tracker	Wrist	PPG (continuous light-emitting diode (LED) lighting)	HR	NO	Low or moderate exercise intensities	.csv
K-Sport-Shirt [9]	Smart shirt	Shirt on chest	ECG	HR, ECG	YES (On PC)	A, HL	.csv, .json (in some cases)
Basis Peak [10] [17]	Activity tracker	Wrist (above the wrist bone)	PPG	HR	NO	Activities like: Cycling, Walking, Jogging, Running, Resisted arm raises, Resisted lunges, and Isometric plank.	.csv

Table 1. Cont.

DEVICE	TYPE	AREA OF APPLICATION	MODE OF DETECTION	CARDIAC SENSOR	ECG VIEWING/ REMARKS	RECOMMENTED AS USABLE AND TRUSTWORTHY FOR:	SIGNAL OUTPUT FORMAT
Fitbit Charge HR [10] [17]	Activity tracker	Wrist (above the wrist bone, and when exercising, at least two fingers width above)	PPG	HR	NO	Activities like: Cycling, Walking, Jogging, Running, Resisted arm raises, Resisted lunges, and Isometric plank.	.csv
Huawei Watch GT 2 [11]	Smartwatch	Wrist	PPG	HR, ECG	NO	Physical activities	.csv (via app)
Fitbit Sense [11]	Smartwatch	Wrist	ECG and PPG	HR, ECG	YES	Physical activities	.csv, .tcx (only for some datas)
Polar M400 [12]	Gps Sports Watch	Wrist + chest strap (Polar H7)	ECG (of the Polar H7)	HR	NO	A (used for Speed Skating)	.csv, .tcx, .hrm
Polar M600 [13]	Smartwatch	Wrist	PPG	HR	NO	A (used for front Crawl swim training)	.csv, .tcx, .hrm
Dash Pro [14]	In-ear devices	Ears	PPG	HR	NO	HL (used for Cycling)	.csv, .json
Cosinuss°One [14]	In-ear devices	Ears	PPG	HR	NO	HL (used for Cycling)	.csv, .json
Whoop Strap 2.0 [16]	Wrist HR monitor	Wrist	PPG	HR and HRV	NO (HR data in real time in the Whoop's web portal and HRV measured by the Whoop's software)	PA (used for Golf)	.csv (via app)

Table 1. Cont.

DEVICE	TYPE	AREA OF APPLICATION	MODE OF DETECTION	CARDIAC SENSOR	ECG VIEWING/ REMARKS	RECOMMENTED AS USABLE AND TRUSTWORTHY FOR:	SIGNAL OUTPUT FORMAT
Scosche Rhythm [17]	Wearable tracker	Forearm	PPG	HR	NO	HL (Used for Walking and Running)	.csv (via app)
Mio Alpha [17]	Wearable tracker	Wrist (above the wrist bone and preferably higher when utilising the HR monitor, especially with a small wrist)	PPG	HR	NO	HL (Used for Walking and Running)	.csv (via app)
Microsoft Band [17]	Wearable tracker	Wrist (can be worn with the face either on the inside or on top of the wrist)	PPG	HR	NO	HL (Used for Walking and Running)	.csv
TomTom Runner Cardio [17]	Wearable tracker	Wrist (on the wrist area, away from the wrist bone)	PPG	HR	NO	HL (Used for Walking and Running)	.tcx, .csv
Apple Watch IV [18]	Wrist-worn wearable	Wrist	ECG and PPG	ECG, HR	YES	HL (used for Walking, Running at different velocities and intermittent sprints)	.csv, .xml, .pdf (via app)
Fitbit Versa [18]	Wrist-worn wearable	Wrist	PPG	HR	NO	HL (used for Walking, Running at different velocities and intermittent sprints)	.csv

AM amateur athletes, A athletes, C coach, D doctors, E electrode(s), ECG electrocardiogram, E-T electrical techniques, HL healthy lifestyle, HR heart rate, L lead(s), mApp mobile application, N not applicable, P professional athletes, PPG photoplethysmography, PPG-T PPG techniques.

In the present review, only devices satisfying the eligibility criteria were considered and also only devices with all information. Wristbands (41/73, 56,2% in this study) are becoming increasingly popular and investigated, in particular smart watches, which are fashion commodities offering purposes beyond visual appeal that in many cases provide users with a plethora of health-related data. The user's choice of which device to pick also depends on activity type.

Sensor placement depends on sport, athletic movement or external factors, such as presence of possible concussions/contacts. Further different sports of application and different types of users define the design of wearable and portable devices and the components needed. Some devices embed other sensors or exploit the ones embedded in the receiving device, usually a smartphone. Other components usually are breathing sensors to derive respiration rate; accelerometers and gyroscopes to derive body orientation, activity, steps, cadence, calories burned and sleep data; altimeters to derive floors climbed; and positioning systems based on satellites to derive distance covered and speed [3].

The devices included in this study mainly utilize two different types of technology to measure HR, photoplethysmography (PPG) and electrocardiography (ECG). Both technologies have been around for decades and have been important innovations for biosensors, fitness trackers, and wearable technology. Both technologies have been investigated to determine their validity and reliability during exercise. While ECG technology continues to out-perform PPG technology, the rapid rise in popularity of PPG devices warrants a more in-depth look at the current state of validity, possible advantages or disadvantages, and appropriate use-cases for each technology [10].

Countless ECG-based HRM devices have been developed. In these devices, the data are obtained from two electrodes that exhibit a voltage difference and allow the recording of HR and/or single-lead ECGs (e.g., Frontier X2). With three electrodes, a three- to six-lead ECG (KardiaMobile 6L) can be obtained. These electrodes can be in a chest strap (Garmin Forerunner 910XT), in a handheld device (KardiaMobile 6L), or at any point on the body where a potential difference can be recorded (Life Signal Biosensor Patch) [8].

Among the best overall Sports Watch are Garmin Fenix 5 and Suunto Spartan Sport Watch. The first watch offers highly accurate GPS tracking, heart rate monitoring, and various sport modes, which make them suitable for triathletes and professional runners. The Fenix 5 stands out for its rugged design and extra features like oxygen saturation measurement and offline maps. Also, Suunto Spartan Sport Watch is known for its accuracy in challenging conditions, making it great for mountain and trail athletes [25, 26].

A chest strap is recommended for precise heart rate monitoring, for example Polar H10 Chest Strap. It is one of the most reliable chest straps with highly accurate heart rate readings, even during intense workouts. Also, Scosche Rhythm is good, it is worn on the forearm, it provides accuracy similar to chest straps but with greater comfort. Although chest bands offer greater accuracy in HR monitoring and cost less, wristbands are more desirable, because of their multifunctionality and comfort. In sport, sensor-embedded equipment and smart textiles are also exploited to enable users to have high-quality signals without hindering any movement. In some HRMs, like the LifeSignals Biosensor, athletes can have their data transmitted wirelessly from the biosensor to a secure cloud-based platform with high reliability. Health-care professionals in the athlete's care continuum can then remotely access such data and rapidly make treatment decisions independently of the athlete's actual location. However, it is a device for single use and not suitable for every- day training, although it can play a very important role when an athlete's symptoms occur only with intense and long-term loads (e.g., when participating in semi-marathon, marathon, and ultramarathon competitions) [8].

The best wearables for ECG Monitoring are KardiaMobile 6L and Apple Watch [27].

The KardiaMobile 6L provides clinical-grade ECG measurements, perfect for users monitoring cardiovascular health; it is the only one FDA-cleared. Pilot data have showed adequate diagnostic power in identifying rhythm alterations in athletes and T-waves alternans. This portable device is also able to detect atrial fibrillation, bradycardia, tachycardia and normal heart rhythm. Monitoring for heightened risk of atrial fibrillation seems needed amongst endurance athletes. Most others, on the other hand, estimate the user's maximum HR based on actual HR zone, i.e., a set range of heart beats per minute. Many runners and other athletes are using HR zones to measure and increase their cardiovascular strength and improve their level of fitness [3].

Starting with Series IV, Apple Watches offer ECG capabilities, which is useful for tracking irregular heart rhythms. The diagnostic accuracy of derived data is dependent on the type of the device in use and on the algorithm update, with a sensibility ranging from 88% to 100% and specificity from 81.9% to 99.20%, provided that physical activity negatively affects its reliability.

The commercially sold Hexoskin shirt (Carré Technologies Inc., San Francisco, CA, United States) is one of the most lightweight and cost-effective physiological telemetry devices. Studies supported the validity and reliability of the Hexoskin wearable body metrics telemetry shirt in measuring HR during moderate and vigorous intensities [28].

The innovative devices are: Motiv Ring, Jabra Elite Sport Earbuds and Sensoria Fitness Sports Bra + HRM. The first one is a smart ring that tracks heart rate, steps, and sleep discreetly, making it a good alternative for those who prefer not to wear a traditional watch.

Jabra Elite Sport Earbuds are earbuds track heart rate and are designed to be worn during exercise, combining audio entertainment with fitness tracking.

The last one is smart sports bra that combines comfort with heart rate monitoring, which can be particularly appealing for female athletes [29].

Of note, some devices were found to be discontinued and one recalled, namely, Fitbit Ionic, whose battery could overheat, posing a burn hazard to consumers. The devices still in production can be connected to another system via a specific application to display the data obtained during acquisition. Some wrist devices present a monitor that allows one to check data in real time [3].

The potential for devices that do not yet exist on the market is now limited by the lack of suitable materials (breathable, flexible and stretchable materials, such as super- flexible wood) as well as the limitations imposed by the laws of physics and engineering. Wearable devices are designed to be worn on different body locations for noninvasive sensing of an individual's parameters without interrupting or restricting the user's movements. Market research forecasts significant growth in the sport and fitness industry and heavy future investment in terms of industrial research, with the aim of improving sensors in terms of flexibility, motion, and the use of smart textiles [8].

3 Wearable sensors of interest

Nowadays there are many wearable devices, but they are not all the same. For this study, all signal acquisitions were done with 5 wearable devices. In particular, the devices used are KardiaMobile 6L, Polar M400 + Polar H7, Garmin Forerunner 245, BioHarness 3.0 Zephyr and Frontier X2.

3.1 Kardia AliveCor

Kardia devices have some characteristics:

- ◊ The largest number of FDA-approved determinations

Kardia devices can detect more arrhythmias than any other device. Rather than simply reporting "low heart rate" or "high heart rate," they detect what's happening to heart. It is the best solution, second only to having a cardiologist.

- ◊ Unmatched clinical validation

Kardia devices are the most clinically validated personal ECGs in the world, meaning they have more research and clinical studies supporting their technology than any other device (over 150 peer-reviewed articles).

- ◊ Portable and convenient

Kardia devices are small enough to fit in pocket or bag and can even be clipped to the back of the phone. However, as easy and convenient as it is to carry them, it's not needed to use them 24/7. Simply grab KardiaMobile when there is a symptom and start recording the ECG right away.

- ◊ Convenient

Kardia devices cost less than half of some wearables, which can cost more than €350. KardiaMobile single lead and KardiaMobile 6L represent a much more convenient way to take care of heart [30,31].

There are two types of Kardia devices: KardiaMobile and KardiaMobile 6L, shown in Fig.13. The major differeces between them are summarized in Table2.

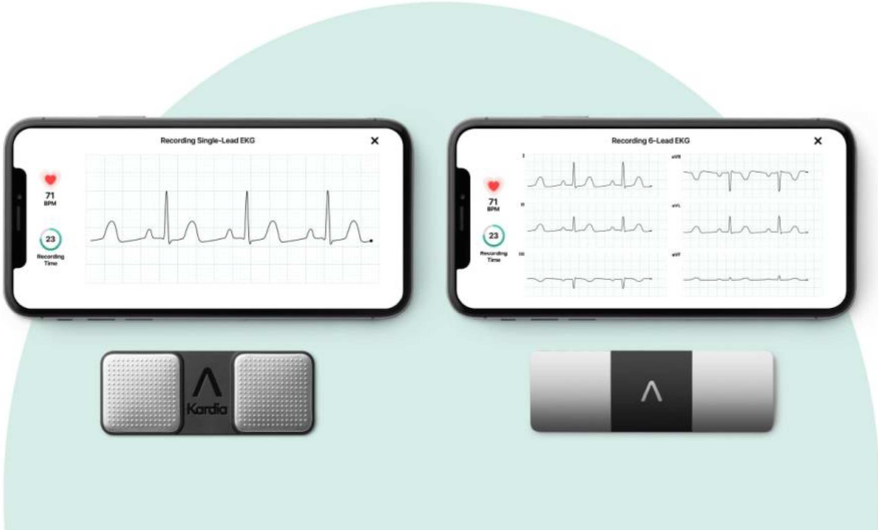


Figure 13. KardiaMobile and KardiaMobile 6L.

Table 2. Differences between KardiaMobile and KardiaMobile 6L.

	Kardia Mobile	**Kardia Mobile 6L**
ECG LEADS	1 lead (D1)	6 leads (D1,D2,D3,Avl, avf, avr) 1 lead (D1)
CONTACT POINTS	Fingers	Fingers and/or lower leg (knee or ankle)
REGISTRATION TIME	From 30 seconds to 5 minutes, settable	From 30 seconds to 5 minutes, settable
DATA TRANSMISSION	Ultrasound	Bluetooth low energy
DISTANCE FROM THE PHONE	Within 10cm	Up to 1 meter
DRUMS	CR2016	CR2016 Small screwdriver needed to change it
		

3.1.1 KardiaMobile

KardiaMobile is a smart device that can record a medical-grade electrocardiogram (ECG) directly to your smartphone. ECGs measure the electrical activity of the heart and are used in hospitals to detect irregularities in the heart rate or rhythm that may indicate a heart condition, such as atrial fibrillation (AFib). KardiaMobile records a single-lead ECG, which provides reliable information about heart health. KardiaMobile can detect the most common arrhythmias, including AFib, bradycardia, tachycardia, premature ventricular contractions (PVCs), sinus rhythm with wide QRS, and sinus rhythm with supraventricular ectopy (SVE) in just 30 seconds.

3.1.2 KardiaMobile 6L

KardiaMobile 6L is the only FDA-approved 6-lead personal ECG in the world. Six leads equal 6 times the cardiac data, giving the most detailed view of the heart that could be get outside of a hospital. KardiaMobile 6L is a 3-electrode personal ECG device that records ECG and bluetooth wirelessly transmits the data to smartphone or tablet. It contains two electrodes on the top surface (Fig.14), for use with the left and right hands, and one on the bottom surface (Fig.14), for use with the bare skin of the left leg. It is powered by a replaceable battery located under the bottom electrode. All the specific characteristics of the device are reported in Table 3 [32, 33].

KardiaMobile 6L is capable of recording two ECG types:

◊ A Single-Lead ECG: provides a single view of the heart’s electrical activity (ECG taken with top two electrodes)

◊ A Six-Lead ECG: provides six views of the heart’s electrical activity (ECG taken using all three electrodes).

KardiaMobile 6L can detect the most common arrhythmias, including atrial fibrillation (AFib), bradycardia, tachycardia, sinus rhythm with premature ventricular contractions (PVCs), sinus rhythm with wide QRS and sinus rhythm with supraventricular ectopy (EVS).

Table 3. Specific characteristics of KardiaMobile 6L.

Dimensions	9.0 cm x 3.0 cm x 0.72 cm Three 3 cm x 3 cm stainless steel electrodes
Weight	24 grams
ECG Characteristics	Six Lead ECG 10 mV peak-to-peak input dynamic range 30 second to 5 minute recording duration 300 samples per second sampling rate 14 bit resolution
Power	3V CR2016 coin cell battery (included) 200 hours operational time 12 months typical use
Connectivity	Bluetooth Low Energy technology 1m wireless range
Requirements	Compatible Apple or Android device Kardia App

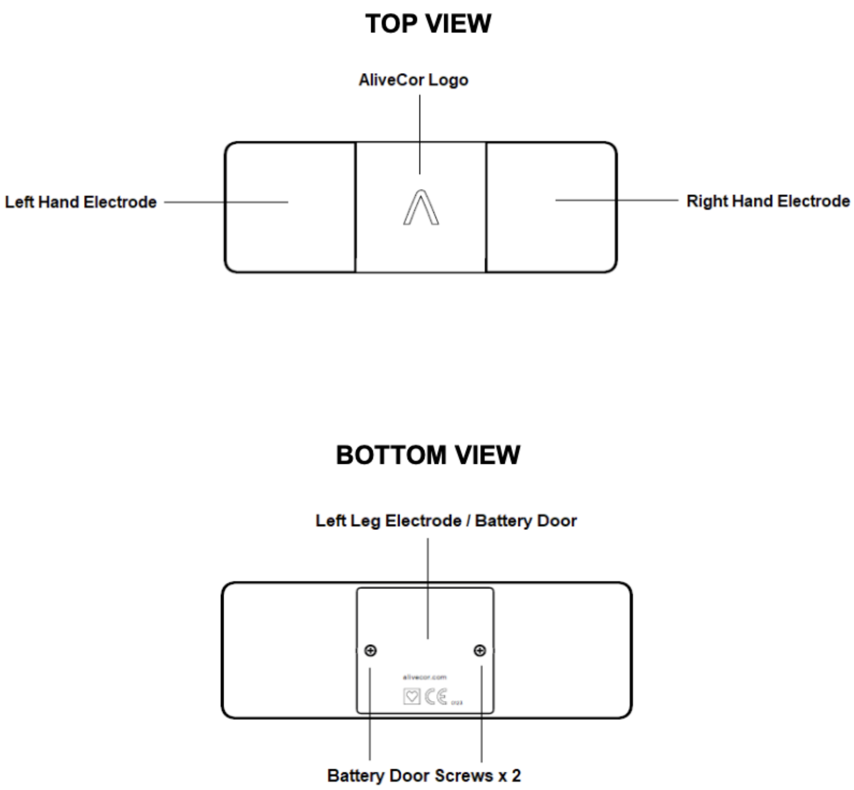


Figure 14. Top and bottom view of KardiaMobile 6L.

KardiaMobile 6L transmits the ECG data to the Kardia mobile app. The ECG is then processed by AliveCor's Instant Analysis algorithms. The app will display your full Single-Lead or Six-Lead ECG and the Instant Analysis result with description.

Representative Instant Analysis results, descriptions, and additional information are displayed in the Table 4. Note that Instant Analysis noted as "Advanced Determinations" will be provided only if you have access to them, such as through a KardiaCare membership.

Table 4. Representative Instant Analysis results.

Instant Analysis	Description	Additional Information
Normal Sinus Rhythm	ECG shows sinus rhythm and no rhythm or rate abnormalities are detected in the ECG; heart beat was 50-100 beats per minute (bpm)	Kardia does not check for heart attack. If the subject believes he/she is having a medical emergency, calls emergency services. Do not change medication without talking to the doctor.
Atrial Fibrillation	ECG shows signs of atrial fibrillation.	Kardia does not check for heart attack. If the subject believes he/she is having a medical emergency, calls emergency services. Do not change medication without talking to the doctor.
Bradycardia	The heart rate is less than 50 beats per minute, which is slower than normal for most people. Atrial fibrillation is not detected.	Kardia does not check for heart attack. If the subject believes he/she is having a medical emergency, calls emergency services. Do not change medication without talking to the doctor.

Table 4. Cont.

Instant Analysis	Description	Additional Information
Tachycardia	The heart rate is faster than 100 beats per minute. This can be normal with stress or physical activity. Atrial fibrillation is not detected.	Kardia does not check for heart attack. If the subject believes he/she is having a medical emergency, calls emergency services. Do not change medication without talking to the doctor.
Sinus Rhythm with Supraventricular Ectopy (Advanced Determination)	ECG shows sinus rhythm with occasional supraventricular ectopy (SVE). This can be present in healthy adults and in adults with heart conditions.	Kardia does not check for heart attack. If the subject believes he/she is having a medical emergency, calls emergency services. Do not change medication without talking to the doctor.
Sinus Rhythm with Wide QRS (Advanced Determination)	ECG shows sinus rhythm with Wide QRS. This can be present in healthy adults and in adults with heart conditions.	Kardia does not check for heart attack. If the subject believes he/she is having a medical emergency, calls emergency services. Do not change medication without talking to the doctor.
Sinus Rhythm with Premature Ventricular Contractions (Advanced Determination)	ECG shows sinus rhythm with occasional premature ventricular contractions (PVCs). This can be present in healthy adults and in adults with heart conditions.	Kardia does not check for heart attack. If the subject believes he/she is having a medical emergency, calls emergency services. Do not change medication without talking to the doctor.

Table 4. Cont.

Instant Analysis	Description	Additional Information
Too short	ECG recording must be at least 30 seconds to allow Instant Analysis algorithms to perform an analysis.	Re-record the ECG. Try to relax and hold still, rest arms, or move to a quiet location that will allow for a full 30 second recording.
Unclassified	Atrial fibrillation was not detected and ECG does not fall under the algorithmic classifications of Normal, Bradycardia, or Tachycardia. This may be caused by other arrhythmias, unusually fast or slow heart rates, or poor quality recordings.	Kardia does not check for heart attack. If the subject believes he/she is having a medical emergency, calls emergency services. Do not change medication without talking to the doctor.
Unreadable	There is too much interference in this recording. Please re-record the ECG. Try to relax and hold still, rest arms, or move to a quiet location or away from electronics and machinery.	Kardia does not check for heart attack. If the subject believes he/she is having a medical emergency, calls emergency services. Do not change medication without talking to the doctor.

3.2 Polar M400 heart rate monitor and H7 heart rate sensor

A sensor used in data acquisition for training of athletes, including figure skaters, is the Polar M400 heart rate monitor with the H7 heart rate sensor, shown in Figure 15. The battery type of the heart rate monitor is Li-Pol at 190 mAh lasting up to 8 hours with the use of GPS and heart rate sensor. The operating temperature ranges from -10°C to +50°C and has water resistance up to 30 meters. The materials it is made of are: stainless steel, polycarbonate/acrylonitrile butadiene styrene, acrylonitrile butadiene styrene, thermoplastic urethane, polymethyl methacrylate and silicone. The H7 heart rate sensor is a chest strap with a CR2025 battery. The operating temperature and water resistance are the same as the heart rate monitor. The band consists of a polyamide transmitter and elastic (38% polyamide, 29% polyurethane, 20% elastane and 13% polyester).

Figure 15. M400 heart rate monitor and H7 heart rate sensor.

The Polar M400 heart rate monitor has numerous functions to monitor athletes' workouts: heart rate, speed zones, GPS, workload, percentage of fat burned and training benefits. It also features a built-in accelerometer that can detect movements 24/7. There is also the possibility to connect the device to the Polar Flow app or Flow web service to immediately view all training data, as it is shown in Figure 16.

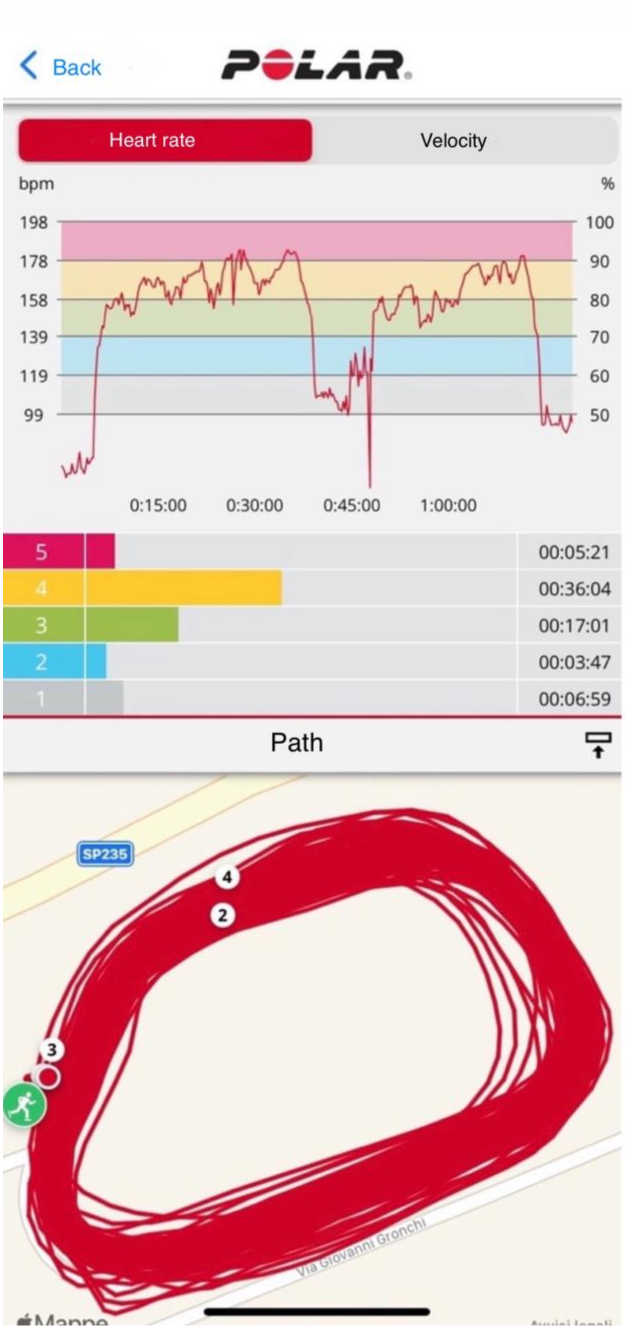


Figure 16. Viewing a workout via Polar Flow app.

Heart rate data offers a detailed description of physical condition and allows to understand the body's response to sporting activity. The information received is useful in refining training plans, for example, regularity and intensity, and allows to achieve maximum performance. The workout is divided into five heart rate zones, based on the percentage of the maximum heart rate as shown in Table 5. With heart rate zones it is possible to easily choose and monitor the intensity of the workout.

Table 5. Heart rate zones, where HRmax=Maximum heart rate (220-age) and HR zones are in beats per minute for a 30-years-old person, whose maximum heart rate is 190 bpm (220-30).

Target zone	**% intensity of HR_{max}**	**Example: HR zones**	**Example of duration**	**Training effect**
MAXIMUM 	90–100%	171-190 bpm	Less than 5 minutes	Benefits: Maximum or near maximum effort for breathing and muscles. Perception: very tiring for breathing and muscles. Recommended: for experienced and fit athletes. Only short intervals, usually final preparation for short events.
DIFFICULT 	80–90%	152-172 bpm	2-10 minutes	Benefits: Increased ability for high-speed endurance. Perception: muscle fatigue and heavy breathing. Recommended: for expert athletes during training sessions of varying duration throughout the year. It becomes more important in the run-up to the races.

Table 5. Cont.

Target zone	% intensity of HR_{max}	Example: HR zones	Example of duration	Training effect
INTERMEDIATE 	70–80%	133-152 bpm	10–40 minutes	Benefits: Improves overall training pace, makes moderate-intensity efforts more bearable, and improves efficiency. Perception: constant, controlled, rapid breathing. Recommended: for athletes close to competitions or looking for improved performance.
LIGHT 	60–70%	114-133 bpm	40-80 minutes	Benefits: Improves overall fitness, recovery and metabolism. Perception: pleasant and bearable, low muscular and cardiovascular effort. Recommended: For everyone for extended training sessions during core training periods and for recovery training during the racing season.

Table 5. Cont.

Target zone	% intensity of HR_{max}	Example: HR zones	Example of duration	Training effect
VERY LIGHT 	50–60%	104-114 bpm	20–40 minutes	Benefits: facilitates warm-up and cool-down and allows recovery. Perception: very bearable, little effort. Recommended: for recovery and cool-down exercises in general.

Training in heart rate zone 1 is done at very low intensity. The basic principle of training is that performance increases during recovery after a training stimulus, not during the training itself. Speed up the recovery process with very low intensity workouts.

Training in heart rate zone 2 builds endurance capacity, an essential part of any training program. Training sessions in this zone are light and aerobic. Long-term training in this light zone causes an effective expenditure of energy. Progress requires consistency.

Aerobic power increases in heart rate zone 3. The intensity of the training is higher than in sport zones 1 and 2, however the training remains mainly aerobic. Training in zone 3 may, for example, include interval phases followed by recovery phases. Training within this zone is particularly effective for improving the efficiency of blood circulation in the heart and skeletal muscles.

If the goal is to compete at a competitive level, you need to train in heart rate zones 4 and 5. In these areas, training is anaerobic, with repetitions of a maximum of 10 minutes. It is very important to observe sufficient recovery periods between intervals. The training scheme in zones 4 and 5 is designed to produce competitive performance. Polar heart rate zones can be customized using a laboratory-measured max HR value or by performing a field test to measure the value. With these zones you can easily choose and monitor training intensities and follow Polar programs based on different heart rate zones. Speed and pace zones are a new way to guide training efficiency during sessions. They work like heart rate zones, but the intensity of your workout is based on speed or pace rather than heart rate. They provide a simple way to select and monitor training intensity based on speed or pace and allow to mix training with different intensities for optimal effects. It is possible to use the predefined zones or define own ones.

With built-in GPS, the M400 tracks speed, distance, altitude and route. There is the possibility to view the route on the map in the Flow app or website after session. A-GPS data tells Polar device the predicted positions of GPS satellites.

Training load is an assessment of the intensity of a single training session. The workload calculation is based on the consumption of important energy sources (carbohydrates and proteins) during training. The training load function allows to compare various types of training sessions. For example, there is the opportunity to compare the load of a long, low-intensity skating session to a short, high-intensity running session. To allow for a more precise comparison between sessions, the workload is converted into a rough estimate of the recovery needed.

The percentage of fat burned function allows to calculate an estimate of calories burned during a workout, expressed as a percentage of total calories burned. This estimate is important for weight control. During training, energy comes from two sources: carbohydrates and fats. The percentage of fat burned varies based on the intensity of the training. The principle is that, at high training intensities, the percentage of fat burned of total energy expenditure is lower than at lower intensities. So, for example, a 40-minute brisk walk at a low intensity burns more fat calories than a 30-minute jog at a higher training intensity.

The training benefit function provides feedback on each training session, allowing to better understand the benefits obtained from the physical activity performed. It is possible to view feedback in the Flow app and Flow web service. To get feedback, the subject must have trained for at least 10 minutes in total in your heart rate zones. Training benefit feedback is based on heart rate zones and takes into account the time spent and calories burned in each zone [34].

3.3 Garmin Forerunner 245

A sensor used in data acquisition for training of athletes is the Garmin Forerunner 245 + HRM-Dual Garmin shown in Figure 17. The battery type of the heart rate monitor is rechargeable, built-in lithium-ion battery lasting up to 24 hours with the use of GPS and heart rate sensor (up to 7 days in smartwatch mode). The operating temperature ranges from -20°C to +60°C and has water resistance up to 50 meters.

The materials it is made of are different and are reported in Table 6.

Table 6. Different materials of the device.

STRAP MATERIAL	Silicone
LENS MATERIAL	Corning® Gorilla® glass 3
BEZEL MATERIAL	Fiber-reinforced polymer

The weight of device is 38.5 gr with 1.2" (30.4 mm) diameter and 240x240 pixel of resolution.

The HRM-Dual Garmin heart rate sensor is a chest strap with a CR2032 battery, 3V. Its battery life is up to 3.5 years with the usage of 1 hour for day. This premium heart rate strap transmits real-time heart rate data over ANT+® connectivity and Bluetooth® Low Energy technology, giving more options to train indoors, outdoors or even online. The operating temperature ranges from 0°C to +40°C and water resistance up to 1 meter.

Figure 17. Garmin Forerunner 245 and HRM-Dual chest strap.

The Garmin Forerunner 245 has numerous functions to monitor athletes' workouts: heart rate, speed zones, GPS, training status, VO_2 max, recovery time, training load, predicted race time, performance condition, saturation of oxygen and body battery. It also features a built-in accelerometer that can detect movements 24/7. You can also connect your device to the Garmin Connect app or Garmin connect web service to immediately view your training data, as you can see in Figure 18.

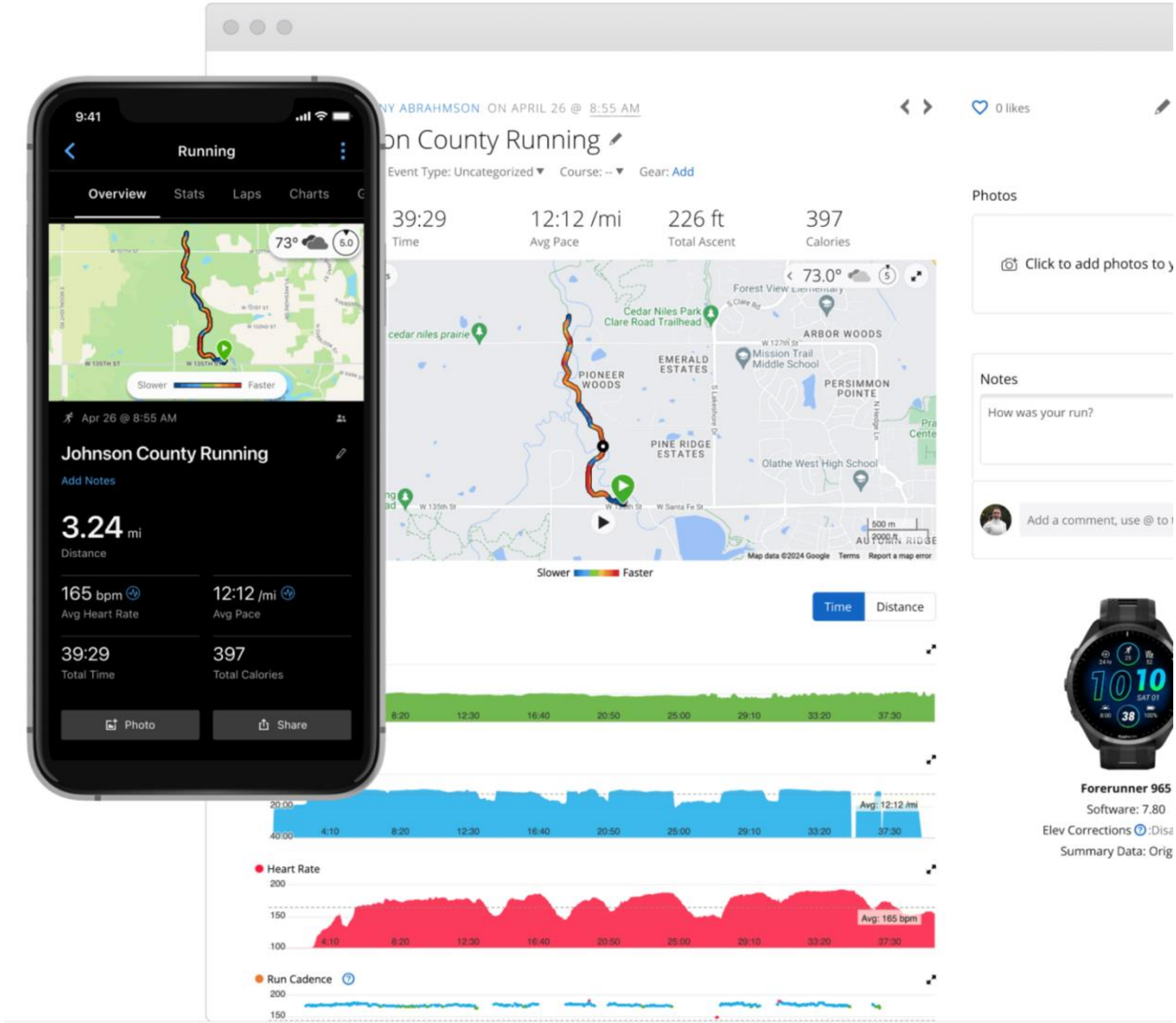


Figure 18. Viewing a workout via Polar Flow app.

Heart rate data are very important because it offers a detailed description of physical condition and allows to understand the body's response to sporting activity. The information received is useful in refining training plans, for example, regularity and intensity, and allows to achieve maximum performance. The workout is divided into five heart rate zones, based on the percentage of the maximum heart rate as shown in Table 7. With heart rate zones it is possible to easily choose and monitor the intensity of the workout [35, 36, 37].

Table 7. Heart Rate Zone Calculation

Zone	% of Maximum Heart Rate	Perceived Exertion	Benefits
1	50-60%	Relaxed, easy pace, rhythmic breathing	Beginning-level aerobic training, reduces stress
2	60-70%	Comfortable pace, slightly deeper breathing, conversation possible	Basic cardiovascular training, good recovery pace
3	70-80%	Moderate pace, more difficult to hold conversation	Improved aerobic capacity, optimal cardiovascular training
4	80-90%	Fast pace and a bit uncomfortable, breathing forceful	Improved anaerobic capacity and threshold, improved speed
5	90-100%	Sprinting pace, unsustainable for long period of time, labored breathing	Anaerobic and muscular endurance, increased power

3.3.1 Performance measurements

These performance measurements are estimates that can help to track and understand training activities and race performances of the subject. The measurements require a few activities using wrist-based heart rate or a compatible chest heart rate monitor.

These estimates are provided and supported by Firstbeat (NOTE: The estimates may seem inaccurate at first. The device requires to complete a few activities to learn about the performance of the athlete). Garmin Forerunner 245 can analyze some performance measurements: training status, VO_2 max, recovery time, training load, predicted race time, performance condition, saturation of oxygen and body battery.

Training status

Training status (Fig.19) shows how the training affects the fitness and performance of the athlete. The training status is based on changes to the training load and VO_2 max. over an extended time period.

Figure 19. Training status.

VO_2 max.

VO2 max. is the maximum volume of oxygen (in milliliters) that a person can consume per minute per kilogram of body weight at maximum performance. The device adjusts the VO_2 max. values for heat and altitude, such as when the subject is acclimating to high heat environments or high altitude.

Recovery time

The recovery time displays how much time remains before the athlete is fully recovered and ready for the next hard workout.

Training load

Training load is the sum of all excess post-exercise oxygen consumption (EPOC) over the last 7 days. EPOC is an estimate of how much energy it takes for the body to recover after exercise.

Predicted race times

The device uses the training history, the VO_2 max. estimate, and published data sources to provide a target race time based on the current state of fitness of the subject. This projection also presumes the individual has completed the proper training for the race.

Performance condition

The performance condition is a real-time assessment after 6 to 20 minutes of activity. It can be added as a data field so subject can view his/her performance condition during the rest of the activity. It compares the real-time condition of the athlete to his/her average fitness level.

Saturation of oxygen

The Forerunner device has a wrist-based pulse oximeter to gauge the saturation of oxygen in the blood. Knowing the oxygen saturation can be valuable in understanding overall health and help determine how the body is adapting to altitude. The device gauges blood oxygen level by shining light into the skin and checking how much light is absorbed. This is referred to as SpO_2.

On the device, the pulse oximeter readings appear as an SpO_2 percentage. On Garmin Connect™ account, it is possible to view additional details about pulse oximeter readings, including trends over multiple days.

Body Battery

The device analyzes the heart rate variability, stress level, sleep quality, and activity data to determine overall Body Battery™ level (Fig.20). Like a gas gauge on a car, it indicates the amount of available reserve energy. The Body Battery level range is from 0 to 100%, where 0 to 25% is low reserve energy, 26 to 50% is medium reserve energy, 51 to 75% is high reserve energy, and 76 to 100% is very high reserve energy.

There is the possibility to sync the device with Garmin Connect™ account to view the most up-to-date Body Battery level, long-term trends, and additional details [36].

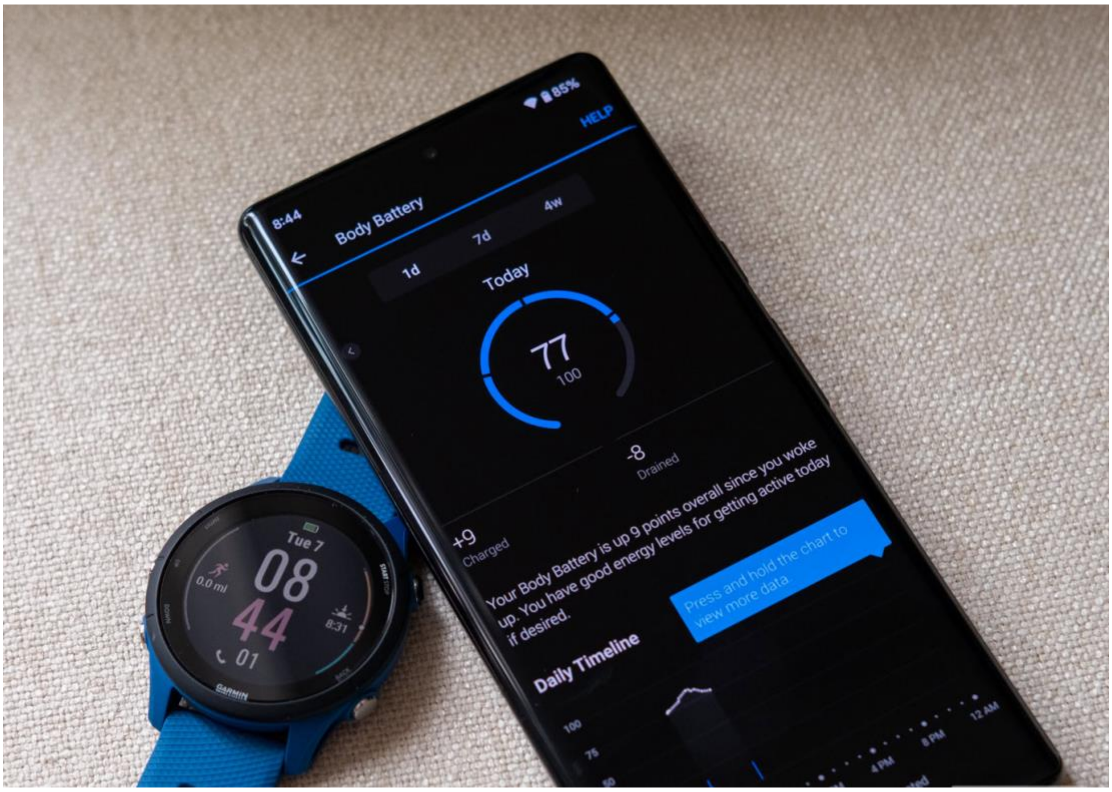


Figure 20. Body battery of Garmin Forerunner 245.

3.4 BioHarness 3.0 Zephyr

The BIOPAC BioHarness™ Physiology Monitoring System, shown in Fig.21, is a state-of-the-art lightweight portable biological data collection and analysis system [38].

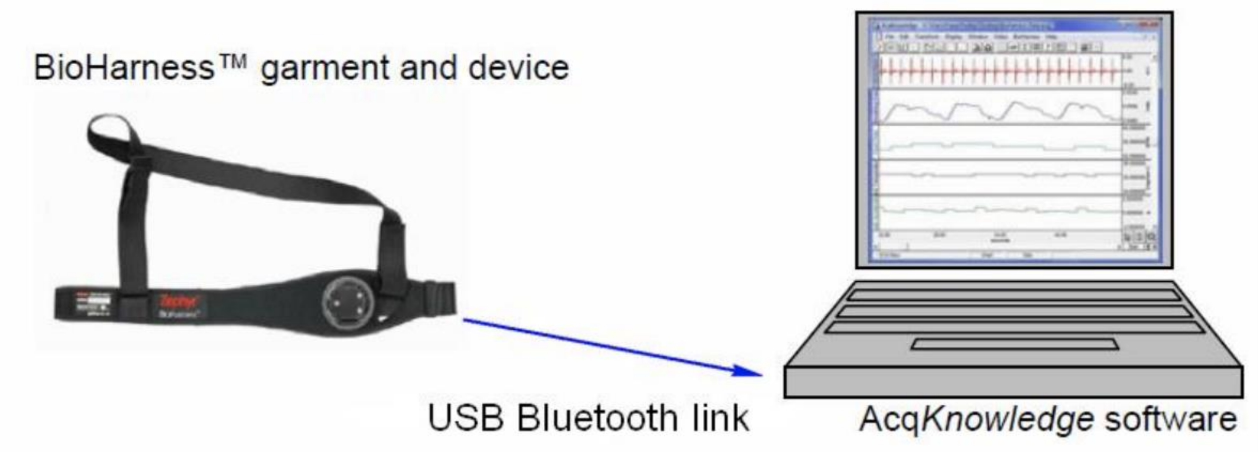


Figure 21. BioHarness 3.0 Zephyr.

It monitors, analyzes and records a variety of physiological parameters. Historical and Logged data can be displayed. The system operates in Bluetooth transmitting mode for live viewing of data. (NOTE In order for Bluetooth to operate with BioHarness, a connection must be established with the computer.)

Live data viewing features include:

- ◊ A variety of selectable waveforms and trend data including: 250 Hz filtered ECG, 18 Hz respiration, 1 Hz for all trend, activity and 3-axis acceleration-based parameters and time-stamped Heart Rate RR values
- ◊ Activity level in vector magnitude units (VMU)
- ◊ Posture – vertical position of device, in degrees
- ◊ Recording of data

The BIOPAC BioHarness™ Physiology Monitoring System includes:

- AcqKnowledge software (it is used to view, record and analyze data with the BioHarness unit) and BioHarness drivers (on installation CD)
- BioHarness™ Garment incorporating Smart Fabric sensors
- BioHarness™ Device
- Docking/charging cradle with USB lead
- BioHarness and AcqKnowledge Guides

3.4.1 BioHarness garment

The BioHarness Garment, illustrated in Fig.22, is composed of 12 elements of different materials, shown in Table 8.

All the specific characteristics of the BioHarness Garment are specificated in Table 9.

Figure 22. BioHarness Garment.

Table 8. Component parts and their materials.

Component Parts	Material
1.Main fastener hook	Steel
2.Main fastener sleeve	----
3.Size adjustment slider	Steel
4.Internal breathing rate sensor	EVA foam
5.ECG sensors	Silver-coated nylon
6.Care label with Size, Serial # and Wash symbols	Nylon
7.Brand label	Polyester
8.Strap main body	Nylon
9.Device receptacle	Polycarbonate
10.Electrical contacts	Stainless steel
11.Tension indicator loop	Nylon
12.Strap (rear)	Elasticized webbing

Table 9. Specific characteristics of BioHarness Garment.

Material	*Elasticized webbing incorporating Smart Fabric sensors*
Width	50mm
Weight	105 grams
Sizes	S-M fits 69-84 cm chest (27”-33”,) M-XL fits 84-104 cm chest (33”-41”)

3.4.2 BioHarness device

The BioHarness Device is the sensor of the BioHarness 3.0 Zephyr and it is possible to see it in Fig.23.

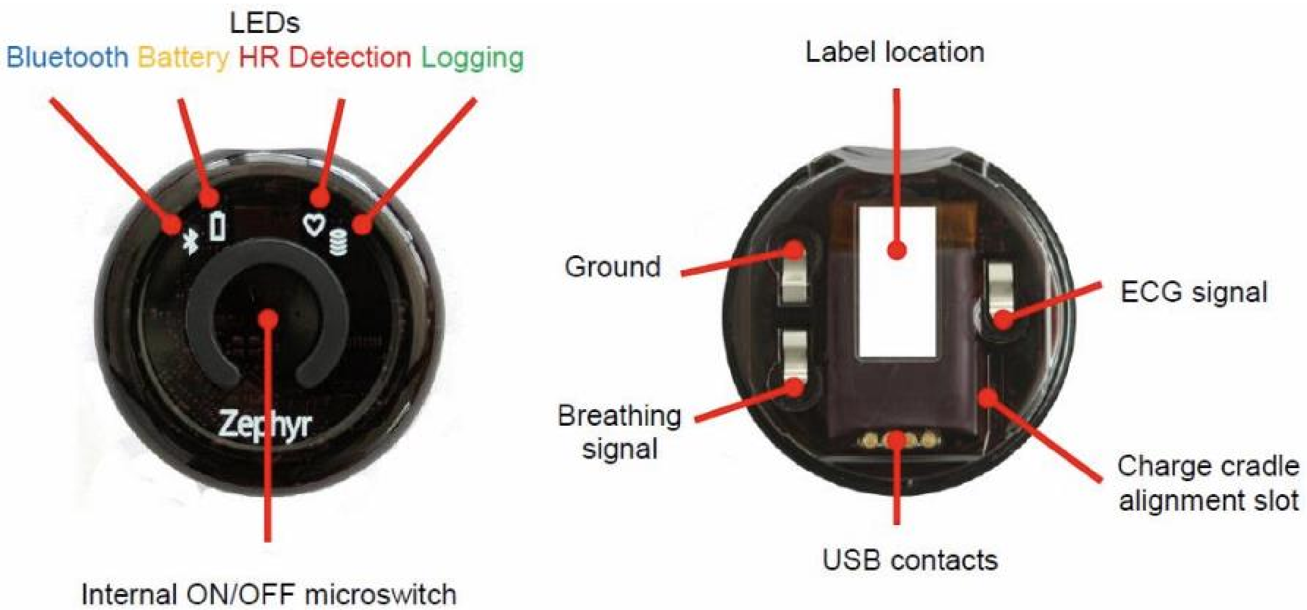


Figure 23. BioHarness Device.

All the specific characteristics of the BioHarness device are specified in Table 10.

Table 10. Specific characteristics of BioHarness Device.

Transmit Range	Up to 10m, environment and antenna dependent
Memory Capacity	~500 hours
Sample Rate	250 Hz Max.
Frequency	Bluetooth 2.4 to 2.835GHz
Battery Life	12-28 hrs (transmitting,) 35 hrs (logging)
Weight	18 grams
Dimensions	28 x 7 mm
Compliance	This device complies with Part 15 of the FCC Rules. Operation is subject to the following: · This device may not cause harmful interference · This device must accept any interference received, including interference that may cause undesired operation.

3.4.3 Signals acquired

The BioHarness 3.0 Zephyr acquired different types of signals:

- Acceleration: High pass 0; Low pass limited to 10.5 Hz and sampled at 18 Hz. The maximum and minimum measured in each second are reported.
- Posture: High pass 0. Based on the accelerometer with a 6.5 Hz low pass filter to limit the noise resulting from movement and provide a stable reading.
- Activity: Requires the magnitude of the AC components of each axis; uses a digital 0.1 Hz high pass filter and a 10.5 Hz lowpass hardware filter. Sampled at 18 Hz and accumulated for 1 second reporting.
- Respiration: Detect breathing rates from 3 BPM to 70 BPM (0.05 Hz to 1.166 Hz).
- ECG: In hardware, the signal is filtered with a high pass filter at 15 Hz and a low pass filter at 78 Hz. The low-end filter cut-off enables heart rate measurement under vigorous activity (high resistance to motion artifact). The sample frequency is 250 Hz.

3.4.4 Data channels

The device has many channels, and each one acquires a specific data signal. In the Table 11, it is possible to see all of them.

Table 11. All channels of the BioHarness 3.0 Zephyr and their data signal.

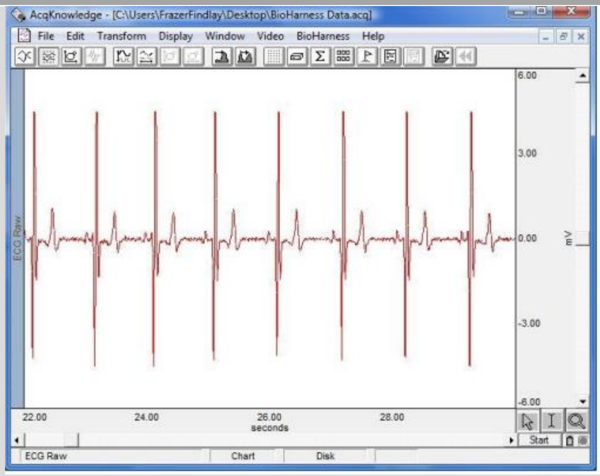
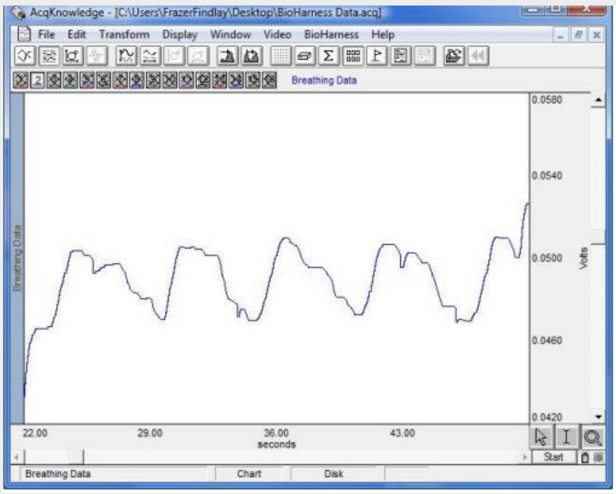
Channel	Data Signal		
CH 1 ECG Raw	Description	Raw, filtered ECG data	
	Data Frequency	250 Hz	
	Units	mV	
CH 2 Breathing Data	Description	Raw bit output of breathing sensor. Unfiltered, unprocessed. Raw breathing sensor output in volts. The variation during breathing action compared to the absolute value is small.	
	Data Frequency	18 Hz (0.056 seconds)	
	Units	Volts	
CH 3 R-R Data	Description	Event driven/Per QRS detection.	

Table 11. Cont.

Channel	Data Signal	
CH 4 Heart Rate	Description	ECG data is filtered and processed to produce this value
	Data Frequency	1 Hz (1.008 Seconds)
	Units	BPM (Beats per minute)
	Min – Max Value	0 to 240
CH 5 Respiration Rate	Description	Respiration rate. It will take 30-45 seconds from start of data processing to stabilize. Respiration rate can be subject to artifacts (peaks and troughs) as the sensor responds to non-breathing related input such as movement of the torso, speech, coughing, etc.
	Data Frequency	1 Hz (1.008 Seconds)
	Units	BPM (breaths per minute)
	Min – Max Value	0 - 70
CH 7 Posture	Description	Degrees off vertical in any orientation. A positive value indicates an anterior (subject lean forward) component, negative a posterior component. See Section 4.4.2 A subject's natural posture may mean an 'upright' position does not generate a value of 0°
	Data Frequency	1 Hz (1.008 Seconds)
	Units	Degrees from vertical
	Min – Max Value	- 90 to + 90
CH 6 Unnavailable	Description	Non-operational placeholder channel

Table 11. Cont.

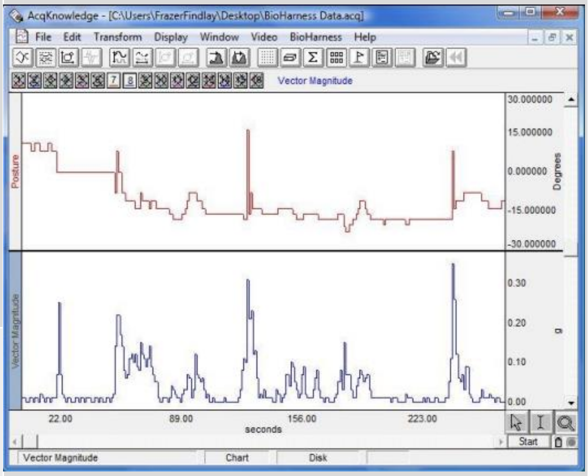
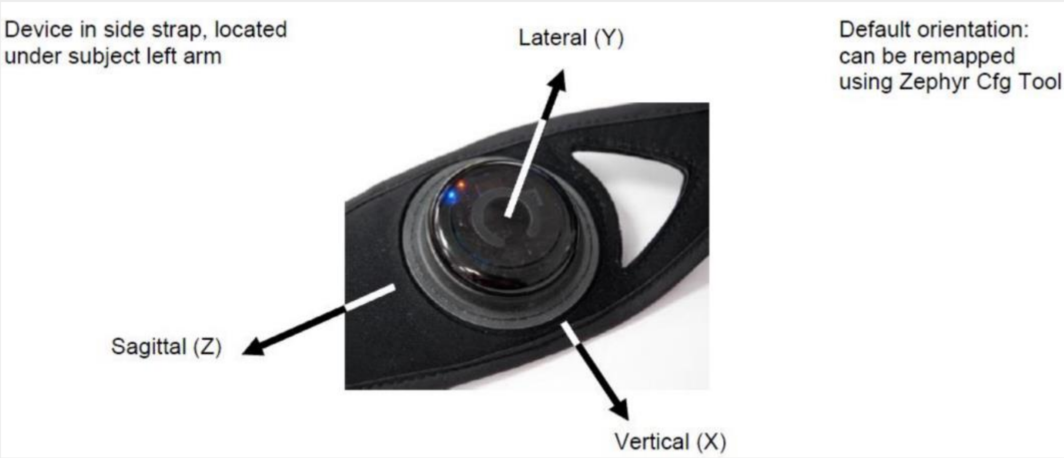
Channel	Data Signal		
CH 8 Vector Magnitude	Description	Average vector magnitude achieved in previous 1 second epoch. To calculate VM Units over longer time period, simply add the required number of 1 second epochs.	
	Data Frequency	1 Hz (1.008 seconds) reporting, 18Hz (0.056 Seconds) sampling Units Vector Magnitude Units (VMU) measured in g seconds	
	Min – Max Value	0 to 5.7	
CH 9 Peak Acceleration	Description	Maximum 3-axis acceleration magnitude achieved during previous 1 second epoch	
	Data Frequency	1 Hz (1.008 seconds) reporting, 18Hz (0.056 Seconds) sampling	
	Units	g (gravitational force)	
	Min – Max Value	0 – 5.7	

Table 11. Cont.

<table>
<tr><th>Channel</th><th colspan="2">Data Signal</th></tr>
<tr><td rowspan="3">CH 10 Breathing Wave Amplitude</td><td>Description</td><td>Average filtered breathing sensor output over previous second. This is indicative of breathing depth.</td></tr>
<tr><td>Data Frequency</td><td>1 Hz (1.008 Seconds)</td></tr>
<tr><td>Units</td><td>Volts</td></tr>
<tr><td>CH 11 X Acceleration Min</td><td colspan="2" rowspan="6">Accelerometer Axis Orientation


Min Description — Minimum is the smallest acceleration value recorded during the previous 1 second epoch. This could be a negative value if there is acceleration in a negative direction, or positive if all accelerations during that period are positive.
Data Frequency sampling — 1 Hz (1.008 seconds) reporting, 18 Hz (0.056 Seconds)
Units — g
Min – Max Value — - 3.3 to + 3.3 in each axis
Peak Description — Peak is the largest acceleration value recorded during the previous 1 second epoch. This could be a negative value if all accelerations are a negative direction, or the largest positive value
Data Frequency — 1 Hz (1.008 Seconds) reporting, 18 Hz (0.056 Seconds) s sampling
Units — g
Min – Max Value — - 3.3 to + 3.3 in each axis</td></tr>
<tr><td>CH 12 X Acceleration Peak</td></tr>
<tr><td>CH 13 Y Acceleration Min</td></tr>
<tr><td>CH 14 Y Acceleration Peak</td></tr>
<tr><td>CH 15 Z Acceleration Min</td></tr>
<tr><td>CH 16 Z Acceleration Peak</td></tr>
</table>

3.5 Frontier X2

The Frontier X2 is a smart heart wearable, which is worn directly over the heart, offers continuous heart monitoring to inform the subject about the health of own heart. This device offers optimized training within pre-established restrictions with real-time vibration alerts. The Frontier X2 is appropriate for all activities, including swimming, because it also delivers precise readings of respiratory rate that allow to evaluate the effort putted out by the athlete.

The Frontier X2 is composed by 2 products, shown in Fig.24:

• Frontier X2 Device
• Chest Strap

The Frontier X2 has numerous metrics to monitor athletes' workouts, some of these related to heart, like heart rate, strain, HRV (Heart Rate Variability) and some related to performance, such as breathing rate, training load, body shock and step cadence. This device, shown in Fig.25 with all its components, also registers 24/7 Continuous ECG for comprehensive heart health insights. It can register ECG during exercise and exports PDF version of ECG data, with the possibility to have live-stream ECG [39, 40].

Figure 24. The box of Frontier X2.

Figure 25. Inside the Frontier X2 device.

All the device specifications are reported in Table 12.

Table 12. Device specifications.

Weight	25 grams
Dimensions	73 mm x 24 mm x 13 mm
Water resistant	Up to 1.5 meters
Battery	1 Lithium Polymer batteries
Connectivity	• Frontier X2 now has Bluetooth 5.0 for 3X speed and greater range. • Frontier X App available for iOS and Android phones, as well as the Apple Watch • Displays Heart Rate on compatible BLE sports watches

With AI-generated cardiac rhythm markers, the Frontier X2 smart heart monitor can detect changes in heart's health and function as it accurately records heart rate throughout exercise and sleep.
With real-time vibration signals, athletes may exercise safely while making sure that heart rate, breathing rate, and cardiac strain are always within the ideal ranges.
The device can recognize cardiac strain and changes in heart rhythm, so the subject can learn more about his/her heart health.
The heart rate can be recorded, streamed live, and safely shared with anybody in the world. The data are property of the user and there is the possibility to share heart rate's data. The Frontier X2 heart monitor can be used while exercising outdoors and inside, including jogging, cycling, rowing, swimming, and going to the gym. The Frontier X2, represented in Fig.26, is three times faster than the Frontier X and is completely waterproof up to 1.5 meters.
Heart rate (HR) can only be recorded by Heart Monitor watches and handheld devices when users are stationary for 30 seconds. When exercising and the heart is working the hardest, there is the necessity to use a gadget that continuously records high-quality overall heart parameters on chest.

Figure 26. Frontier X2.

3.5.1 Features

High Quality ECG

The world's first and only consumer wearable that allows to record high-quality ECG in real-time for up to 24hrs during any activity, as shown in Fig.27. There is the possibility to share Live ECG in real-time with experts, family, or friends, in any moments, even while exercising.

The Frontier X2's patented ECG technology gives the unique ability to record up to 24 hours of highly detailed, accurate data through any activity. It is possible to correlate ECG data with GPS data to gain unprecedented insights into ECG response to pace, elevation, intensity and distance.

Heart Health Metrics

- Accurate Chest-Based Heart Rate: the device tracks accurate chest-based Heart Rate through sleep, rest or exercise and get detailed post-activity insights.
- Heart Rate Variability (HRV): Frontier X2 can get insights into how body manages stress and recovery and by measuring HRV before and after workouts.
- Strain monitoring: 'Strain' measures the amount of oxygen deprivation experienced by the heart. Manage training intensity to avoid high strain on heart for prolonged periods.
- Rhythm Chart: Get a rhythm chart identifying deviations from the norm, with data explaining the duration, frequency, and occasions when these rhythms occurred.

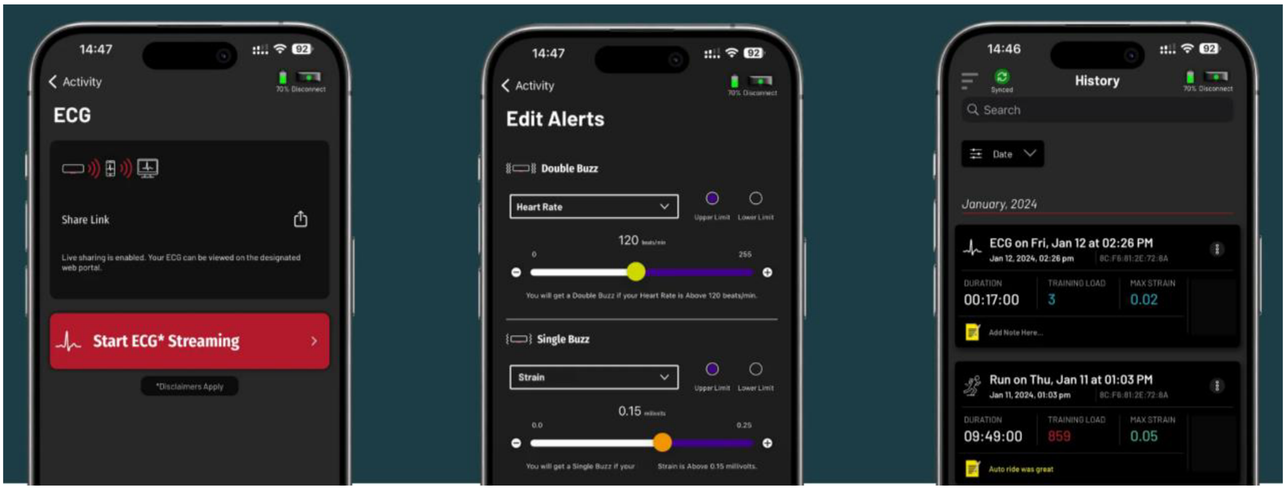


Figure 27. Frontier X2 features.

Heart Health Insights

- Activity Tagging & Health Entries: Frontier X2 allows to capture key events, feelings, or choices in the day to help better understand the response of heart health to those aspects.
- Heart Rate Zone Training: Training in different Heart Rate Zones achieves different goals. Frontier X2 ensures stay within the chosen zone so the goals are achieved most efficiently.

- Monitor progress over time: Analyze the daily, weekly, and monthly progression of all key heart metrics including Heart Rate, Breathing Rate, Strain, and HRV.
- Detailed physiological graphs: Use the dynamic web dashboard to view detailed graphic representations of all the physiological metrics measured by the Frontier X2.
- Heart Rate Zone Insights: Use the dynamic web dashboard to view detailed graphic representations of all the physiological metrics measured by the Frontier X2.
- AI-generated recommendations: Push safely with personalized workout insights and AI-generated recommendations for future workouts.

Exercise and Training

- Monitor 20 types of activities: Track and analyze 20 different types of activities, including running, cycling, meditation, sleep, rest, swimming, trekking etc
- Effortless zone-based training: Set real-time vibration alerts for a range of metrics so the subject can stay within the right workout zone without needing to look at the phone or smartwatch.
- Train without distraction: Use the Frontier X2 without connecting it to the mobile app. Review all physiological metrics without repeated glances at the phone or smartwatch.
- Real-time vibration alerts: Train with confidence knowing the heart is protected. Set custom alerts to give real time feedback when the user is overstraining himself/herself.
- Light, sturdy and durable: The Frontier X2 is very light, but also so durable that no activity is off limits.
- Waterproof: The Frontier X2 is IP67 rated - waterproof and sweatproof up to 1.5 meters. Perfect for swimming.

Performance Insights

- Sustainable Training with Training Load: Get a true estimate of total exertion during any activity. Weekly Training Load goals help ensure that there are improvements in the performance without over-training.
- Prevent injury by monitoring Body Shock: Monitor Body Shock to analyze the impact of running surfaces, gear, form changes or fatigue, helping prevent injuries during high impact activities.
- Step Cadence: Measure the number of steps taken per minute while running to get additional insights into running, walking or hiking performance.

4 A-priori comparison between the 5 devices

The BioHarness 3.0 by Zephyr was used in a great variety of sports to evaluate the health status of athletes based on HR variability and to characterize ECG during the pre-exercise phase, providing reference values for future diagnosis. ECG has also been acquired using a portable device called AliveCor Kardia, which helps the diagnosis of arrhythmias during exercise in athletes. Only the AliveCor Kardia was FDA-cleared, whereas all other devices are not clinically approved and thus cannot be used for cardiac diagnosis. Typically, wearable sensors provide a reduced number of ECG leads, which do not necessarily match with one of the 12 standard ECG leads. Additionally, acquisition settings of these sensors do not match the typically strict protocols followed in the clinical setting. Consequently, they cannot be used for diagnoses: considering that the normal reference values used in clinics are defined considering the standard 12-lead ECG, measured ECG values by wearable sensors should not be considered to evaluate the athlete's health. Validation studies and a recent study on the development of normal reference values for ECG acquired through wearable chest straps in the pre-exercise phase can play a pivotal role in the implementation of wearable devices in clinical practice [3].

Polar M400 GPS (Polar GPS, Polar Electro, Kempele, Finland) watches weigh 56.6 g and are 11.5 mm thick. It can provide Bluetooth Smart connection with mobile phone and sensors, for example Polar H7. GPS sampling rate is 1 Hz per second. Polar Flow web service compatibility and Polar Flow mobile app compatibility with PC Windows XP, Windows 7, Windows 8 or later. Data from M400 GPS watches used in TSSC protocol can be transferred to cloud storage area via Bluetooth [41].

The Garmin Forerunner 245 uses Global Positioning System (GPS) and has a built-in optical sensor to measure wrist HR. This device tracks HR using proprietary algorithms for LED light sampling. Optical-based HR monitors use a series of lights that flash against the skin, illuminating capillaries in the body to detect changes in blood volume. For Garmin, the frequency at which HR is estimated varies and depends on the activity level. Data are automatically saved in the personal Garmin account and made downloadable from the personal page [42].

The Frontier X2 HRM is a set that includes a recording device and a mobile app and web platform to monitor HR and rhythm, which is compatible with third-party devices (smartwatch, smartphone, and/or PC) and connected through Bluetooth Low-Energy. According to the manufacturer, the device is designed for extreme sports (including water sports), and the recorded data can be easily transferred to a mobile device or tablet immediately after a run. The device records a single-lead ECG on a chest strap recorder. Evaluation of the ECG on the "third device" in the sequence should be performed by a physician. There are not studies confirming the reliability of the recordings by the Frontier X2. The device appears to be relatively immune to artifacts from vibration during extreme exercise [8].

4.1 Validation of KardiaMobile 6L

A pilot study was done with the aim to examine and compare the level of similarity between resting 6L and 12L readings in athletes with a view to building evidence for the utility of the 6L-ECG as a practical and accurate clinical tool in athletic populations [43].

4.1.1 Results

The results of this study were relatively high levels of agreement between the mean 6L and 12L measures for QTc and PR interval and QRS duration, with the 6L readings slightly but significantly shorter on average. The largest difference was seen in the QTc intervals (391 ms vs 401 ms, p = 0.003). QRS durations were shorter on average by 3 ms (89 ms vs 92 ms, p = 0.025) and PR intervals were shorter on average by 6 ms (163 ms vs 169 ms, p < 0.001) (Table 13, Fig.28). The QRS axis was normal in 26/30 (87%) of athletes in both 6L and 12L, while the remaining 4/30 (13%) showed evidence of right axis deviation.

Table 13. Average mean differences between 6L and 12L values for ECG measures.

	6L average mean value ± SD	12L average mean value ± SD	Average mean difference (6L – 12L) (negative indicates 6L shorter) ± SD	P value
Heart rate (bpm)	71±14	68±12	3±9	0.067
QT interval (ms)	363±28	381±26	−18 ± 14	<0.0001
QTc interval (ms)	391±24	401±25	−10 ± 18	0.003
QRS duration (ms)	89±7	92±9	−3 ± 7	0.025
PR interval (ms)	163±20	169±22	−6 ± 8	<0.001

Measurements based on mean of 4 cardiologist readings. 6L, 6 lead smartphone electrocardiogram; 12L, 12-lead electrocardiogram; SD, standard deviation; bpm, beats per minute; ms, milliseconds.

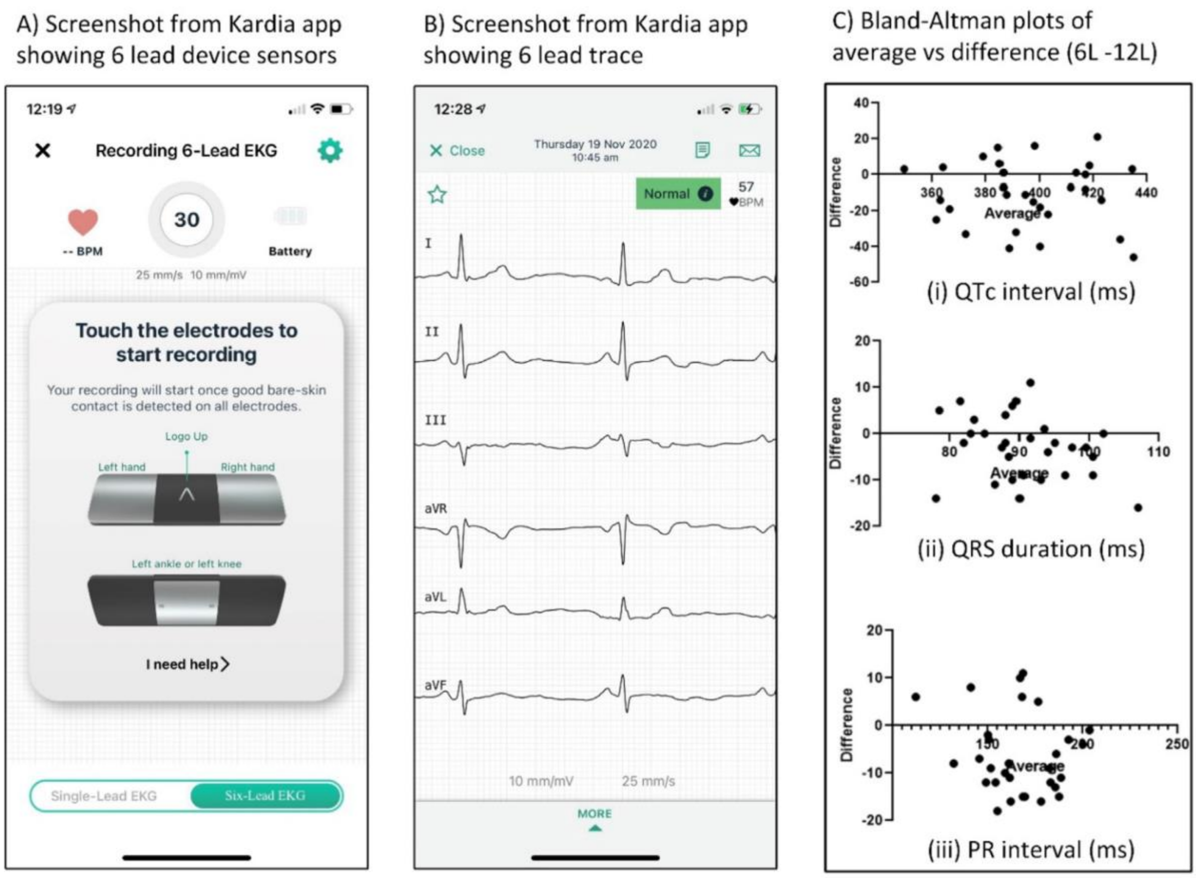


Figure 28. 6 lead smartphone ECG screenshots and Bland-Altman plots [43].

There was complete agreement for all cardiologists for sinus rhythm and the presence of atrial and ventricular ectopics for the 6L and 12L readings. All ECGs showed sinus rhythm. In one of the 30 6L readings, one ventricular ectopic was noted. There were no atrial ectopics in any of the ECGs.

4.1.2 Discussion

The 6L readings had relatively high agreement with the standard 12L. All 6L measures (except heart rate) were slightly shorter on average than 12L, with the largest difference observed in QTc. This small difference is unlikely to have any diagnostic significance (unless close to the diagnostic thresholds, in which case a 12L would likely be undertaken) and is similar to findings comparing the 1L to a 12L. In addition, the results showed smaller mean differences than previous studies comparing the 1L to a 12L in athletes, suggesting the 6L may improve accuracy. The heart rates were slightly higher in the 6L readings, which may be explained by seated compared to lying position and sequential acquisition of ECG readings. The reading with the greatest variation was QT interval, some of which is explained by the heart rate variation. Some of the 6L readings had issues with artefact. This emphasises the need to ensure patients stay very steady during the reading, which may be more challenging if associated with intense exercise. It is known that the accuracy of other wearables in terms of measuring heart rate can vary according to the type of exercise. Therefore, future studies are required to compare the 6L against 12L during high intensity physical activity (e.g. during exercise testing) in addition to resting ECG data. If shown to be accurate during exercise, the 6L may provide more useful diagnostic data than the 1L in this setting.

It is important to clarify that the primary clinical use of the 6L in athletes is somewhere between the 'quietest' environment of screening and the 'noisiest' environment of high intensity exercise. It may be that its greatest utility is 'on the sidelines': to take a reading for an exercise-induced arrhythmia after an athlete has 'left the field' or stopped exercising but is not completely at rest. In this situation, the 6L may be the fastest way to obtain a trace with reasonable (but not perfect) information before a transient arrhythmia has reverted. It can be noted that it is difficult to test the accuracy of the 6L under these exact conditions, mainly because obtaining a 12L as a 'gold standard' under these conditions is problematic.

Larger studies showing higher levels of agreement with 12L and sensitivity for detecting conditions associated with sudden cardiac death would be required to expand the role of 6L beyond an event monitor. If supported by additional data, the 6L is relatively cheap and convenient for both athletes and team doctors. For example, it could also be used as a more accessible 'interim' screening tool for arrhythmias performed more frequently than full cardiac screening in athletes. A full 12L would still be required periodically to assess precordial leads and/or arrhythmias which could have a cardiomyopathy aetiology.

4.2 Validation of Polar H7

A study was done to assess the accuracy of Polar H7 wearable HR monitor under various forms of aerobic exercise conditions [44].

4.2.1 Results

Average differences from the ECG standard were less than 1 bpm for the Polar H7 under all exercise conditions (Table 14). The average differences from the ECG standard were calculated as both relative error (which averages positive and negative differences from the ECG standard) and the absolute value of error, regardless of direction. HR values on the monitor varied from the ECG standard depending on the activity (Table 14). Bland–Altman analysis revealed that monitor has some measurements that did not reflect HR accurately (Fig. 29); however, this variation was not linked to specific HR values, meaning that variability was not influenced by the HR magnitude. Under all conditions combined, when compared with ECG, the Polar chest strap had high agreement with ECG with a Lin's concordance correlation coefficient (r_c) of 0.99 (Fig.29). The Polar H7 Chest Strap performed well during all different aerobic exercise modalities (r_c = 0.99).

Table 14. HR monitor differences from ECG according to activity.

	HR (bpm) Differences from ECG						
	Paired Relative Difference		Paired Absolute Difference		Absolute Percent (%) Difference		Agreement
Activity	Mean	SD	Mean	SD	Mean	SD	r_c
Treadmill	0.4	3.1	1.2	2.9	1.1	2.4	0.99
Bike	0.1	1.9	0.6	1.8	0.6	1.6	0.99
Elliptical (no arms)	0.1	2.0	0.6	1.9	0.6	2.3	0.99
Elliptical (with arms)	0.5	2.7	1.0	2.6	0.9	2.4	0.99
Rest	-0.3	1.0	0.7	0.8	0.8	1.0	0.99

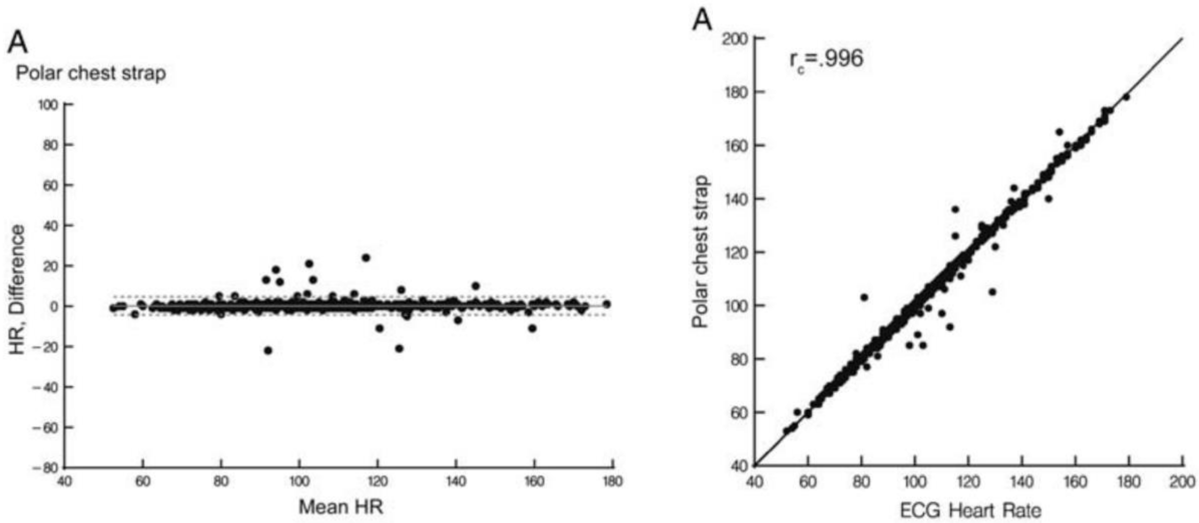


Figure 29. Bland–Altman plots and 95% limits of agreement with electrocardiographically measured HR (at left) and concordance correlation coefficients depicting agreement of device-measured HR with ECG (at right) [44].

4.2.2 Discussion

Chest strap–based HR monitors function much like an ECG, sensing cardiac electrical activity. Several studies confirm the accuracy of most of these HR monitors under conditions of both rest and moderate exercise. Although chest strap–based HR monitors have been favored by elite athletes because of their proven accuracy, they are relatively inconvenient and have not been widely adopted by the public.

It is found that the Polar H7 chest strap containing an electrically based monitor provided accurate measurements, regardless of exercise intensity or modality.

Although that study is the largest of its kind and included nearly 4000 HR measurements, it has limitations. The current study methodology (e.g., visual recording of HR on ECG) may have contributed to some error as compared with a more rigorous approach wherein time stamped raw device data were extracted.

4.3 Validation of Forerunner 245

The objective of the study was to investigate the agreement between HR values, which are estimated by two wearable systems with different designs (i.e., a watch embedding an optical sensor and a single lead ECG chest belt) during an outdoor run session. It is a pilot experiment that allow to assess the wearables in different phases: during the warm-up (characterized by the presence of motion and HR is expected to increase quickly), running (characterized by the presence of motion and HR is expected to be almost constant) and recovery (characterized by absence of relevant movements and HR is expected to decrease quickly). In particular, the training consisted of 6 running phases of 3000 m, 2000 m, 2000 m, 1000 m, 1000 m, and 1000 m with a 120 s rest between each block [42].

4.3.1 Results

Fig. 30 and Fig. 31 show the MAPE and MAE values, respectively, calculated during the warm-up, recovery and running intervals of the 6 experimental phases. Considering all six experimental phases, the warm-up interval shows higher MAPE values (MAPE of 16.7 % ± 5.5 %, expressed as mean± standard deviation) than the recovery (4.4 % ± 1.1 %) and running (1.5 % ± 0.8 %) phases.

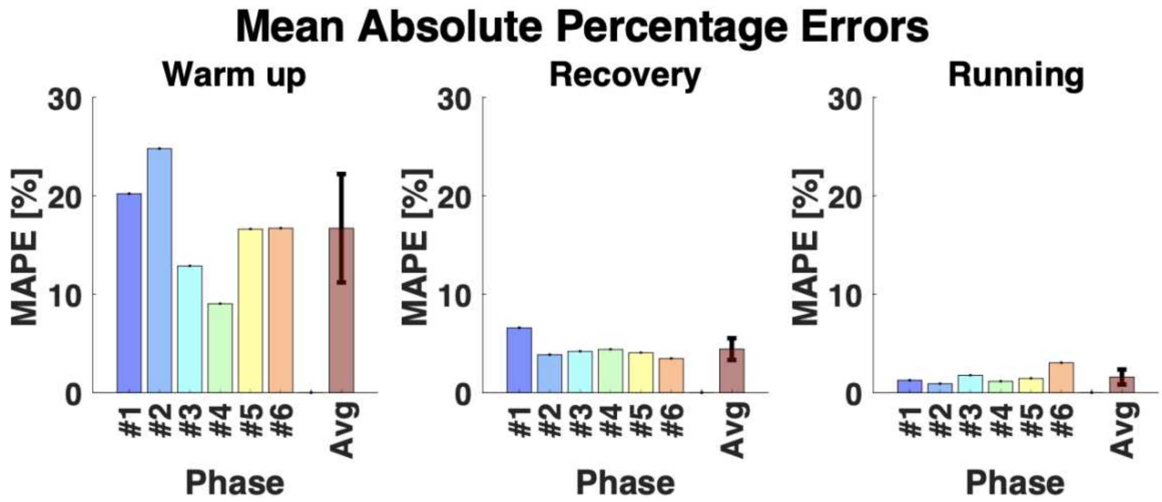


Figure 30. Mean Absolute Percentage Errors (MAPEs) during warm-up, recovery, and running during the six phases and average value. The wishes represent the standard deviation [42].

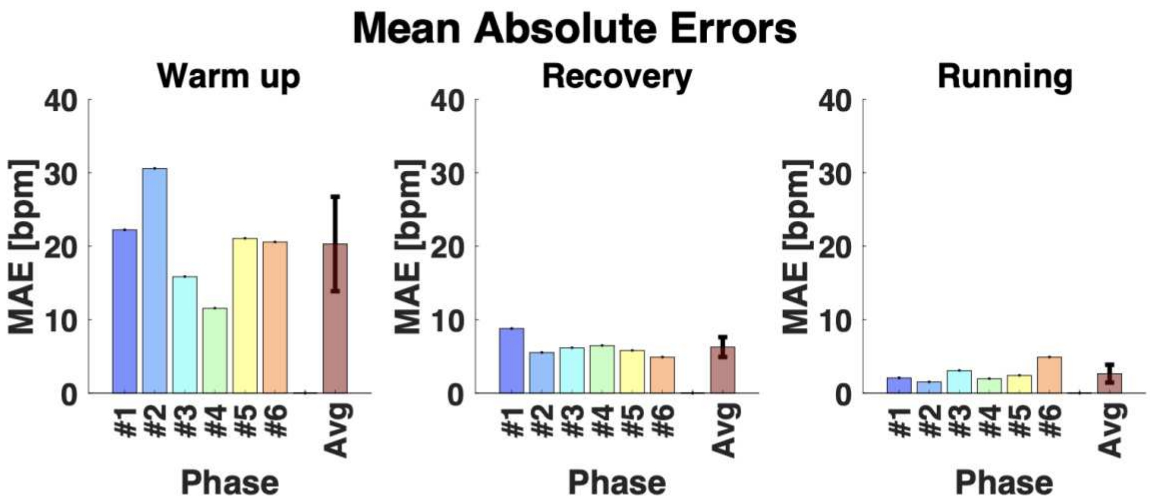


Figure 31. Mean Absolute Errors (MAEs) during warm-up, recovery, and running during the six phases and average value. The wishes represent the standard deviation *[42]*.

In terms of MAE (see Fig. 31), the warm-up phase shows average values close to 20 bpm, less than 7 bpm during recovery, and less than 3 bpm during physical activity, again confirming comparable performance between the instruments in the case of intensive activity and considerable differences in the case of the warm-up phase.

Table 15 reports the performance index results for each exercise phase and during the three conditions. On the warm- up interval, only the 22.6% (on average) of HR estimated by the Optical methods fall within ± 5 bpm the HR estimated by the ECG. This Performance Index rises to 43.9% in the case of recovery and reaches 84.6% in the case of running interval.

Table 15. Performance index.

Phase	Warm-up	Running	Recovery
#1	17.5%	92.5%	30.4%
#2	2.6%	99.0%	54.5%
#3	39.3%	76.2%	31.2%
#4	53.3%	94.9%	61.1%
#5	17.8%	92.7%	38.1%
#6	5.4%	52.3%	48.3%
Avg	**22.6%**	**84.6%**	**43.9%**

4.3.2 Discussion

Results obtained during the three different conditions (warm-up, running, and recovery) show comparable performances between devices during running, with an average MAPE equal to 1.5 % among the six phases. This result demonstrates the good accuracy of the optical-based device in estimating the HR even during intense exercise, with differences on HR in the 85% of cases within the range ± 5 bpm compared to reference. Differently, the higher differences between the instruments were found during the warm-up condition in all the trial phases. At the onset of running exercise, whether the initial session or any session following a rest period, ECG can quickly identify physiological changes through the electrical signals caused by the heart. Optical technology, worn on the wrist, appears less adept at detecting these physiological changes in response to varying exercise conditions. This behavior might be attributed to a decrease in total peripheral resistance, which can mask variations in pulse pressure and, as a result, impede the ability to accurately detect the blood pulse, leading to a delayed HR reading. This delay seems to persist until the body adjusts to the new level of intensity and seems to be reduced at high-level exercise (running condition). Hence, although optical technology is effective during consistent and high-intensity workouts, the research shows that it does not match the accuracy of ECG-based heart rate monitoring when it comes to abrupt activity shifts, particularly during warm-up periods. These findings support observations made in laboratory tests with similar technologies (optical-based HR monitors) during cycling warm-ups. Moreover, it should still be noted that the optical device processes the raw photoplethysmographic data with company algorithms to extract HR value, making it impossible to evaluate the error introduced by these algorithm and filtering stages in the HR value estimation.

4.4 Validation of BioHarness 3.0 Zephyr

The research identifies two studies that assessed the validity of BioHarness Zephyr (ZB) heart rate variable against other commercially used devices (Polar T31), and six studies that assessed validity against gold standard criterion measure (ECG). Validity measures were established at resting, physical activity, and recovery phases, including both healthy recreational active males and females, as well as older patients with atrial fibrillation [45].

4.4.1 Results

In summary, the ZB displayed strong to very strong correlations of ≥0.67 during physical activity phases when compared with Polar T31 device. In addition, the device demonstrated very strong correlations of ≥0.87 at rest, strong to very strong correlations of ≥0.74 during various activities and very strong correlations of ≥0.99 throughout recovery when compared with a gold standard criterion measure (ECG).

Three studies reported heart rate biases of ≤3.00 beats per minute with (− 3.10–2.42) 95% limits of agreement in pairwise device comparison of ZB at rest, recovery phases or during various activities against ECG. Furthermore, the inter-device agreement between ZB and Polar T31 heart rate measures yielded agreement biases of ≤3.05 with (− 79.20–79.20) 95% limits of agreement during a treadmill walk/run testing protocols.Overall, ZB heart rate variable displayed better agreements (i.e. narrower limits of agreement) with ECG than with Polar T31 device, supporting criterion validity and suggestive of possible interchangeable use.

4.4.2 Discussion

After synthesizing ten studies addressing the measurement properties of the Zephyr BioHarness device, it can be noticed that there is good to excellent quality evidence supporting the reliability and validity of this device. That review suggests that the Zephyr BioHarness device can provide reliable and valid measurements of heart rate across multiple contexts, and that it might be useful for prevention or rehabilitation applications where field-based monitoring of heart rate is required in low-risk patient populations. The use of the devices in high-risk populations was not studied.

In that review, the validity of ZB heart rate variable against Polar T31 (ZB vs. Polar T31), and against gold standard criterion measure (ZB vs. ECG) yielded similar, strong to very strong correlation coefficients. However, the pairwise agreement parameters between ZB vs. Polar T31 (two studies), and ZB vs. ECG (six studies) varied.

4.5 Validation of Frontier X2

It is not possible to find any validation for the Frontier X2 because it is a new device so no studies have yet been done on it.

4.6 Comparison between devices

The Kardia Mobile 6L is the only one of the 5 devices that do not use a chest strap, in fact it utilizes an ECG method applied to left and right hands and the bare skin of the leg. Instead, the BioHarness 3.0 and the Frontier X2 are two chest straps with ECG device. The last 2 devices: Polar M400 and Garmin Forerunner 245 are GPS Sports Watch where the first one works only with polar H7 chest strap instead the second one uses both wrist-based optical monitoring and the option to use the HRM-Dual chest strap.

For what concerns the mode of detection, all devices use ECG monitoring, less than Garmin Forerunner 245 that uses PPG. With the HRM-Dual chest strap, also this device uses an ECG detection mode.

KardiaMobile 6L measures electrical impulses of the heart, capturing arrhythmias and other abnormalities; Polar M400 and Garmin Forerunner 245 has numerous functions to monitor athletes' workouts: heart rate, speed zones, GPS and other ones; BioHarness 3.0 offers multiple physiological metrics, including heart rate variability and respiratory rate; Frontier X2 focuses on providing high-fidelity ECG data, suitable for detecting various heart conditions.

All the monitoring capabilities are summarized in the Table 16.

Table 16. Summary of Monitoring Capabilities

Device	Monitoring Type	Key features	Use Case
Kardia Mobile 6L	ECG	- 6-lead ECG for more comprehensive data. - Ability to share ECG readings with healthcare providers. - App integration for tracking heart health over time.	Ideal for individuals wanting detailed heart health insights, especially those at risk for heart conditions.

Table 16. Cont.

Device	Monitoring Type	Key features	Use Case
Polar M400	ECG (Chest Strap H7)	- GPS tracking for outdoor activities. - Smart coaching features based on heart rate zones. - Data synchronization with the Polar Flow app for comprehensive analysis.	Great for runners and fitness enthusiasts who need reliable heart rate data and additional activity tracking.
Garmin Forerunner 245	PPG + ECG (HRM-Dual Chest Strap)	- Advanced metrics such as VO2 max, training load, and recovery time. - Smart coaching features based on user's data - Syncs with the Garmin Connect app for in-depth analysis and community sharing.	Suitable for serious athletes who need detailed performance metrics alongside heart rate data.
BioHarness 3.0	ECG	- Advanced research-grade metrics useful for sports science and clinical settings. - Data transmission via Bluetooth to compatible devices. - Long battery life and water resistance.	Ideal for researchers, coaches, and athletes needing in-depth physiological analysis during training.

Table 16. Cont.

Device	Monitoring Type	Key features	Use Case
Frontier X2	ECG	- Real-time data transmission to smartphones or computers. - Alerts for abnormal heart rhythms. - User-friendly app for tracking and sharing data.	Best for those monitoring specific heart health conditions or requiring continuous ECG data for clinical evaluation.

5 Experimental part: devices validation

In recent years, there has been a growing interest in the use of wearable technology to monitor physiological parameters in real-time, especially in sports and fitness contexts. Athletes, trainers, and healthcare providers increasingly rely on heart rate and other cardiac metrics to assess training intensity, recovery status, and overall cardiovascular health. Accurate cardiac data allows for tailored training, injury prevention, and improved performance outcomes.

While many consumer-grade wearables claim to provide accurate heart rate and electrocardiogram (ECG)-like data, these devices vary widely in terms of precision, especially when compared to clinical-grade ECG equipment. Differences in measurement technology, sensor placement, and algorithms used for data processing often led to inconsistencies. This variability is particularly problematic in sports, where movement and sweat may further affect device accuracy [27].

Furthermore, a recent systematic review reported that most older models of wrist-worn devices that are presently on the market from manufactures such as Apple, Fitbit, Garmin, Polar, and Samsung displayed variable results for heart rate and have poor accuracy for energy expenditure during a wide range of physical activities (e.g. walking, running and cycling) in young healthy adults. Nevertheless, newer models are constantly being developed by manufacturers and sold in the marketplace usually without publicly providing any information on how their research studies were conducted and/or without presenting any of their results. Thus, conducting proper validation studies by independent research laboratories becomes of importance [46].

This chapter aims to evaluate the accuracy and reliability of the five devices descripted before: KardiaMobile 6L, Polar M400 + Polar H7, Garmin Forerunner 245, BioHarness 3.0 Zephyr and Frontier X2. The object is to evaluate them by comparing their output with clinical-grade ECG readings in a controlled environment and in the field. The study also explores each device's potential applications, limitations, and effectiveness in sports settings. By establishing the degree of conformance of each device with the ECG standard, this research provides insights into their practical use and reliability in athletic training and performance monitoring.

5.1 Validation with Holter

The Holter monitor has long been regarded as the clinical gold standard for continuous cardiac monitoring. This portable ECG device records heart activity, offering a detailed view of heart function that is used to diagnose arrhythmias, ischemia, and other cardiac conditions. In clinical settings, the Holter monitor's accuracy and reliability make it an essential diagnostic tool. However, its size and complexity limit its use outside of controlled settings, particularly in sports, where lighter, less intrusive devices are preferred [47].

While new wearable devices offer a range of heart monitoring functionalities, their accuracy compared to clinical devices like the Holter monitor is often unclear. Validation against the Holter monitor is crucial to determine how closely these devices can approximate medical-grade accuracy. For athletes and active individuals, accurate heart data is essential for safe training and performance tracking, making validation studies indispensable in assessing each device's reliability in real-world sports applications.

5.1.1 Data acquisition

The analysis of the signals of a 26-year-old female athlete who practices aerial dance is carried out. For the acquisition of data, an information consent was signed pursuant to art. 13 of the European Regulation (EU) 2016/679 in relation to personal data for the Cardiovascular Bioengineering Lab of the Department of Information Engineering (Polytechnic University of Marche). The acquisition of the signals has been done in the Cardiovascular Bioengineering Lab. The devices used in the data acquisitions are: Holter ECG, BioHarness 3.0 Zephyr, Frontier X2, KardiaMobile 6L and Forerunner 245. In Figure 32, it is shown all the instruments used.

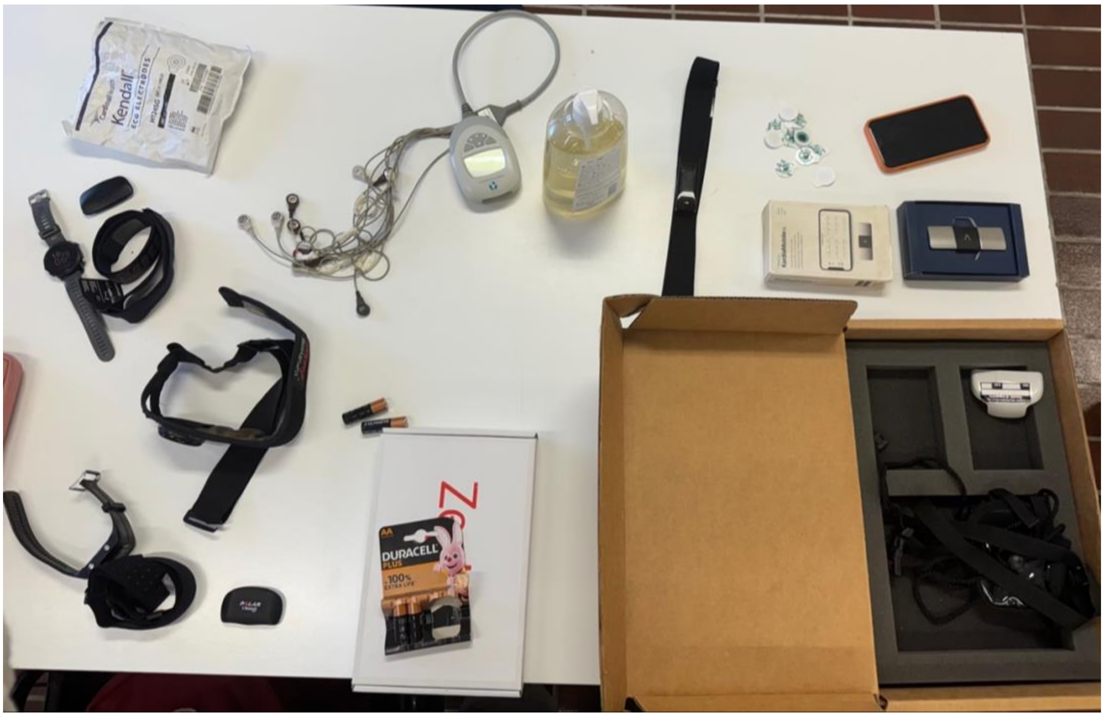


Figure 32. All the devices utilized in the acquisition.

The subject was in a resting position on outpatient bed and all devices are applied, as illustrated in Fig.33 and Fig.34.

Figure 33. Subject with worn devices.

Figure 34. Forerunner 245 on the subject’s wrist.

The Holter ECG used is a Holter M12A from Global Instrumentation. This device detected cardiac electrical activity using ten electrodes were appropriately positioned on the body surface of the subjects they have participated in the recording. The ten electrodes were positioned according to the configuration Mason Likar. The device was detached from the subject only once, at the end of the recording, as equipped with a battery that makes long acquisitions possible. The Holter device is also equipped with a memory card, which stores the signals that will be read and analyzed at the end of recording. The signals returned by the Holter ECG have µV amplitude and are sampled at 1kHz. The BioHarness 3.0 Zephyr is a wearable sensor with all the characteristics cited in the chapters before and it was positioned on the chest of the subject; the same for the Frontier X2. These devices were detached from the subject only at the end of the acquisition. The signals acquired from these two instruments are sampled respectively at 250 Hz for the BioHarness 3.0 and at 125 Hz for the Frontier X2. The Garmin Forerunner 245 is a device with a lot of characteristics already mentioned in the chapters before and it was applied on the wrist of the subject. The last one device KardiaMobile 6L is an important sensor to acquired ECG signals and with a lot of other features already specified. The acquisition of signal was performed by placing two ECG sensor electrodes under the fingers of the subjects, one on the right side and one on the left side and the last one up to the ankle of the user. The signals relating to this sensor are sampled at 300 Hz. The acquisition was carried out for a duration of approximately 30 s.

5.1.2 Methodology

To carry out the correlation analysis between the signals, Matlab software was used. After the loading the signals into the Matlab environment, the 12 electrocardiographic leads were resampled at 250 Hz for the BioHarness 3.0, at 125 Hz for the Frontier X2 and at 300 Hz for the KardiaMobile 6L. Once the alignment was done, the correlation analysis was carried out between the signals of the wearable sensors and all the individual derivations of the Holter ECG.

5.1.3 Results

The results of the clinic validation between the wearable sensor signals and the individual derivations are shown in the following tables. All the results related to Frontier X2 respect to the Holter ECG are represented in the Table 17, Table 18 and Table 19.

Table 17. Mean of the error of the Frontier X2.

LEADS	MEAN OF THE ERROR (ε)
I	51.0797
II	78.5520
III	29.0298
V_1	-61.5772
V_2	12.5889
V_3	53.6503
V_4	234.4301
V_5	278.1521
V_6	366.6187
aVR	150.2965
aVL	28.4691
aVF	28.1967

Table 18. Correlation index of the Frontier X2.

LEADS	CORRELATION INDEX (R)
I	0.1240
II	0.1485
III	0.1233
V_1	-0.1535
V_2	-0.0657
V_3	0.1397
V_4	-0.0810
V_5	-0.0214
V_6	0.0010
aVR	0.1769
aVL	0.1623
aVF	0.1479

Table 19. RMSE related to Frontier X2.

LEADS	RMSE
I	265.3435
II	479.7964
III	404.5640
V_1	392.1276
V_2	288.2335
V_3	433.9434
V_4	403.4708
V_5	539.2232
V_6	642.3697
aVR	475.2319
aVL	408.2559
aVF	277.2663

All the results related to KardiaMobile 6L respect to the Holter ECG are represented in the Table 20, Table 21 and Table 22

Table 20. Mean of the error of the KardiaMobile 6L.

LEADS	MEAN OF THE ERROR (ε)
I	-56.8401
II	335.1291
III	273.6470
aVR	47.3929
aVL	-14.1818
aVF	11.4560

Table 21. Correlation index of the KardiaMobile 6L.

LEADS	CORRELATION INDEX (R)
I	0.5169
II	0.3145
III	0.1630
aVR	-0.9154
aVL	-0.5763
aVF	0.9186

Table 22. RMSE related to KardiaMobile 6L.

LEADS	RMSE
I	230.3046
II	1274.8130
III	2174.4084
aVR	295.5583
aVL	187.5749
aVF	401.7940

5.1.4 Discussion

The mean error of the Frontier X2 ranges from negative to positive, with the highest errors in leads V_6 (366.62), V_5 (278.15) and V_4 (234.43), indicating a larger discrepancy in these leads compared to the Holter ECG (the device overestimates the data). The leads with the lowest error are V_2 (12.59), aVL (28.47) and aVF (28.19). Instead, the error values of the KardiaMobile 6L are more concentrated in certain leads, such as II (335.13) and III (273.65), with a significant negative error in lead I (-56.84). The leads aVL (-14.18) and aVF (11.46) have the lowest errores.

The correlation index of the Frontier X2 is generally low. The most correlated leads are aVR (0.1769) and aVL (0.1623), while other leads, such as V_6 (0.0010) and V_5 (-0.0214), show very weak correlations with the Holter ECG. Conversely the correlation index of the KardiaMobile 6L is much higher. The most positive correlated leads are aVF (0.9186) and I (0.5169), while aVR (-0.9154) and aVL (-0.5763) show the best negative correlations.

The RMSE value of Frontier X2 ranges from 265.34 in lead I to 642.37 in lead V_6, with the largest errors in lateral leads (V_5 and V_6). For KardiaMobile 6L the lead with the lowest RMSE is aVL (187.57), while the most problematic leads are III (2174.41) and II (1274.81).
The comparison between the Frontier X2 and the KardiaMobile 6L reveals notable differences in terms of performance in relation to the Holter ECG. While both devices show varying levels of error and correlation across the 12 leads, the KardiaMobile 6L generally demonstrates higher correlation indices and lower RMSE values, particularly in leads such as aVF and I, suggesting better alignment with the Holter ECG in those regions.
On the other hand, the Frontier X2 presents a more inconsistent performance, with significant errors and weaker correlations in most leads, especially in the lateral leads like V_5 and V_6. Its performance, while more variable, might still be useful for certain applications but shows considerable room for improvement in matching the precision of the Holter ECG.
In conclusion, the KardiaMobile 6L seems to provide more reliable results in terms of both correlation and RMSE, making it a more promising wearable ECG solution in comparison to the Frontier X2. However, further refinement and calibration could potentially improve the performance of both devices.

5.2 Comparative evaluation in the field

5.2.1 Study population

Data were acquired in 5 young athletes (S1-S5; age=18±5 years; body mass index=21.6±2.8; 5 females). All subjects were athletes practicing sport regularly. The anamnestic features of athletes are reported in Table 23. All participants signed an informed consent.

5.2.2 Data acquisition

Each subject was asked to do 3 activities, separated each other: running, speed skating and cycling. The activities were always recorded with 5 minutes of rest at the beginning and at the end of the training.

Cardiac signals were acquired while doing activities by means of 5 devices applied all to the subject at the same time less than one, as it is shown in Figure 35. The devices used were: Polar M400 with Polar H7, applied respectively one on the wrist and the other on the chest; Frontier X2 applied on the chest; Bio-Harness 3.0 Zephyr on the chest; Garmin Forerunner 245 on the wrist and the last one KardiaMobile 6L used only in the rest phases applied on the left and right fingers and on the left ankle or knee of the subject.

Figure 35. One subject with all the instrumentations utilized in the sport activity.

The speed of athletes in each phase were computed by considering the length (in km) of each phase and the timing recorded by the sport watches. Table 24 reports all the information related to athletes' acquisitions.

Table 23. Athletes' anamnestic features.

Subject	Age (years)	Gender	Body mass index	Smoker	Athlete
S1	13	Female	20.45	No	Yes
S2	16	Female	19.22	No	Yes
S3	21	Female	27.24	No	Yes
S4	15	Female	20.96	No	Yes
S5	26	Female	20.55	No	Yes

Table 24. Time (hour:min:sec) and speed ([km/h]) related to athletes' acquisitions.

Subject	Running	Speed Skating	Cycling
S1	21:52 [4.56]	21:21 [16.7]	20:53 /
S2	21:31 [5.42]	23.37 [18.1]	21:09 /
S3	20:57 [7.2]	22:04 [19.3]	20:23 /
S4	20:25 [7.23]	21:46 [20.3]	20:19 /
S5	1:21:56 [7.23]	53:18 [21.5]	1:26:50 [19.1]

5.2.3 Methodology

CaRiSMA [48, 49] is a Matlab code for cardiac monitoring during sport and it was used to analyze all data of this study. Anamnestic data are manually inserted by the user, while ECG and HRS data are transferred from the sensor to the computer or smartphone.

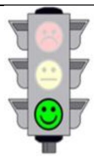
Briefly, CaRiSMA analyzes ECG and HRS and provides as output two traffic lights, one related to resting QT (QT- TL; QT interval being the most popular electrocardiographic marker of cardiac risk in clinical trials) and the other to exercise HRS (HRS-TL). Green, yellow and red QT-TL lights indicate normal, suspicious and pathologic QT interval, respectively, and thus a low, medium and high cardiac risk. The color is set comparing the measured QT interval with three thresholds, the minimal Threshold (minThrQT), the first maximal QT threshold (max-Thr1QT) and the second maximal QT threshold (maxThr2QT). These thresholds are based on clinical Seattle Criteria (defined by an international group of experts in sports cardiology in 2015) and depend on the athlete's anamnestic data. If the measured QT interval is comprised between minThrQT and maxThr1QT,QT-TL is green (normal QT); if measured QT interval is comprised between maxThr1QT and maxThr2QT, QT-TL is yellow (possible long QT interval-clinical consultation is suggested); finally, if measured QT is shorter than minThrQT longer than maxThr2QT, QT-TL is red (short or long QT interval-clinical consultation is required). Green, yellow and red lights of HRS- TL indicate a safe, suspicious and risky training intensity, respectively. The color is set by comparing exercise HRS against two thresholds, the theoretic maximum HR (TMHR) and user-specific HRS-related threshold (thrHR). These thresholds are computed considering the anamnestic data of the athlete. If HRS exceeds thrHR for less than 10% of exercise duration, HRS-TL is green (safe training intensity);if HRS exceeds thrHR for more than 10% of the exercise duration, but never exceeds TMHR, HRS-TL is yellow (training intensity reduction is suggested); finally, if HRS exceeds both exceeds thrHR for more than 10% of the exercise duration and TMHR, HRS-TL is red (training intensity reduction is required). Further details about CaRiSMA algorithm (such as thresholds and equations for lights determination) can be found in [49].

5.2.4 Results

Next tables report CaRiSMA Matlab code outputs (QT-TL and HRS-TL) and values of minThrQT, maxThr1QT, maxThr2QT, TMHR (calculated with Tanaka formula) and thrHR for each athlete. Moreover, resting QT intervals and HR values (mean value±standard deviation) in each sport are reported.

In Table 25 are illustrated all the results about BioHarness 3.0 Zephyr.

Table 25. Carisma output for all athletes involved in the study related to BioHarness 3.0 Zephyr.

		S1	S2	S3	S4	S5
TMHR (bpm)		199	197	193	198	190
thrHR (bpm)		169	167	164	168	161
HR (bpm)	**R**	152±33	170±22	158±21	148±28	153±27
	S	151±31	153±30	151±31	155±31	145±35
	C	150±32	152±29	144±34	152±33	151±32
HRS-TL	**R**					
	S					
	C					
minThrQT (ms)		321	321	321	321	321
maxThr1QT (ms)		479	479	479	479	479
maxThr2QT (ms)		499	499	499	499	499
QTc (ms)	**R**	331	357	374	379	331
	S	374	329	367	369	386
	C	328	328	370	374	328
QTc-TL	**R**					
	S					
	C					

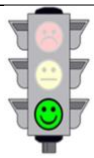
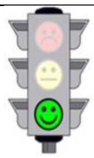
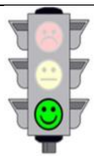
In Table 26 are illustrated all the results about Frontier X2.

Table 26. Carisma output for all athletes involved in the study related to Frontier X2.

		S1	S2	S3	S4	S5
TMHR (bpm)		199	197	193	198	190
thrHR (bpm)		169	167	164	168	161
HR (bpm)	**R**	177±13	143±35	148±35	113±29	152±22
	S	179±16	140±24	139±26	136±10	137±28
	C	124±9	101±12	113±29	104±21	135±29
HRS-TL	**R**					
	S					
	C					
minThrQT (ms)		321	321	321	321	321
maxThr1QT (ms)		479	479	479	479	479
maxThr2QT (ms)		499	499	499	499	499
QTc (ms)	**R**	333	466	425	398	387
	S	333	447	436	427	404
	C	417	413	398	400	414
QTc-TL	**R**					
	S					
	C					

In Table 27 are illustrated all the results about Forerunner 245.

Table 27. Carisma output for all athletes involved in the study related to Forerunner 245.

		S1	S2	S3	S4	S5
TMHR (bpm)		199	197	193	198	190
thrHR (bpm)		169	167	164	168	161
HR (bpm)	**R**	141±34	122±12	144±26	140±5	156±17
	S	94±3	116±4	122±10	129±15	110±10
	C	124±6	125±13	107±5	101±4	113±30
HRS-TL	**R**					
	S					
	C					
minThrQT (ms)		321	321	321	321	321
maxThr1QT (ms)		479	479	479	479	479
maxThr2QT (ms)		499	499	499	499	499
QTc (ms)	**R**	/	/	/	/	/
	S	/	/	/	/	/
	C	/	/	/	/	/
QTc-TL	**R**	/	/	/	/	/
	S	/	/	/	/	/
	C	/	/	/	/	/

In Table 28 are illustrated all the results about Polar M400+Polar H7.

Table 28. Carisma output for all athletes involved in the study related to Polar M400+Polar H7.

		S1	S2	S3	S4	S5
TMHR (bpm)		199	197	193	198	190
thrHR (bpm)		169	167	164	168	161
HR (bpm)	R	103±35	130±35	93±34	138±8	154±19
	S	100±48	108±37	84±36	129±15	131±31
	C	125±11	96±12	108±2	100±4	127±31
HRS-TL	R					
	S					
	C					
minThrQT (ms)		321	321	321	321	321
maxThr1QT (ms)		479	479	479	479	479
maxThr2QT (ms)		499	499	499	499	499
QTc (ms)	R	/	/	/	/	/
	S	/	/	/	/	/
	C	/	/	/	/	/
QTc-TL	R	/	/	/	/	/
	S	/	/	/	/	/
	C	/	/	/	/	/

In Table 29 are illustrated all the results about KardiaMobile 6L.

Table 29. Carisma output for all athletes involved in the study related to KardiaMobile 6L.

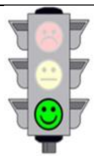
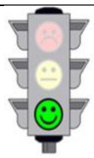
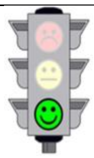
		S1	S2	S3	S4	S5
TMHR (bpm)		199	197	193	198	190
thrHR (bpm)		169	167	164	168	161
HR (bpm)	**R**	/	/	/	/	/
	S	/	/	/	/	/
	C	/	/	/	/	/
HRS-TL	**R**	/	/	/	/	/
	S	/	/	/	/	/
	C	/	/	/	/	/
minThrQT (ms)		321	321	321	321	321
maxThr1QT (ms)		479	479	479	479	479
maxThr2QT (ms)		499	499	499	499	499
QTc (ms)	**PRE R**	416	358	382	386	420
	POST R	428	432	397	399	423
	PRE S	386	369	397	399	434
	POST S	426	397	407	399	444
	PRE C	405	428	388	394	423
	POST C	385	371	375	399	429
QTc-TL	**PRE R**					
	POST R					
	PRE S					

Table 29. Cont.

		S1	S2	S3	S4	S5
QTc-TL	**POST S**					
	PRE C					
	POST C					

5.2.5 Discussion

After reviewing the graphs and delving into the characteristics of the devices provided, it was done a detailed comparison of the results, incorporating both data and insights from existing literature.
The data examined in this study are related to HR and QTc for all the 5 athletes, in particular the values of each different sport activity are analyzed. Only for the KardiaMobile 6L' s registrations of QTc are divided in pre and post activity evaluations.
Regarding the BioHarness 3.0 Zephyr, the QTc graphs produced appeared unclear and of low quality. This device utilizes a chest strap equipped with sensors capable of recording ECG and respiratory rate. Although designed for use under physical stress, the quality of the signals seems affected by artifacts, particularly during high-intensity movements. The Zephyr BioHarness 3.0 is praised for providing raw data access but is often criticized for its complex software and usability challenges. Its single-lead ECG recordings are insufficiently precise for clinical diagnostics or reliably assessing QTc during intense physical activity [3] [38].
The Frontier X2 is the device who provided the best QTc graphs among all the devices analyzed. Its chest strap appeared to deliver stable, high-quality results with minimal interference compared to others. The Frontier X2 is renowned for its accuracy in ECG acquisition and reliable heart rate monitoring. The combination of chest-based sensors and advanced software makes it particularly suitable for sports and non-diagnostic medical applications. However, it lacks the ability to provide full 12-lead ECG diagnostics, which limits its clinical value [39] [40].

The Polar H7 chest strap combined with the Polar M400 sport watch generally showed HR values consistent with other devices when functioning correctly. However, numerous *NaN* values were observed, likely due to interference from using multiple devices simultaneously. Polar chest straps are widely used in group sports but are susceptible to interference in environments with multiple Bluetooth devices or sensors. Their accuracy is usually good, but reliability can suffer in scenarios with multiple disturbance sources [41].

Garmin Forerunner 245, which uses wrist-based optical sensors, demonstrated HR performance similar to other devices. However, the precision may be lower compared to chest straps during high-intensity activities. Optical sensors are more comfortable but are affected by motion, lighting, and positioning. This explains possible discrepancies in HR data compared to chest straps, which are more reliable for continuous and high-intensity monitoring [42].

The KardiaMobile 6L provided high-quality QTc graphs for two subjects (S3 and S4) but struggled to acquire data for others. As it was used at rest, the lack of motion likely contributed to better recordings compared to other devices. The Kardia is FDA-cleared and designed for detecting arrhythmias at rest. It is not intended for ECG monitoring during exercise, which may explain the difficulties encountered with some subjects, particularly in pre- or post-exercise scenarios [32] [33].

In summary, Frontier X2 and KardiaMobile 6L stood out in terms of QTc signal quality. However, the Frontier X2 provided more consistent performance across all subjects, while Kardia was limited to resting periods.

For what concerns the HR data the simultaneous use of multiple devices may have negatively impacted the Polar H7, causing numerous *NaN* values in HR data. In general, chest straps (Frontier X2 and Polar H7) demonstrated greater precision compared to wrist-based sensors like Garmin Forerunner 245.

The BioHarness 3.0, despite its advanced capabilities, appears less user-friendly compared to other devices due to software limitations. Devices like the Garmin Forerunner 245 or Frontier X2 are more practical and user-friendly for daily sports use.

The study underscores the importance of matching device capabilities with the specific demands of the activity or monitoring goal. While chest-strap devices generally outperformed wrist-based sensors in accuracy, resting devices like Kardia provided exceptional data quality under optimal conditions. For sports or dynamic activities, the Frontier X2 emerges as the most reliable option, whereas Polar and Garmin devices are better suited for recreational or less demanding scenarios.

Further research could explore multi-device synchronization and signal enhancement techniques to improve the reliability of HR and QTc monitoring during exercise. By understanding each device's strengths and limitations, athletes and researchers can make informed decisions tailored to their specific needs.

Conclusion

In conclusion, the widespread adoption of wearable devices in the sports sector has revealed substantial potential for advancing performance monitoring and injury prevention. The results of this study highlight the accuracy and reliability of devices such as KardiaMobile 6L, Polar M400 with H7 sensor, Garmin Forerunner 245, BioHarness 3.0 Zephyr, and Frontier X2 in supporting athletes, coaches, and healthcare professionals in developing personalized training strategies. These devices provide a wide range of data, including heart rate variability, motion patterns, and physiological metrics, enabling real-time feedback and long-term monitoring. However, technological challenges remain, such as the need for more flexible materials, enhanced algorithms for data interpretation, and improved integration with existing sports practices. Future advancements in wearable technology are expected to address these gaps, paving the way for safer, more efficient, and scientifically informed athletic training. By continuing to evolve, wearable devices have the potential to become indispensable tools not only for elite athletes but also for recreational users, promoting a more accessible and data-driven approach to sports and health management.

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